Expanding Cement's Energy Flexibility: Indirect Heating, Electric Calcination and Energy Balancing

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Abstract*—Flexible solutions that help mitigate imbalances between supply and demand are an increasingly essential tool to increase the resilience of today's electricity grids. Demand side flexibility, in which industrial users of electricity increase or decrease their consumption based on the grid's balancing needs, offers a potentially efficient grid stabilization solution. The energy intensive heating processes in cement manufacturing, however, have previously been considered unsuited to demand side flexibility services, as the heat source is neither electrified nor interruptible, and therefore unable to vary its load on demand.*

This paper presents recent progress to overcome these barriers and unlock cement's potential as an energy flexible load balancing service. Indirect heating is shown to enable the electrification of the calcination process. Further advances in indirect heating technology demonstrate the potential to create hybrid-fuelled solutions that may dynamically use a combination of electricity and the combustion of conventional or alternative fuels in response to varying market conditions. Two potential benefits to cement producers are explored: 1) Enabling responsive switching to lowest cost energy inputs, and 2) generating new revenues through the provision of demand-side flexibility, in which a plant may decrease or increase its load at the grid's request, without impacting production.

Keywords—indirect heating, electrification, hybrid-fuel, demand side flexibility, grid load balancing.

INTRODUCTION:

Future proofing the long-term commercial viability of cement plants is one of the great challenges facing the industry. Economic and environmental pressures require simultaneous efforts to reduce costs – despite inflationary pressures and energy volatility – while also responding to commitments, where they exist, to reduce carbon emissions. Retaining a competitive and productive cement industry that can navigate these conditions is crucial to industry longevity.

Fuel and energy price volatility is a significant and growing contributor to the challenge of future proofing cement production **[1][2][3].** The availability and prices for various energy sources has fluctuated considerably over the last two decades **[4].** This type of volatility exists on all electricity grids and can be observed in other energy markets; natural gas (NG) and oil markets being a salient example **[5] [6].** Volatility in the natural gas markets has had direct and destabilising effect on wholesale electricity prices, as recent global crises have proven.

From the grid operator's perspective, there is a necessity for sources of electricity production to match – in real time – the fluctuating demands of electricity consumers **[7]**. This balancing act exists on all grids and is becoming increasingly challenging for regional transmission system operators (TSO's). Conventional generators such as coal, lignite and nuclear have shown a limited ability in providing grid flexibility, due to restrictions surrounding ramp-up, ramp-down rates and hot start-up durations **[8].**

This variability in energy supply is increasing the need for grid flexibility and energy balancing services to keep power grids stable and reliable **[9].** Sources of grid flexibility are being expanded and implemented across many regions, including interconnection capacity, and demand side flexibility.

Cement plants have long utilised their milling and grinding systems for the provision of services that artificially reduce demand for the grid's benefit **[10]**, with many cement plants already under contracts to stop or decrease some of their consumption at the request of their local grid. As this paper will argue, however, the cement industry has the potential to act as a much more valuable tool for electrical energy balancing activities, beyond the current demand reduction approaches taken to-date. Cement's intensive heating processes present a stranded potential for the provision of artificial demand creation and other energy balancing activities. Technical barriers, including a lack of electrification, have thus far prevented this potential from being realised.

This paper explores how a new technical approach, that combines indirect heating and hybrid-fuel use, could be used by the cement industry as a new source of energy flexibility. This approach could enable a plant to swiftly balance its energy consumption towards lowest cost sources, enabling lower cost production. This same system could potentially create new revenue streams for cement plants by providing a new source of demand-side flexibility to energy grids. This includes a novel

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approach to true grid balancing services, in which a cement plant may either *decrease* or *increase* its load at the grid's request, without impacting production.

I: The need for flexibility

Electricity generation has always required a mix of assets to match the demand of the grid. Traditional power generating assets are not particularly well suited to changing their output to match variable demand. Idle generation increases system costs, while global fuel price volatility and aging assets compound the challenge. Due to its benefits of low generation cost, low greenhouse gas emissions, and security of supply, global renewable energy capacity is expected to almost triple by 2030 **[11].** However, generation from renewable assets is typically dependent on daily and seasonal weather conditions and can therefore be expected to increase volatility of electricity supply.

