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Potentials for Energy Savings and Carbon Dioxide Emissions Reduction in Cement Industry

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Abstract. Cement production accounts for 7% of global carbon dioxide emissions, 3 to 4% of greenhouse gas emissions, and 7% of global industrial energy use. Cement demand is continuously increasing due to the rising worldwide population and urbanisation trends, as well as infrastructure development needs. By 2050, global cement production is expected to increase by 12 to 23% from its current level. Following the net-zero carbon 2050 agenda, both energy and emissions must be significantly reduced. Different production routes exist to produce cement that differs in energy intensity as well as carbon intensity. Similarly, a range of values exists related to energy and emissions for the major cement production stages i.e., raw meal preparation, clinkerisation and cement grinding. The same is the case with cement types produced. This study presents a literature review-based investigation and comparison of cement production practices in terms of energy consumption and CO_2 emissions. This will provide perspectives to the cement industry by identifying approaches that are the least energy and emissions intensive.

Keywords: Cement Production · Clinker · Energy · CO_2 Emissions · Net-Zero Carbon

1 Introduction

The cement sector accounts for around 7% of worldwide CO_2 emissions (the second-largest industrial CO_2 emitter after the agriculture industry [1]) and is the third-largest industrial energy consumer [2]. The growth and development of societies have amplified the demand for construction materials, cement especially has been an essential material due to its superior binding capabilities required in making concrete. By 2050, global cement production is expected to rise by 12–23% from its present level, 4200 Mt [2].

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Cement can be produced in large volumes from easily attainable materials from the earth's upper crust [3]. The most widely used type of cement is Ordinary Portland Cement (OPC), with Portland clinker content of 95%. Portland clinker cement-based concrete has come to be one of the most manufactured products in the world in terms of quantity and the most globally expended substance after water [4]. Conversely, the dependence of cement on the accessibility of natural resources is one of its limitations [5]. To put the matter in context, in order to manufacture a ton of Portland cement, 1.5 t of raw material is required [6], mainly limestone and clay (or marl) with lower amounts of gypsum. Clinker is the primary component of cement, and its use directly correlates to the CO_2 emissions produced during cement manufacturing as a by-product of fuel burning and limestone decomposition during clinker synthesis [7].

The cement industry is a massive consumer of raw materials, electrical power, and heat. Since the present study aims to review the literature and identify opportunities for the cement industry to get on track for the Net-zero agenda, it is essential to comprehend the cement manufacturing process and its principal mechanism in relation to energy utilisation and CO_2 emissions. The first process of OPC manufacturing is the production of Portland clinker. By adding up to 5% of gypsum, OPC is manufactured. By adding mineral additives (Supplementary Cementitious Materials – SCMs), different types of cement can be obtained. Therefore, it is also vital to highlight the different cement types and their substitutes that have a large impact on carbon reduction. In the next section, the research methodology followed is presented. Section 3 discusses the main cement production routes. Section 4 extensively examines the production process. Section 5 presents cement types and the latest advancements in binding materials with lower CO_2 footprints. Finally, Sect. 6 concludes the paper.

2 Methodology

The literature reviewed in this study was selected based on relevance to energy consumption and CO_2 emissions in cement manufacturing. Priority was given to recently published articles in scientific journals and technical reports from reputable organisations like the IEA. The aim was to compile comprehensive global perspectives on best practices, process enhancements, and efficiency opportunities across the main stages of cement production and the clinker substitutions. The main limitation is that some proprietary data on efficiency gains by individual manufacturers could not be accessed. The results should allow the industry to get an outlook on the current and emerging techniques for reducing energy consumption as well as carbon emissions.

3 Cement Production Routes

OPC is typically composed of calcareous and argillaceous minerals, with small amounts of iron-bearing elements and sand. The initial phase in making cement is to combine various raw materials that are readily available locally with fuel additives so that the final cement has the necessary chemical makeup.

Usually, the basic cement manufacturing process is divided into three production stages: 1) raw material preparation which involves mining, crushing, and grinding, 2) clinker production which entails calcining the materials in a rotary kiln then cooling the resulting clinker and mixing it with gypsum, and 3) cement finishing in which the cement is milled and then stored. Electrical motors, compressors, pumps, fans, conveyors, coolers, kilns, transportation systems, and lighting systems are the principal components of machinery used in the production of cement [8]. Cement can be manufactured using four methods, namely dry, semi-dry, semi-wet, and wet. The dry method is the most commonly used approach globally, with 90% of Europe employing this technique [9]. Generally, the state of the resources and raw materials have a major impact on the method selected.

The election of the manufacturing method is greatly impacted by the composition of raw materials and energy sources availability. Other factors also require consideration such as input materials quality and homogeneity, energy consumption, dust and CO_2 emissions, and operational cost and time. On average, the total energy cost of production using the wet process is approximately 50% higher in cement production than in the dry process [10, 11]. The energy efficiency can be improved from 26% to 58% by changing from a wet to a dry process [12]. Hence, the next section will focus on upgrades for the dry production route to further enhance its attributes.

