Journal of Building Engineering 86 (2024) 108861

Contents lists available at ScienceDirect

Journal of Building Engineering

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

# Decarbonising cement and concrete production: Strategies, challenges and pathways for sustainable development

Salim Barbhuiya [a,*], Fragkoulis Kanavaris [b], Bibhuti Bhusan Das [c], Maria Idrees [d]

[a] Department of Engineering and Construction, University of East London, UK
[b] ARUP, London, UK
[c] Department of Civil Engineering, NIT Surathkal, Karnataka, India
[d] Faculty of Civil Engineering, University of Engineering and Technology Lahore, Pakistan

ARTICLE INFO

*Keywords:*
Decarbonisation
Cement industry
Concrete production
Sustainable construction
Low-carbon technologies
Policy considerations

ABSTRACT

This paper provides a comprehensive analysis of decarbonising cement and concrete production, addressing strategies, technologies, policy considerations, case studies, economic implications, challenges and future recommendations. The cement and concrete industry are major contributors to carbon emissions and environmental degradation, making decarbonisation crucial for sustainable development. The paper explores various strategies, including alternative clinker technologies, carbon capture and storage, improved energy efficiency, low-carbon cements and circular economy approaches. Additionally, it examines technologies such as supplementary cementitious materials, carbonation, low-carbon concrete mixes, recycling and novel manufacturing processes. The importance of policy interventions, collaboration and standards and certifications is emphasised. Case studies and best practices highlight successful decarbonisation initiatives, while economic implications and market opportunities are considered. The paper also identifies challenges, including technological limitations, financing constraints, resistance to change and the need for awareness and education. Finally, future recommendations focus on pathways for deep decarbonisation, policy measures, research priorities and fostering collaboration. This review serves as a valuable resource for researchers, policymakers and industry professionals striving to achieve sustainable and low-carbon cement and concrete production.

## 1. Introduction

Cement and concrete production have emerged as significant contributors to greenhouse gas emissions, necessitating urgent decarbonisation efforts. The environmental impact of these industries is driven by the carbon dioxide ($CO_2$) released during cement manufacturing, along with energy-intensive processes involved in grinding and transportation. Concrete, which heavily relies on cement, further amplifies these environmental challenges. Thus, decarbonising cement and concrete production is crucial for sustainable construction practices and mitigating climate change. Decarbonisation offers several key benefits. First, it is an essential element of global climate change mitigation strategies, aligning with international goals and targets. By reducing $CO_2$ emissions from cement and concrete production, significant progress can be made towards achieving climate objectives [1–4]. Additionally, decarbonisation supports sustainable development in the construction industry, ensuring long-term environmental preservation and resource conservation [5]. As sustainability becomes increasingly important, businesses that prioritise decarbonisation gain a competitive advantage, attracting environmentally conscious consumers and adapting to evolving market demands.

---

* Corresponding author.
*E-mail address:* s.barbhuiya@uel.ac.uk (S. Barbhuiya).

https://doi.org/10.1016/j.jobe.2024.108861
Received 12 September 2023; Received in revised form 5 February 2024; Accepted 17 February 2024

One of the primary motivations for decarbonisation is the urgent need to mitigate climate change. Cement and concrete production contribute significantly to greenhouse gas emissions, particularly $CO_2$ [6–8]. By reducing carbon emissions from these industries, we can make substantial progress in addressing the global climate crisis. Decarbonisation aligns with international agreements and targets, such as the Paris Agreement, which aim to limit global temperature rise and combat the adverse effects of climate change [9–11].

Decarbonisation plays a crucial role in promoting sustainable construction practices. The construction industry is a major consumer of cement and concrete and their production processes have a significant environmental impact. By decarbonising these materials, we can reduce their carbon intensity and minimise the overall ecological footprint of the construction sector. This transition towards sustainable construction practices contributes to the conservation of resources, minimises waste generation and supports the preservation of ecosystems [12–14]. Furthermore, embracing decarbonisation offers companies a competitive edge in the market. With increasing public awareness and demand for sustainable solutions, businesses that prioritise decarbonisation can attract environmentally conscious consumers and meet evolving market expectations. By adopting low-carbon production methods and offering environmentally friendly products, companies can position themselves as leaders in the industry and enhance their brand reputation [15,16].