The load placed on a grid, or demand that generators must consequently meet, is also becoming more variable. Reduced industrial output and increased demand from new data centers and non-industrial consumers all contribute to increased daily volatility.

Disparities between generation and use on the grid can create a power imbalance. Left unmitigated, these imbalances can destabilize power grids, leading to load shedding, cascading failures, infrastructure damage and blackouts **[12].**

Taking Belgium as an example, recent monitoring reports have highlighted a growing gulf between the minimum and maximum reference prices observed in intra-day markets in 2022 / 2023 **[13]**. As shown in table 1, extremes in both directions have become more pronounced over time.

Negatively priced electricity is becoming more common across many European electricity markets **[14].** In these instances, transmission system operators (TSOs) will set the day ahead electricity price to a negative value, essentially paying consumers to purchase excess load. In Belgium, the recorded hours of negatively priced electricity rose from 112 hours in 2022 to 222 hours in 2023 **[13].** This sharp rise in negative hours can be attributed to a lack of flexibility from generators to respond to changing demand profiles **[15].**

II: Flexibility and energy security

A recent report by the International Energy Agency (IEA), *Electricity Grids and Secure Energy Transitions* highlighted the risks associated with a lack of flexibility and sector coupling across energy systems **[9].** The report suggested that electricity systems will need to be upgraded and diversified if they are to cope with the instability and congestion that results from increasingly volatile demand from users and inflexible generation.

Year	2018	2019	2020	2021	2022
Minimum	-51.0	-150,0	-127.2	-184.4	-230.8
Maximum	590.0	276.5	612.2	604.2	1,891.7

Table 1. Minimum and maximum intraday reference prices in Belgium (Euro). Source: CREG Monitoring Report 2023 [14].

The report concluded that as a result of this instability and congestion, the need for system flexibility will likely double between 2022 and 2030 **[9].** If this need for flexibility is unmet, then the volatility of electricity costs is set to dramatically increase – hindering assets that are increasingly reliant on price stability to run economically **[9].** New sources of grid flexibility will likely need to be identified and developed across all grids.

III: Conventional sources of grid flexibility

Current sources of grid flexibility can be split into four broad categories: supply-side flexibility (power plants and generation management); interconnection flexibility (balancing loads between separate regional grids); energy storage infrastructure (hydro reservoirs and battery storage projects); and demand-side flexibility (industrial consumers that can reduce or shift in time their electricity consumption to help stabilize the grid) **[16].**

Some supply-side load balancing methods are in decline, reducing the flexibility available to power grids. For example, the rise of renewable generators, primarily due to their lower cost of production and certainty of operation in the longer term **[17]**, reduces supply side flexibility, and instead increases daily and seasonal supply variability. As such, the need for other forms of grid flexibility is growing and will continue to grow as the energy transition progresses.

Interconnection capacity is on the rise. Many countries are increasing their interconnector systems to enhance energy security and reliability **[9]**. For example, the UK is set to boost its interconnection capacity to over 18 GW by 2032 through several new undersea energy links **[18].**

Energy storage projects are becoming more prevalent worldwide, the global battery energy storage capacity rose by 40 GW in 2023, nearly doubling the total increase in capacity observed in the previous year **[19].**

Whilst some of these developments are promising for grid reliability, demand-side flexibility resources remain generally untapped. Existing providers typically only focus on energy arbitrage: decreasing, or changing, their base electricity demand to profit from fluctuating market prices.

A study carried out by German transmission operator, TenneT, has highlighted the need for industrial consumers to participate in the European balancing market, whereby demand side consumers could provide energy balancing services **[20].** The report highlighted that, at the time of publication, only a fifth of available industrial flexibility resources were participating in the balancing market, across any of the balancing products available. The report concluded that unlocking more of this potential could significantly increase the flexibility available to regional transmission operators, creating a new sector coupling between electricity markets and heavy industrial consumers.