4 Cement Production Process (Dry Route)

The production of one ton of cement generally requires 3.4–3.5 GJ of thermal energy and 110 kWh of electrical energy are needed (dry process) [13, 14]. Furthermore, manufacturing a ton of OPC releases 0.67–0.94 tons of CO_2 [11] which primarily depends on the fuel type and production route. Despite the superiority of the dry method in terms of production expenses and CO_2 emissions, it remains a highly energy-intensive process. Therefore, in order to analyse production characteristics and highlight points of possible improvements, a more profound outlook on the cement production process is crucial. The typical dry process of producing OPC consists of three major steps i.e., raw material processing, clinker production and finish grinding [14]. The majority of the carbon emissions are stemming from the clinker production stage which accounts for 85% of the total emissions. This stage is also the primary thermal energy consumer (99%) due to the kiln requiring a high temperature of up to 1450 °C [15]. Cement finishing is the most electrical energy-intensive stage (34%) due to the inherent inefficiency of the grinding process [16] as well as the small Blaine finesses required compared to the raw meal preparation stage [17].

Overall, energy conservation measures can range from straightforward ones like good housekeeping to complex ones with substantial capital expenses like replacing outdated equipment with energy-efficient ones. Several studies have generated a directory of possible measures and their associated possible energy savings per tonne of cement produced. Mokhtar and Nasooti [18] proposed several measures and the corresponding savings in terms of electrical and thermal energy of 0.1–18 kWh/t and 0.1–2 GJ/t. Hasanbeigi et al. [19] and Worrell et al. [20] presented possible technological advancements and processing measures concerning the three production stages in addition to general practices and plant wide procedures. Furthermore, they identified consequent fuel and electrical energy savings of up to 2.4 GJ/t and 24 kWh/t respectively along with CO_2

emissions reductions of up to 200 $KgCO_2$/t resulting from undertaking a specified action. The major production stages have been discussed in the following sections highlighting the key upgrades and prospective savings.

4.1 Grinding

The grinding process occurs at the beginning (raw material grinding) and the end of the cement making process (cement grinding) [21]. It is the main consumer of electrical power in cement production [22] which involves mills and air separators operating together in grinding circuits [23]. By analysing multiple dry cement production plants, Putra et al. [24] found that using vertical roller mills in the raw material grinding reduces the amount of energy required by 25% as well as the CO_2 produced by 57% when compared to ball mills. The efficiency of the roller mill can be further enhanced by utilising waste heat from the kiln for drying raw materials prior to grinding [25]. Upgradation of the mill for finish grinding has the potential to save up to 40% kWh/t electrical energy [11].

4.2 Clinker Production

In terms of clinker production, the most considerable improvements are related to energy efficiency measures in the kiln system which entails reducing the amount of fuel needed while maintaining clinker production volume [26]. Energy savings can be obtained through the realisation of a profitable trade-off between kiln fuel minimization and meal flow rate maximization, this also implies a significant emission reduction [27]. Dry-process kilns with a precalciner, a multistage cyclone preheater, and multichannel burners are considered to be at the forefront of current technology for clinker production. This results in the consumption of 3.0–3.4 GJ/t clinker which is deemed the best available energy level [2]. Operating the kiln with oxygen-enriched air can lead to up to 5% thermal energy savings. Grate clinker coolers are considered principal equipment that can enable greater heat recovery from hot clinker and can lead to up to 0.3 GJ/t clinker energy savings [28]. Beyond operating state-of-the-art kilns, increasing the burnability of raw materials can enhance the thermal efficiency of the process. Emission reduction of 112.61 $kgCO_2$/t can be achieved by implementing a preheater or precalciner kiln system [11].

4.3 General Measures

Afkhami et al. [14] found that general maintenance and plant optimisation can greatly enhance energy efficiency by minimising energy waste. They also indicated the importance of having the right auxiliary equipment which complement the systems in place. For instance, replacing outdated fans and pumps with more suitable models can reduce electrical energy consumption by 4%.

Assuming the best available energy efficiency technologies are fully implemented by 2030, Zhang et al. [29] quantified that 44% energy savings and 12% CO_2 emission reduction could be realised in China's major cement producing regions. This is mainly accomplished by upgrading outdated equipment to new high efficiency ones. An extensive variety of technologies, at different development stages, exist in the literature from research to commercialisation with the objective of reducing energy consumption and CO_2 emission. Advancing energy efficiency necessitates the strategic deployment of the Best Available Technologies (BAT) and the exploration of innovative methods to evaluate energy efficiency whenever possible.

By adopting relevant KPIs, the cement industry can successfully monitor their environmental impact at various levels of operations which can further inform decision-making and drive sustainable practices [30]. The energy benchmarking approach developed by Sarfraz et al. [31] revealed the elements responsible for actual energy use in the cement production (grinding) process. The proposed concept was applied to assess the efficiencies of grinding machines in relation to their theoretically required minimum energy, based on Gentani approach [32]. This analysis identified the most efficient equipment and highlighted the energy that is not directly utilized for production and could be utilised to assess retrofitting plans.