Decarbonisation also drives innovation and technological advancements. The pursuit of alternative cementitious materials, such as fly ash or slag, encourages research and development in the construction sector. It fosters the exploration of innovative manufacturing processes, carbon capture and storage technologies, energy-efficient practices and sustainable construction methods. These advancements not only contribute to reducing carbon emissions but also stimulate economic growth, job creation and technological progress [17,18]. Additionally, decarbonisation promotes resource conservation and waste reduction (Anouzla & Chew, 2023 [null]). By incorporating recycled materials and embracing circular economy principles, the demand for new cement production can be minimised [19–21]. This reduces the strain on natural resources and decreases the environmental impact associated with extracting and processing raw materials.

Various strategies are being pursued to achieve decarbonisation. Exploring alternative cementitious materials, such as fly ash, slag and silica fume, presents opportunities to reduce the reliance on traditional cement and lower the overall carbon footprint of concrete production [22–24]. Carbon capture, utilisation and storage (CCUS) technologies capture $CO_2$ emissions from cement plants, preventing their release into the atmosphere. The captured $CO_2$ can be stored underground or used in other industrial processes, fostering a circular economy [25–27]. Energy efficiency measures, coupled with the integration of renewable energy sources like solar and wind power, play a crucial role in reducing emissions throughout the cement and concrete manufacturing processes. Embracing circular economy principles, such as optimising material use, promoting recycling and reuse of concrete and incorporating recycled aggregates, minimises the demand for new cement production and reduces waste generation [28–30]. Lastly, ongoing technological innovations focus on developing carbon-neutral binders, advanced manufacturing methods like 3D printing and ultra-high-performance concrete that require less cement [31–33].

The motivation behind this review paper is to comprehensively explore and analyse the importance of decarbonising cement and concrete production. With a clear understanding of the significant impact these industries have on greenhouse gas emissions and their role in climate change, the paper aims to highlight the urgent need for decarbonisation. By examining the benefits of sustainable construction practices, market competitiveness, innovation, resource conservation and waste reduction, the review seeks to emphasise the multifaceted reasons why decarbonisation is essential. Through a thorough examination of the subject matter, the paper aims to provide valuable insights and promote the adoption of low-carbon alternatives in the cement and concrete industry.

While this review paper aims to provide a comprehensive analysis of the importance of decarbonising cement and concrete production, it is essential to acknowledge its limitations. Firstly, the paper may not cover every aspect or development in the field of decarbonisation, as the topic is vast and continually evolving. Additionally, the review relies heavily on existing literature, which may have inherent biases or limitations. The paper's conclusions and recommendations are subject to the quality and availability of the reviewed studies. Furthermore, the review may not delve into specific regional or contextual variations, as the impact and feasibility of decarbonisation strategies can vary depending on geographic location and local conditions.

## 2. Carbon footprint of cement and concrete

### 2.1. Overview of cement and concrete production

Cement production is a complex and essential process that involves several stages and impacts various aspects of the construction industry and the environment. The first step in cement production is the extraction of raw materials, primarily limestone, clay and shale [34]. These materials are typically obtained from quarries or mines, where they are carefully selected and excavated. The quality and composition of the raw materials play a crucial role in the final properties of the cement [35,36]. Once extracted, the raw materials undergo a series of preparation processes. The materials are crushed into smaller pieces and then transported to the cement plant. At the plant, the raw materials are further ground into a fine powder to increase their surface area and facilitate chemical reactions during clinker formation.

The heart of cement production is the kiln, where the raw materials are heated at high temperatures. The kiln operates at temperatures reaching around 1450 °C and allows for the chemical transformation of the raw materials into clinker [37–39]. During this process, a series of complex reactions occur, including the decarbonation of limestone and the formation of calcium silicates and aluminates, which are the main constituents of clinker [40]. After leaving the kiln, the clinker is rapidly cooled to prevent the formation of undesired crystal structures. The cooled clinker is then ground into a fine powder, along with a small amount of gypsum, to produce the final cement product. Gypsum is added to regulate the setting time of the cement and control its early strength development [41]. The schematic diagram of cement production is shown in Fig. 1 [42].