Grid flexibility in Cement Manufacturing: Current Function and Limtations

I: Conventional, limited interruptible sub-processes.

A recent review of the feasibility of heavy industries such as steel, glass, aluminum and cement manufacturing to provide demand reduction (only) services highlighted some of the opportunities and barriers these processes present in co-functioning as demand-side flexibility providers **[21]**. The review highlighted that heavy industrial sub-processes are often critically interdependent. It is often neither economically nor operationally feasible to interrupt these processes for an auxiliary purpose, such as performing energy balancing activities. Other industrial processes can only be interrupted on advance notice, making them unfeasible for the immediate and responsive capabilities required to qualify as a grid balancing provider **[21].**

This same review argued that, within cement manufacturing, the integrated sub-processes of crushing and kiln feed preparation held the most promise for demand-side flexibility. The authors observed that flexibility is most often delivered through artificial *demand reduction*. Demand is reduced using an operational buffer, in the form of production storage silos, meaning that the grinding mills can be switched off from the grid without halting the greater cement manufacturing process. The sub process is thus grid integrated and load interruptible.

Cembureau has noted that there are limits to this operational buffer, and by proxy, limits to the downtime grinding mills can provide for grid-contracted demand reduction (roughly 5 – 7 days at a time) **[22].** Start-up and shut-down timeframes prevent this process from reacting to shorter market notice periods. The repeated starting up and shutting down of the grinding mills can cause wear to components over time.

To expand on this point, this paper notes that for over a decade now, cement plants have successfully used grinding processes for grid-integrated, energy balancing activities including frequency balancing products, load management capabilities, voltage control and reactive power delivery **[23]**. However, given that the grinding process is powered by electricity alone, its demand-side flexibility is generally delivered in only one direction, through temporary demand reduction, on advance notice.

II: Industrial Heat and Stranded Flexibility

The same review of heavy industries argued that the heating processes involved in clinker production, despite being highly energy intensive (39 – 45 kWh/ton), offer little to no potential for demand-side flexibility. Another review of demand flexibility at operational cement plants concluded that these heating processes are an uncontrollable continuous duty process and thus restricted in its available flexibility **[24]**. A comparative review of these two papers concludes that the current restrictions on heating processes within cement plants are two-fold.

Firstly, the heating processes involved in clinker production are neither grid integrated, nor electrified; the industrial heat required for this process is typically generated through the combustion of fossil fuels (primarily petcoke, coal, and oil), along with an increasing ratio of waste fuels and biomass **[25]**. The pyro-processing steps involved in clinker production have yet to be electrified at a commercial scale. Given that this process does not consume electricity, it is therefore incapable of providing flexibility in any direct or effective manner.

Secondly, these heating processes are difficult to interrupt. Conventional pyro-processing apparatus is operated on a continuous duty basis and is unlikely to possess the response capabilities necessary to participate in the balancing market. Ramping up and / or ramping down energy consumption, at pace, could cause instability across the manufacturing train, hurting product quality and plant efficiency. The repeated cycles of cooling and heating across the process would likely cause degradation to the refractory materials that protect the rotary kiln; temperature cycling being the leading cause of refractory failure within industrial heating systems **[26].**

Taking these points in combination, previous research has highlighted that conventional heating processes possess a high energy intensity, and therefore a high transfer potential. However technical barriers, involving grid integration and process stability, have restricted the flexibilities that industrial heating can offer.

Core Concept: Indirect Heating for Calcinatiom

Indirect heating, as depicted in Figure 1, is an emerging mineral processing approach, pioneered by the European Union funded LEILAC1 and LEILAC2 projects, that physically separates the heat source from the chemical reaction. For cement, this innovation provides two critical benefits:

- Reaction products are uncontaminated by flue gases and air and are not subject to air-ingress. When processing carbonates such as $CaCO_3$, unavoidable process CO_2 emissions are kept pure, making them readily available for capture, use and/or storage **[27]**.
- The heat transfer mechanism is independent of the energy input, thereby enabling multiple fuel options, including electrification and potentially hybrid fuel use.

