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RESEARCH ARTICLE

CO_2 MITIGATION OF A CEMENT INDUSTRY IN NORTH MACEDONIA, BALKANS PENINSULA: A SHORT REVIEW

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ABSTRACT

The cement industry is one of the largest industrial sources of CO_2 emissions, contributing approximately 1.8 Gt emissions annually. This study examines various strategies for reducing CO_2 emissions caused by the cement industry. Direct CO_2 emissions stem from the calcination process and fuel combustion in kilns, while indirect emissions arise from electricity generation and transportation. Measures to reduce CO_2 emissions include lowering the clinker-to-cement ratio with additives, replacing fossil fuels with alternative fuels, and enhancing the energy efficiency of kiln processes. At the Usje plant, the clinker-to-cement ratio is already low at 0.57, with variability between 0.72 and 2.58. Further reductions without affecting cement quality are limited. However, implementing a calciner and upgrading to advanced kiln technology, which lowers specific thermal energy consumption from 3.7 GJ/t clinker to 3.0 GJ/t clinker, are proposed to enhance efficiency. These improvements are projected to reduce CO_2 emissions by 65.7 kt in 2020. This review analyzes various CO_2 emission reduction measures in the cement industry to evaluate their environmental effectiveness. The measures examined include the use of alternative fuels, enhancement of kiln process efficiency, and co-production of synthetic fuels. The study also focuses on a cement plant in Macedonia and confirms that implementing these selected mitigation strategies significantly reduces CO_2 emissions.

KEYWORDS

Carbon Capture and Storage, Refuse Derived Fuel, European Union Emission Trading Scheme

1. INTRODUCTION

The cement industry is a major contributor to global carbon emissions, responsible for about 7-8% of total anthropogenic CO_2 emissions. Despite this, the industry has been instrumental in developing and implementing energy-efficient technologies and strategies to mitigate its environmental impact. This review explores the various approaches used by the cement industry in North Macedonia, situated in the Balkans Peninsula, to tackle the challenge of reducing carbon emissions (Khayium et al., 2023).

The cement industry in North Macedonia has implemented several initiatives to enhance energy efficiency and lower its carbon footprint. A key strategy has been the use of alternative fuels, including biomass, waste, and refuse-derived fuels, to replace traditional fossil fuels in the production process. This shift reduces dependence on non-renewable resources and helps divert waste from landfills, contributing to a more circular economy (Khayium et al., 2023).

The cement production process emits substantial quantities of various greenhouse gases, particularly CO_2. The cement industry alone is responsible for roughly 4.1% of the EU's and about 5% of the world's anthropogenic CO_2 emissions (Mikulčić et al., 2013). In line with the EU's commitment to combating climate change, the cement industry being the third largest carbon-emitting industrial sector in the EU must pursue a more sustainable future (Mikulčić et al., 2012b). The EU Emissions Trading Scheme (EU ETS), launched in 2005, requires cement plants within the EU to participate due to their high CO_2 emissions. Cement production is a significant source of both combustion-related and industrial process-related CO_2 emissions (Gordon et al., 2018). The calcination process and the combustion of fossil fuels account for nearly 90% of the CO_2 emitted from cement manufacturing, with the remaining 10% arising from raw material transport and other production activities. Calcination involves the thermal decomposition of limestone into lime, essential for clinker production. The combustion of fossil fuels contributes approximately 40% of these CO_2 emissions (Mislej et al., 2012).

There are four primary cement production processes that significantly impact the final cement quality, fuel consumption, and pollutant formation. These processes include raw material preheating, the calcination process, clinker burning, and clinker cooling. Before raw material preheating, the raw materials are collected, crushed, mixed with additives, and transported to the cyclone preheating system (Mikulčić et al., 2013).