Cement production is known for its significant energy consumption and greenhouse gas emissions. The primary energy source used in cement plants is fossil fuels, such as coal, petroleum coke and natural gas. These fuels are combusted in kilns to provide the high temperatures necessary for clinker formation. The combustion of fossil fuels results in the release of carbon dioxide ($CO_2$) into the atmosphere, contributing to climate change. To address these environmental concerns, the cement industry is actively seeking ways to reduce its carbon footprint. Energy efficiency measures, such as optimising kiln design, improving heat recovery systems and implementing alternative fuels, can significantly reduce energy consumption and $CO_2$ emissions. Alternative fuels include biomass, waste-derived fuels and even non-recyclable plastics, which can be used as a substitute for traditional fossil fuels.

Moreover, the cement industry is exploring innovative technologies like carbon capture and storage (CCS) to capture $CO_2$ emissions from cement plants. CCS involves capturing the $CO_2$ emitted during cement production, transporting it and safely storing it underground or utilising it in other industrial processes. These technologies have the potential to significantly mitigate the environmental impact of cement production. Additionally, sustainable practices in cement production are being emphasised. This includes re-

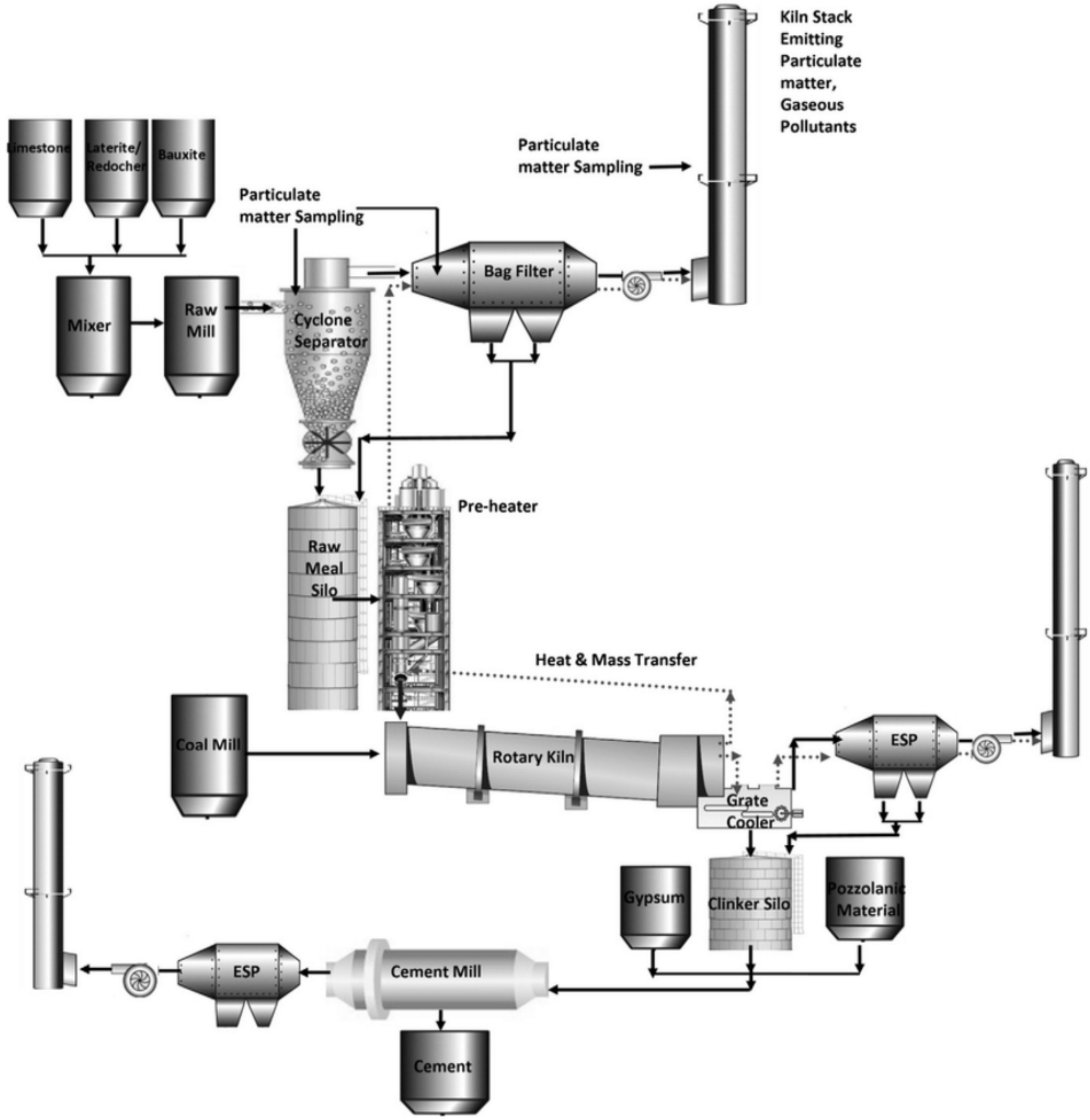


Fig. 1. Schematic diagram of cement production [42].

sponsible mining and quarrying to minimise environmental disturbances, efficient use of water resources and proper waste management to reduce the impact on ecosystems.

Over the past few decades, cement production has witnessed significant growth due to increasing urbanization, population growth and infrastructure development in many regions. The global cement production worldwide from 1995 to 2022 is shown in Fig. 2. China has been the largest producer of cement for many years, followed by India, the United States and other emerging economies. These countries have experienced rapid industrialisation and urban expansion, driving the demand for cement. The global cement industry has undergone technological advancements to improve production efficiency and reduce environmental impact. Energy-efficient kilns, advanced grinding systems and alternative fuels are being employed to optimise production processes and reduce carbon emissions [43–46]. Additionally, initiatives are underway to explore alternative raw materials, such as fly ash, slag and limestone, to reduce the reliance on traditional materials and minimise the environmental footprint of cement production [47–50].