When applied to cement production, indirect heating seeks to replace the conventional pre-calcination sub-processes common to modern cement plants, in which raw cement meal and / or limestone is heated via direct gas exchange **[28].**

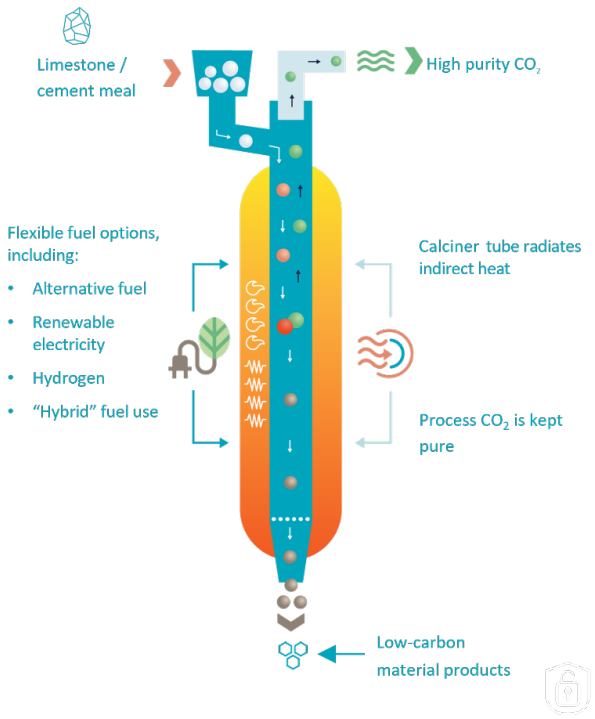

Fig 1. Depiction of an Indirect Heating System

Fig.2. A pilot scale indirectly heated electric calciner (blue tube) next to a demonstration scale natural gas powered indirectly heated calciner, Calix Technology Centre (CTC)), Victoria, Australia

In contrast to conventional pre-calcination, indirect heating operates by routing the materials to an inner alloy 'calciner tube', which is heated externally. The calciner tube radiates thermal energy to the raw materials, driving the calcination reaction through indirect heat exchange. Given that the heat source remains isolated from the calciner tube's contents, the core reaction process is thus kept independent from its heat source.

The physical isolation between heat source and reaction process allows for a greater flexibility on fuel inputs when compared with the conventional preheater / pre-calcination sub-processes. Conceptually, the calciner tube could be heated by a broad range of fuel sources, with varying compositions and thermal properties, including traditional and alternative fuels. Using the same process and equipment, *the calciner tube can be heated via electricity*, effectively treating the tube as a large resistor generating heat: as such, this processing method offers an initial pathway to electrifying industrial heat for the cement industry.

Validating Concepts

I: Electrified, indirect heating for calcination in cement plants

The principal of an electrified indirect heating process has been validated across several pilot technology campaigns. A pilot scale calciner, shown in figure 2, achieved high temperature electric heating by wrapping resistive heating elements around the outer walls of a calciner tube. When a current was applied, these elements transferred resistive heat to the calciner tube, which in turn radiated heat to the raw materials contained within.

As shown in Figure 3, these trials demonstrated the effective calcination of multiple cement raw meal and limestone feedstocks with varying compositions and particle sizes. These feedstocks were fed to the calciner tube in 100kg batches, at a flow-rate of 100kg/hr. The walls of the calciner tube were heated to between 900°C and 1050°C, delivering appropriate heat to drive the calcination reaction.

The trials successfully demonstrated a high extent of calcination (>90%) across all feedstocks that were processed and tested. These results are an encouraging step towards the electrification of industrial heating for cement, progressing the concept to a technology readiness level (TRL) of 5. Future work aims to further validate the concept in a commercially relevant environment.

II:Electrified calciner-tube heating: A pathway to hybrid fuelled calcination in cement plants.