Cyclone preheating systems have been developed to enhance the heat exchange process. Preheating takes place before the cement calciner and the rotary kiln. Once preheated, the raw material enters the cement calciner, where calcination occurs (Mikulčić et al., 2012b). Following

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calcination, clinker burning takes place, which is the most energy-intensive stage in cement production. A temperature of 1450°C is maintained to ensure proper clinker formation. After the clinkering process in the rotary kiln is completed, the cement clinker is rapidly cooled to 100-200°C. This rapid cooling prevents undesirable chemical reactions (Mikulčić et al., 2012b). Several effective measures can be implemented in cement manufacturing to reduce CO_2 emissions (Gartner, 2004). These measures not only lower local environmental impacts but also enhance the competitiveness of the cement industry. Addressing the calcination process, the largest CO_2 emitter, is an optimal starting point (Gartner, 2004). The most effective way to reduce CO_2 emissions from calcination is to use alternative raw materials that lack carbonates in their mineral structure. However, to date, no economically viable minerals have been discovered that produce cement comparable in quality to current Portland-based cements (Mislej et al., 2012).

Some researcher investigated the impact of substituting a portion of clinker with mineral additives on the mechanical properties of cement and the associated reduction in CO_2 emissions (Rosković and Bjegović, 2005). Their study demonstrated that decreasing the clinker-to-cement ratio through the use of various additives significantly reduces raw material consumption, thermal and electric energy usage, and CO_2 emissions. Given the high CO_2 content in flue gases, the most effective strategy for cutting CO_2 emissions in cement manufacturing is to capture the CO_2 from these gases and store it (Rosković and Bjegović, 2005). The cement manufacturing process results in CO_2 emissions from both combustion and calcination. Various effective reduction measures have been proposed and implemented. These methods not only lower global carbon environmental impacts but also enhance the attractiveness of the cement industry (Deja et al., 2010). A group researcher conducted an analysis of CO_2 capture technologies applicable to cement plants, focusing on a newly constructed plant in Scotland, United Kingdom (Barker et al., 2009). They assessed the costs and barriers associated with these technologies. The study concluded that oxy-combustion, as opposed to post-combustion, offers a more economically viable solution for CO_2 capture in cement plants. However, further research and development are necessary to enable the widespread deployment of this technology (Barker et al., 2009).

Additionally, a group researcher examined amine scrubbing and calcium looping technologies as potential CCS methods in the cement industry (Bosoaga et al., 2009). They found that calcium looping technology offers the advantage of utilizing lime extracted from the process cycle for clinker production, thereby reducing CO_2 emissions from cement manufacturing. Moreover, enhancing the energy efficiency of the clinker production process can further reduce CO_2 emissions. Currently, the most energy-efficient cement production technology available is the utilization of a dry rotary kiln in conjunction with a multi-stage cyclone preheater and a calciner (Bosoaga et al., 2009).

In a study focusing on China's cement industry, the importance of enhancing the energy efficiency of cement production processes for reducing CO_2 emissions and energy consumption was emphasized (Ke et al., 2012). Similarly, a group researcher investigated energy technology advancements that could contribute to decreasing energy consumption and CO_2 emissions in the EU's cement industry, highlighting the potential benefits of adopting the best available technology (Ke et al., 2012). A group researcher utilized a life-cycle assessment methodology to compare newly installed best available technology with former clinker production lines (Valderrama et al., 2012). Their findings demonstrated environmental improvements achieved through reduced fuel consumption with the implementation of the best available technology for clinker manufacturing.

Additionally, a group researcher supported by suitable numerical models, showcased the potential of computational fluid dynamics (CFD) in aiding the design and optimization of cement calciner operating conditions (Mikulčić et al., 2012b; Mikulčić et al., 2012c). This approach aims to facilitate the reduction of CO_2 emissions from the cement manufacturing process. The USJE Cement Plant, located in North Macedonia on the Balkan Peninsula, represents a significant industrial operation with a notable impact on local and regional CO_2 emissions. The cement industry is a major contributor to global greenhouse gas emissions, primarily due to the calcination process and the combustion of fossil fuels. Therefore, CO_2 mitigation strategies at such plants are critical for environmental sustainability and climate change mitigation (Barker et al., 2009).