5 Cement Types

The global clinker-to-cement ratio was projected to have climbed from 2015 to 2020 at an average annual rate of 1.6%, reaching an anticipated 0.72 in 2020; this trend was the primary driver of the rise in direct CO_2 intensity of cement production during that time [7]. In contrast, the Net Zero Scenario sees a 1.0% annual decline in the clinker-to-cement ratio, with a global average of 0.65 by 2030 as a result of increased usage of blended cement and clinker alternatives.

Long-term replacements for clinker will be more crucial as the accessibility of by-products from other industries that are currently used as alternatives, such as fly ash from coal power plants and blast furnace slag (GGBS) from the steel industry, decrease due to the decarbonization of other sectors. According to the European standard EN 197 which defines and provides specifications to cement types, there are 5 families of cement products which are further divided into 32 common types of cement. The definitive difference between the types is the varying values of clinker content and SCMs. Due to the significant clinker content present in OPC, clinker substitution can significantly reduce CO_2 intensity from cement production even by 75% [33].

In 2017 the clinker-to-cement ratio in Europe was 77%. This indicates that, on average, 23% of clinker was exchanged for alternative materials [34]. India, after China, is the second largest producer of cement [35], with 9% of the global cement production in 2021, amounting to 300 Mt. It had a 30% share of blended cement production in total quantities of cement manufactured in 1995 which has increased to 73% in 2017, with overall clinker to cement ratio of 71%. This could be attributed to the boosted acceptability by the consumers, growing awareness of sustainability concepts, the obtainability of fly ash from power plants and the employment of advanced technologies [36, 37]. As a result, despite the increase in the overall production of cement, the total direct CO_2 emissions and energy utilisation have reduced over time due to the decline in clinker manufacturing. This is represented in Fig. 1. It can be seen that a considerable CO_2 reduction is possible in a scenario where OPC is completely replaced by Portland Pozzolana Cement (PPC). Further CO_2 reduction can also be achieved by replacing OPC with Portland Slag Cement (PSC) only.

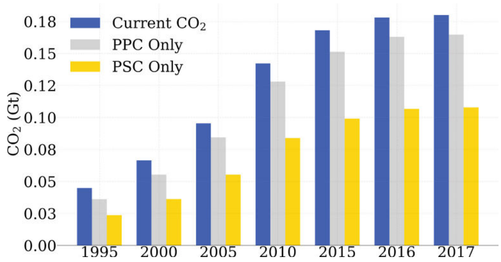

Fig. 1. CO_2 emissions for different scenarios of production in India based on cement type [36–38]

Saraswathy et al. [39] found that mechanical properties are not adapted by using blended cement with GGBS and pozzolana. More specifically, equivalent compressive strength values were obtained for PPC and PSC concrete types when compared with OPC concrete while the corrosion resistant properties for the blended cement were found greatly improved. However, the main limitation for mass production of blended cement is the availability of raw materials.

In recent years, new materials have been introduced to replace clinker with lower environmental impacts. One noteworthy material is calcined clay limestone cement (LC3), a promising new type of cement with 70% lower CO_2 emissions. It consists of clinker, limestone, and calcined clay [40]. Calcined clay being a manufactured product provides a much better opportunity for quality control [41]. Yu et al. [42] found that LC3 achieved the compressive strength that fulfils the requirements as per BS EN 197-1 standard. In comparison to regular Portland cement, blended cement with 50–60% LC3 has adequate compressive strength, lower hydration heat, less negative environmental effects, and lower material costs per unit strength, but less workability.

6 Conclusions

This study provides critical insights that can guide the cement industry practitioners towards enhanced sustainability and reduced environmental impacts. The research indicates multiple priority areas for the cement sector to target in pursuit of energy and emissions reductions.

Transitioning from wet to dry cement production processes is imperative, offering around 50% savings in energy consumption. Within dry processes, vertical roller mills should be adopted for raw material and cement grinding, reducing grinding energy intensity by 25% and the amount of CO_2 produced by 57%. For clinker production, best available technologies including precalciners, multistage cyclones, and modern kiln systems can minimise thermal energy use to 3.0–3.4 GJ/t clinker. Efficiency measures for clinker coolers, oxygen enrichment, and burnability improvements also hold promise.

However, process enhancements can only go so far. Fundamentally transitioning to blended cement products with higher proportions of fly ash, blast furnace slag and other supplementary cementitious materials is essential for deep decarbonization. Global clinker-to-cement ratios must decline, not rise further. Up to 75% reduction in CO_2 intensity can be obtained by substituting clinker with SCMs.

Cement companies must commit to phasing out outdated equipment, investing in efficiency upgrades, increasing clinker substitution, and developing innovative low-carbon solutions. With concerted efforts, the cement industry can overcome its inherent carbon-intensity and contribute positively to economy-wide decarbonization. Policymakers can assist through incentives for emissions reductions and sustainability measures.

The research is limited to commercialised technologies in which tools in development have not been considered, for example, carbon capture and alternative fuels. However, such tools have shown great potential in energy and CO_2 reduction and should have a worldwide implementation in the near future. Further work will be conducted on benchmarking consumption and production values across the cement industry in order to recognise best practices.

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