In a further technology development, a new approach to electric indirect heating was developed at pilot-scale using a recently commissioned electric calciner that operates through an electrified calciner-tube heating approach. This design removes all external conductive heating elements. Instead, a current is applied directly to the calciner tube itself. This innovation simplifies the electrification process by using the calciner's alloy tube directly as a resistive heater and,

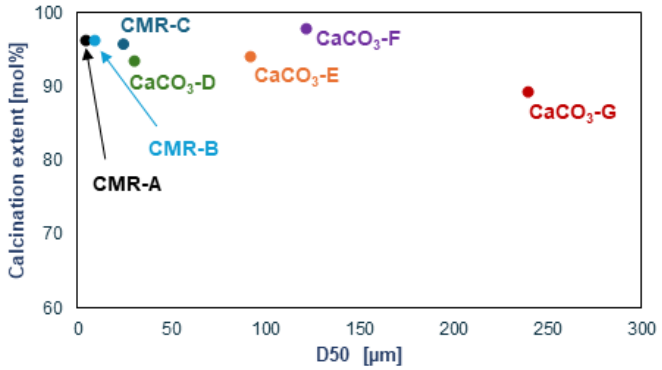

Fig 3. Extent of calcination across various feedstocks and material compositions.

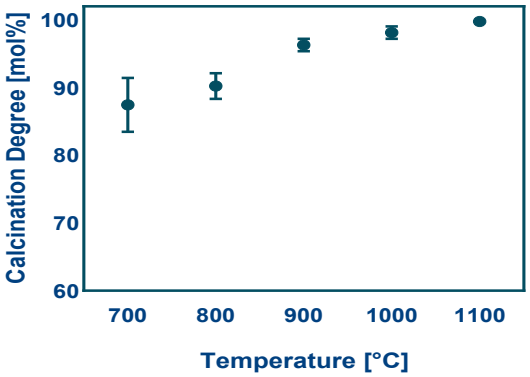

Fig 5. Directly electrified calcination of magnesite at various wall temperatures.

importantly, creates space for a second fuel source to be delivered by an external furnace.

A recent testing campaign sought to validate the concept of indirectly heating raw materials through a electrified calciner-tube. The feedstock trialled in this campaign was magnesite ($MgCO_3$), which was calcined to produce magnesia (MgO) and carbon dioxide (CO_2). During this trial, magnesite was fed to the calciner tube in 10kg batches at a flow rate of up to 6kg/hr. The tube was subsequently heated to between 700°C and 1100°C, delivering adequate heat to drive the internal reaction.

The results shown in figure 5 demonstrate a high extent of calcination at temperatures exceeding 900°C (as shown for the design in Figure 6). While the trial used magnesium rather than calcium-based feedstocks, the high temperatures and calcination rates achieved indicate the applicability of an electrically heated calciner tube to the heating and calcination processes within cement manufacturing. A materials testing campaign involving cement meal is currently ongoing, with results expected to be published in the coming year.

Future Development: Progressing the concept to hybrid-fuelled operations

The proof-of-concept for electrified calciner-tube heating has been successfully demonstrated at pilot-scale, paving the way to a hybrid-fuelled, indirect heating approach.

The results discussed above have provided a demonstration that through electric resistive heating, a calciner tube can deliver sufficient energy transfer to drive the calcination of limestone and cement raw meal. Critically, all electrical sub-systems for powering the tube were installed outside of the furnace walls, so no degradation of electrical components could occur. The success of these campaigns constitutes the first steps towards hybrid-fuelled operations, creating space for a secondary energy source to be introduced via an external furnace. Such a system could enable fuel combustion and electrical heating to occur simultaneously. Through co-regulation, a hybrid-fuelled indirect heating system therefore has the potential to make the critical breakthrough required to *enable the use of a variable, responsive and grid-integrated electric load while maintaining stable and uninterrupted cement production*.