The USJE Cement Plant, owned by TITAN Group, is one of the leading cement producers in the region. The plant has been operational for several decades and has undergone various modernization phases to enhance production efficiency and reduce environmental impact (Fodor and Klemeš, 2012). This review aims to calculate CO_2 emissions from the coproduction of synthetic fuels and propose alternative methods for producing low-carbon fuels. Additionally, it focuses on efficient processes for mitigating carbon emissions and explores different carbon capture and storage (CCS) techniques.

2. METHODOLOGY

Direct CO_2 emissions from cement production arise from two main sources, the calcination process, where raw materials are transformed into clinker, the primary component of cement; and fuel combustion, where fuels (such as oil, coal, and petcoke) are burned in kilns, producing CO_2 through chemical reactions between carbon and oxygen. Indirect CO_2 emissions occur during the generation of electricity needed for clinker and cement production, as well as during the transportation of raw materials, fuel, and final products (Taseska et al., 2008).

Several measures can significantly reduce CO_2 emissions in the cement industry. One effective approach is lowering the clinker-to-cement ratio by incorporating various additives. However, at the Usje cement plant, this ratio is already low (0.57), making further reductions unlikely without compromising the performance and durability of the resulting blended cements. Additionally, replacing fossil fuels with alternative fuels offers substantial CO_2 reduction potential. This strategy not only cuts energy costs but also serves as an environmentally friendly waste utilization method (Keith et al., 2018). Enhancing the energy efficiency of the kiln process presents another opportunity for reducing CO_2 emissions. Furthermore, co-producing synthetic fuels can integrate renewable energy sources into the cement manufacturing process, significantly recycling CO_2 from flue gases and further reducing emissions (Power et al., 2016).

The successful implementation of these measures is largely dependent on environmental policies and the legal framework. Integration of these measures will be feasible only if the policy environment supports the cost-effective deployment of the best available technologies. In this study, CO_2 emissions for each measure were calculated using the methodology outlined by the Intergovernmental Panel on Climate Change (IPCC) (Morgan and Waskow, 2014). The industry implemented a solid-based carbon dioxide capture technology utilizing a calcium-based method. This approach captures carbon dioxide at high temperatures through reversible reactions (Gordon, 2018). The calcium-based technology employs a calcium oxide-carbonate cycle, using limestone, a readily available and inexpensive raw material already used in cement production to separate CO_2 from the cement kiln flue gas at approximately 650°C. When this compound is heated to 950°C in an oxy-fired reactor, the calcination reaction releases CO_2. This CO_2 is then purified, cooled, liquefied, and captured before being stored in deep ocean locations or geologically engineered sites (Keith et al., 2018).

$$CaO + CO2 \rightarrow CaCO3 \quad (1)$$

The above Eq.1 is responsible for cement production, through the energy release system and calcination process.

$$Ca(OH)2 + CO2 \rightarrow CaCO3 + H2O \quad (2)$$

The above Eq. 2 shows the process of the concrete mixture through carbonation capturing.

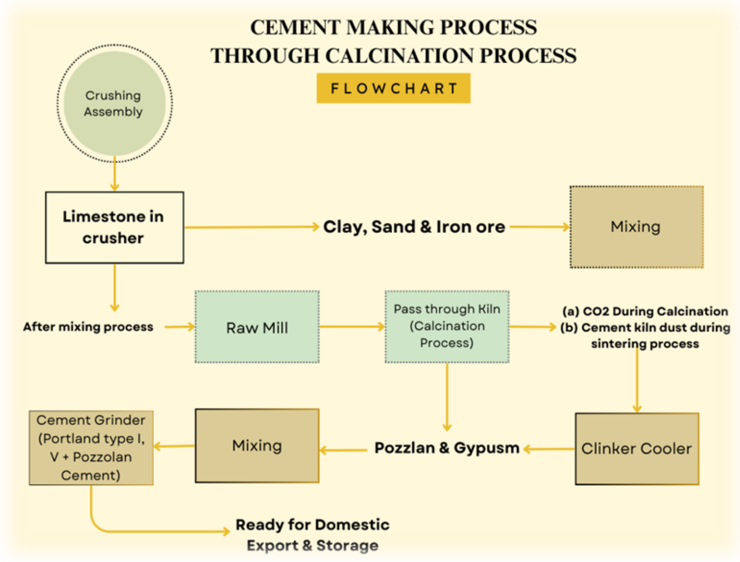

Figure 1: Flow diagram showing the process of cement making through calcination and CO2 emission.

2.1 Approaches

To address the harmful effects of rising global temperatures due to anthropogenic greenhouse gas (GHG) emissions from the cement industry in the US, two complementary approaches have been adopted: mitigation and reduction. Mitigation involves implementing measures to lower atmospheric carbon dioxide concentrations by reducing emissions or increasing the absorption rate of atmospheric CO_2 (Gordan et al., 2018). Currently, the atmosphere contains 3200 Gt CO_2 (870 GtC), with global emissions contributing several Gt CO_2 annually. Any meaningful measurement of impact must therefore be on the scale of at least one Gt CO_2 per year (Gordon et al., 2018).

2.2 Analysis

The cement industry is one of the world's largest industrial sources of CO_2 emissions, contributing 1.8 Gt annually. Over the years, the industry has significantly reduced CO_2 emissions per ton of cement through improved energy efficiency, substituting fossil fuels with waste materials considered 'carbon neutral,' and increasing the cement-to-clinker ratio by using more additives. However, the potential for further reductions through these methods is becoming limited. There is a growing imperative to further cut CO_2 emissions to mitigate anthropogenic climate change (Taseska et al., 2008).

Carbon capture and storage (CCS) offers one of the few viable opportunities for substantial emissions reductions. The cement industry is well-suited for CCS implementation, as cement plants are large point sources of CO_2, and the CO_2 concentration in their flue gas is relatively high. Additionally, over 60% of CO_2 emissions from modern cement plants stem from mineral decomposition, which cannot be mitigated by using alternative energy sources (Ali et al., 2011).

Key findings reveal that significant technological advancements in the cement industry from 2000 to 2020 have led to substantial energy savings and manufacturing improvements. Two major technological aspects were particularly effective, resulting in emissions reductions of 5372.43 Mt and 1291.72 Mt of CO_2, respectively. Efforts to restructure manufacturing processes fostered enhancements in energy efficiency and production practices, further aiding emission reductions (Morgan and Waskow, 2014).

In contrast, improvements in production efficiency and the adoption of biofuels and advanced engineered technologies resulted in CO_2 emissions reductions of 1080.26 Mt and 1135.85 Mt, respectively, indicating a significant decline from previous emission levels (Morgan and Waskow, 2014). Historically, policies and methods to mitigate CO_2 pollution have included carbon taxes and cap-and-trade systems. The cap-and-trade approach sets a maximum allowable level of pollution, and industries can obtain "pollution rights" through licenses. These licenses can be acquired via allocation, auction from the government, or by trading with other companies. On the other hand, a carbon tax is levied based on the amount of emissions, addressing the externality associated with CO_2. Its goal is to provide an incentive for emission reduction while ensuring cost predictability (Majumdar and Deutch, 2018).

Initially, this review focused on reducing CO_2 emissions without considering the carbon price. However, due to the simplicity of implementing a carbon tax policy, we then applied a price range from \$1/ton to \$81/ton of CO_2 to assess how operational decisions and investments change in response to the established price (Majumdar and Deutch, 2018).

Table 1: Raw materials used in cement manufacturing at USJE cement plant and their price for low carbon emissions per ton.