Fig 4: A pilot-scale plant with electrified calciner tube heating, Calix Technology Center (CTC), Victoria, Australia

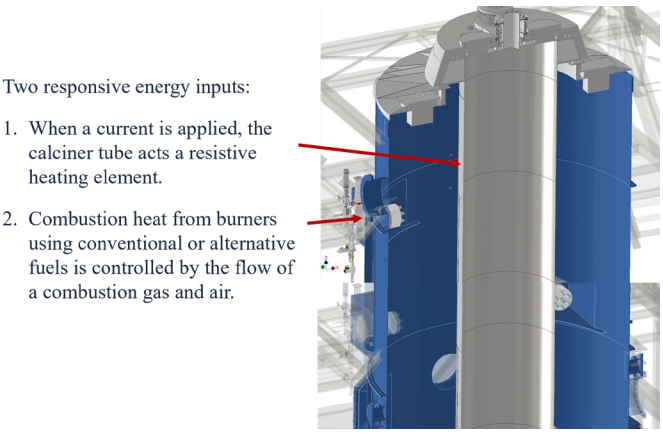

Fig 6. Design of a hybrid-fuelled, indirect calciner.

Some discussion around future designs are included below.

I: Electrified calciner-tube heating could be more effective in the long term

The use of resistive heating elements in an indirect heating system offers a potential pathway to electrify the calcination process. However, in the context of achieving hybrid-fuelling, this approach could present issues.

During hybrid-fuelled operations, fuel combustion and electrical heating must be able to co-occur simultaneously, in the same chamber. Traditional resistive elements experience shorter service lives and reduced reliability when they are consistently exposed to a combustion environment, raising concerns about the longevity of such an approach.

By contrast, the use of electrified calciner-tube heating should circumvent this issue. All components for heating the calciner-tube are installed outside the furnace. The calciner-tube itself will act as an electrical conductor, radiating heat to drive the calcination reaction. Fuel combustion and electric heating will be able to occur simultaneously, within the same chamber, without concerns for the service life of electrical components.

II: Use of a rectifier could potentially improve hybrid-fuel switching speeds

In future designs, a rectifier could be connected to each calciner tube. The rectifier would convert AC current from the grid to DC current that can be fed to the tube directly. This DC current provides a stable and consistent output, which would be well suited for precise temperature control and rapid changes in load. There are a number of possible routes to this integration which will be researched to minimise the switching time.

Expanding demand-side flexibility: The case for hybrid-fuelled heating in cement

I: Potential technical advantages over current approaches in cement

As highlighted earlier, current sources of demand-side flexibility in cement manufacturing are generally centered around the grinding and kiln feed preparation sub-processes. Reviews of this sub-process have highlighted the following limitations to this approach.

- The duration that demand-side flexibility can be provided is limited by the capacity of the grinding mills operational buffer. This process cannot stay off for extended periods of time without impacting greater plant operations.
- The speed at which this process can deliver demand-side flexibility is limited. Start-up and shut-down periods prevent certain capabilities. Generally, flexibility is procured on advance notice from the grid.
- Demand-side flexibility is generally delivered in one direction, through *demand reduction.*

A hybrid fuelled, indirect heating system would be a hot, continuous duty process, capable of running on a dynamic mix of combustible fuels and electric heating. Such a system could run on low cost, combustible fuel, as its base supply for a whole year, or on a seasonal basis. The cement plant would reserve its potential electricity consumption for the periods of excess grid supply: *The system could artificially increase demand during unexpected spikes in generation.*

The same system could run on grid-sourced electricity for a whole year, or on a seasonal basis, swapping to combustible fuels during periods of insufficient electricity supply: *The system could artificially reduce demand during unexpected losses in generation*.

Finally, a hybrid-fuelled, indirect heating system could potentially run on a continuous, dynamically balanced mix of both combustible fuels and electricity. *The system could respond quickly to price volatility, and grid instabilities, reducing costs and providing energy balancing services to the grid* (frequency and voltage stabilization, reactive power delivery).

All of these energy strategies could, in theory, be enacted and swapped between without interrupting the cement manufacturing process, putting energy flexibility in the hands of cement plant managers. To conclude, a hybrid-fuelled, indirect heating system would potentially present the following advantages.