Raw material	Price (\$/ton)
Limestone	1.67
Iron ore	5.03
Clay	4.00
Gypsum	2.67
Pozzolan	20.00

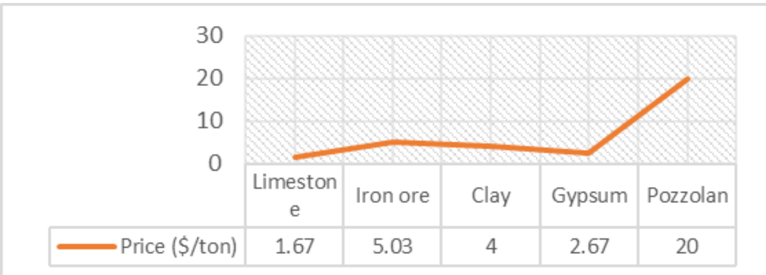

Figure 2: Graph showing the cost of raw materials used in Usje cement plant.

The Usje cement plant employs a dry rotary kiln equipped with a four-stage cyclone pre-heater and a clinker cooler. While the current setup does not include a calciner, the plant operator is planning to enhance cement production and simultaneously reduce CO_2 emissions. To meet both goals, the operator intends to upgrade the kiln process by incorporating a calciner (Ali et al., 2011). The energy efficiency of the cement plant is assessed by comparing its specific energy consumption to that of a benchmark plant. This comparison helps evaluate the plant's energy performance and the effectiveness of any improvements in the cement production process (Ali et al., 2011).

The current average specific thermal energy consumption of the kiln process at the Usje cement plant is 3.7 GJ/t clinker. This indicates potential for further enhancement of the plant's energy efficiency. The next logical step to achieve this improvement is the incorporation of a calciner before the rotary kiln (Ali et al., 2011). Table 2 presents various energy consumption indicators for the Usje cement plant.

Table 2: Energy consumption indicators for production of clinkers and electricity at cement plant (Mikulčić et al., 2013).

Indicators	Energy Consumption
Electricity consumption for production of clinker	80 GWh/y
Electricity consumption for production of cement	73.5 GWh/y
Specific consumption of electricity for clinker	80 kWh/t
Specific consumption of electricity for cement	42 kWh/t
Fuel consumption per kg clinker	3,700 kJ/kg
Total fuel consumption	3,700x109 kJ/y
Electricity consumption for other activities in the plant	40 GWh/y

CO_2 emissions from cement manufacturing in Macedonia saw a significant decline from 2007 to 2015 shown in Table 3, primarily due to reduced cement production during the economic crisis. However, after the economy began to recover post-2009, CO_2 emissions from cement production gradually increased.

Table 3: CO_2 emissions from the Usje cement plant.

Year	CO2 emission (kt/yr)
2007	992
2008	867
2009	812
2010	534
2011	439
2012	412
2013	428
2014	457
2015	409

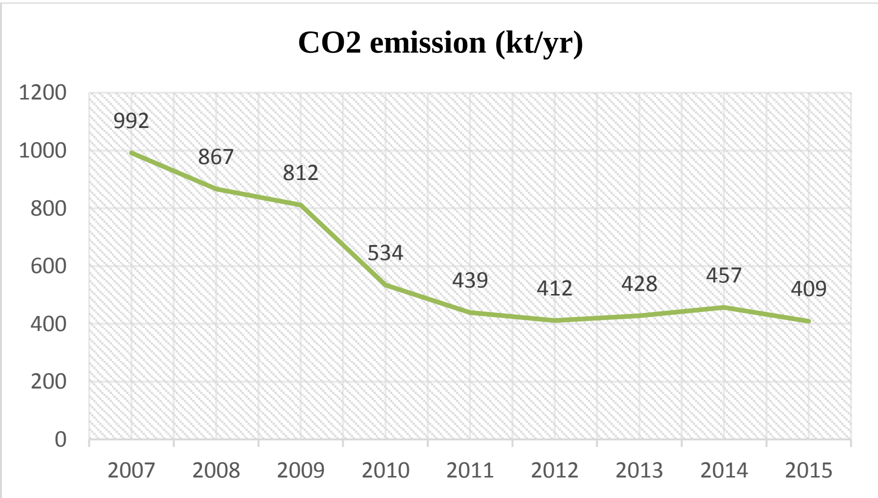

Figure 3: Graph showing the annual CO_2 emission per year at Usje cement plant.

3. Discussion

The advancement of commercial-scale CO_2 capture in the cement industry remains distant from widespread implementation. Research indicates that retrofitting existing cement plants with compatible CO_2 capture technology, particularly using calcium-based sorbents, is still in its early stages (Freund and Ormerod 1997). The development of industrial-scale CCS (carbon capture and storage) involves designing and constructing plants capable of handling real cement plant flue gas conditions, a critical step toward commercial viability (Schneider et al., 2012). Overall, CO_2 sequestration appears technically feasible for the cement industry. However, careful consideration is essential when planning CO_2 storage for community benefit, addressing uncertainties related to impurities (e.g., N_2, NOx, O_2, Ar, SOx) in the CO_2 product and their impact on storage and transportation in geological reservoirs. Additionally, CO_2 storage in areas of oil and gas exploration must account for potential leakage and the interaction with useful minerals (Schneider et al., 2012).

From an anthropogenic perspective, balancing the global carbon budget to achieve economic growth without increasing atmospheric carbon levels is crucial. This requires sequestering all anthropogenically produced CO_2 through environmentally acceptable, stable, and safe methods with minimal leakage risks. A carbon-neutral strategy focused solely on sequestration, without emission reduction, could be compromised by even small leaks, significantly affecting long-term planning for future generations (Aranda et al., 2013).

The potential for CO_2 emissions reduction was calculated by estimating the total energy consumption of the cement factory. It was assumed that Refuse-Derived Fuel (RDF) has a lower heating value of 15 MJ/kg and that RDF will constitute 50% of the fuel mix used for cement production in 2020. The projected amount of RDF to be utilized as an alternative fuel in 2020 is 123.5 kt, which is expected to result in a CO_2 emissions reduction potential of 104.4 kt CO_2 (Aranda et al., 2013).

For a more efficient kiln process, it was assumed that the current kiln process, with an average specific thermal energy consumption of 3.7 GJ/t clinker, will be upgraded to the best available kiln process, which has an average specific thermal energy consumption of 3.0 GJ/t clinker. This upgrade is anticipated to reduce fuel consumption. The projected fossil fuel usage for the more efficient kiln process in 2020 is 89.5 kt, compared to 110.4 kt for the existing process. The CO_2 emissions reduction potential for this more efficient kiln process in 2020 is estimated to be 65.7 kt CO_2.

Table 4: Reduction cost for the reduction potential scenarios for effective working and low emissions.

Reduction Potential Scenarios	**Reduction Cost (kt/CO_2)**
Long-dried rotary kilns	44.39
Dry kilns with the preheating	90.72
Dry kilns with pre-calcination and preheating	92.38
Upgrading the existing long dry kilns to units with preheating	46.33
Upgrading the existing long dry kilns to units with pre-calcination and preheating	47.99
Oxy-fuel combustion carbon storage and capture	61.26

4. Conclusion

The cement industry in North Macedonia has proactively addressed its carbon emissions by adopting energy-efficient technologies and exploring alternative fuel sources. These initiatives have significantly contributed to CO_2 mitigation efforts in the region. As the industry continues to develop and implement innovative strategies, it is anticipated to play a growing role in the transition toward a more sustainable and low-carbon future.

Balancing global carbon budgets and achieving carbon-neutral economic growth requires a multifaceted approach, combining emission reduction and effective sequestration methods. Policies such as carbon taxes and cap-and-trade systems play a critical role in incentivizing these efforts. Ultimately, the cement industry's proactive measures and ongoing innovations are pivotal in mitigating its environmental impact and contributing to global climate change goals.

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