- Demand-side flexibility would not be restricted by the capacity of an operational buffer. Its load can be interrupted without disrupting operations. The indirect heating process would remain continuously online during energy balancing activities, as either heating system can drive calcination independently.
- Demand-side flexibility could be provided on a long-term, seasonal basis (summer versus winter generation), and it could also be utilized on a short-term, fast-response basis (intra-day electricity price fluctuations, energy balancing services).
- A hybrid-fuelled approach could provide demand-side flexibility in both directions, delivering both demand reduction (*decreasing electrical load*) and artificial demand creation *(increasing electrical load).*

II: Potential techno-economic benefits of a hybrid-fuelled approach

For cement plants adopting this approach, the economic case for hybrid-fuelled, indirect heating can be described on two fronts.

a). Cement plants could prioritise the lowest cost of energy for the lowest cost of production

As outlined in the introduction to this paper, electricity markets across the world are experiencing increased volatility in wholesale electricity prices. This trend is due to a number of factors, often peculiar to each regional power grid. Instances of negatively priced electricity are becoming more common across European electricity markets.

If a cement plant were to adopt a hybrid-fuelled approach, then it could consume load during periods of low or even negatively priced electricity. Given that indirect heating is a continuous, hot-duty process, it would be placed to balance fuel consumption and load consumption throughout out the day, making it responsive to intra-day market events. This would increase the control and responsiveness that cement plant managers could exert over their own fuel and heating strategies.

b). Cement plants could access new revenue streams from energy balancing activities.

As outlined earlier in this paper, there are already cases studies of cement plants successfully providing demand-side flexibility via grinding mills. Grinding mills have granted similar revenue streams for other heavy industries. Recently a Swedish copper-mine repurposed its grinding-mill as an energy balancing tool, netting €400,000 in exchange for 8MW of contracted frequency holding reserve, (a reserve which was activated only five times in 2023) **[29]**.

Through a hybrid-fuelled indirect heating approach, the scope for energy balancing activities would likely be larger. A fully sized indirect heating system would create approximately 80MW of flexible, demand capacity, that could be called upon as a frequency holding reserve.

III: Revenue potential of indirect heating in cement

The revenue generated by the provision of grid balancing services is dependent on multiple factors that contribute to fluctuating market conditions. These factors, and the mechanisms used to value them, are specific to each regional grid and vary on a daily, and seasonal basis, with near-real time variable pricing. As such, the value of the contracts enabled by a hybrid-fuelled indirect heating system would vary dramatically per plant, region and market segment. Given the regional nature and number of variables inherent, such an analysis is beyond the scope of the current paper.

However, grid forecasting reports and other industrial cases can provide an initial indication as to the expected magnitude of likely revenues. For, example, a report commissioned by the Regulatory Assistance Project (RAP), estimated that demand-side flexibility has the potential to generate an annual value of €1.6 Billion across the German/Austrian, Nordic, and French electricity markets **[30].**

A handful of industrial consumers are already capitalising on this emerging revenue stream. An American data centre earned $31.7 million in energy credits from the Texas state grid in 2022 by providing demand-side reduction during a month-long instability event. A British water treatment company has projected an annual revenue stream of £5 million in flexibility payments from the national grid, also by providing demand-side reduction services by reducing power usage at its pump facilities **[31]**. As stated earlier, a Swedish copper mine earned €400,000 in annual revenue from re-purposing it's grinding mill into an energy balancing unit.

Early industrial providers of demand-side flexibility are accessing a small, emergent share of this projected market value. The value of demand-side flexibility in cement can be expected to increase considerably through the introduction of artificial demand creation. Future work will develop case studies based on selected regional grids to assess a range of techno-economic scenarios and help quantify the potential value for cement producers using a hybrid-fuelled indirect heating system.

Conclusion

This paper has outlined how a new technical approach – that allows a cement plant to help future proof operations through hybrid-fuel use – could unlock the cement industry's potential in generating new income through the provision of services to regional power grids, or through the ability to switch flexibly to the lowest cost energy sources rapidly. Whilst there is considerable work to be done in developing this technology to the point of commercial adoption, this paper has argued that this approach presents a first-of-a-kind pathway towards unlocking this capability for the cement industry.

We have outlined the operational value of an indirect heating system's capacity to modern energy grids, and its potential to meet the challenges presented by today's energy systems and changing demand profiles. The potential revenue generated for cement manufacturers adopting this approach might encourage a broader three-way sector coupling between the heavy industries, electricity markets and energy generators.

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