The COVID-19 pandemic had a significant impact on global cement production. Lockdown measures, supply chain disruptions and reduced construction activities led to a temporary decline in cement demand and production in many countries. However, as economies recover and infrastructure projects resume, cement production is expected to rebound. To monitor global cement production trends, industry organisations, such as the World Cement Association (WCA) and the Global Cement and Concrete Association (GCCA), compile and publish annual reports and statistics [52,53]. These reports provide comprehensive data on cement production, consumption and trade at the regional and global levels. It is important to note that cement production varies by country and region, influenced by factors such as economic growth, construction activity, government policies and environmental regulations.

Concrete production is a fundamental process in the construction industry, involving the mixing of cement, aggregates, water and sometimes additives to create a versatile and durable construction material. The process of concrete production begins with the selection and preparation of aggregates, which typically include sand, gravel, crushed stone, or recycled materials. Aggregates are carefully graded to achieve the desired strength, workability and durability of the concrete [54–58]. Next, cement, the binding agent, is combined with the aggregates. Portland cement, the most common type of cement used in concrete production, is made by grinding clinker, a product of heating limestone and other materials and adding gypsum to regulate the setting time. Water is then added to the mix to initiate the chemical reaction called hydration, where the cement particles react with water and form a paste that coats the aggregates. The water-cement ratio is crucial as it determines the workability and strength of the concrete [59,60]. Proper control of water content is essential to achieve a concrete mix that is easy to place, compact and has the desired strength and durability.

In some cases, additives are incorporated into the concrete mix to enhance specific properties [61–63]. These additives can include plasticisers, which improve workability; air-entraining agents, which introduce microscopic air bubbles to increase freeze-thaw resistance; or superplasticisers, which enhance flowability without compromising strength. Once the concrete mix is thoroughly mixed, it is transported to the construction site and placed into formwork or moulds. The concrete is then compacted to remove air voids and ensure proper consolidation. Various methods can be used for compaction, including vibration, tamping, or the use of special equipment [64,65]. After placement, the concrete undergoes a curing process to allow the hydration reactions to continue and the

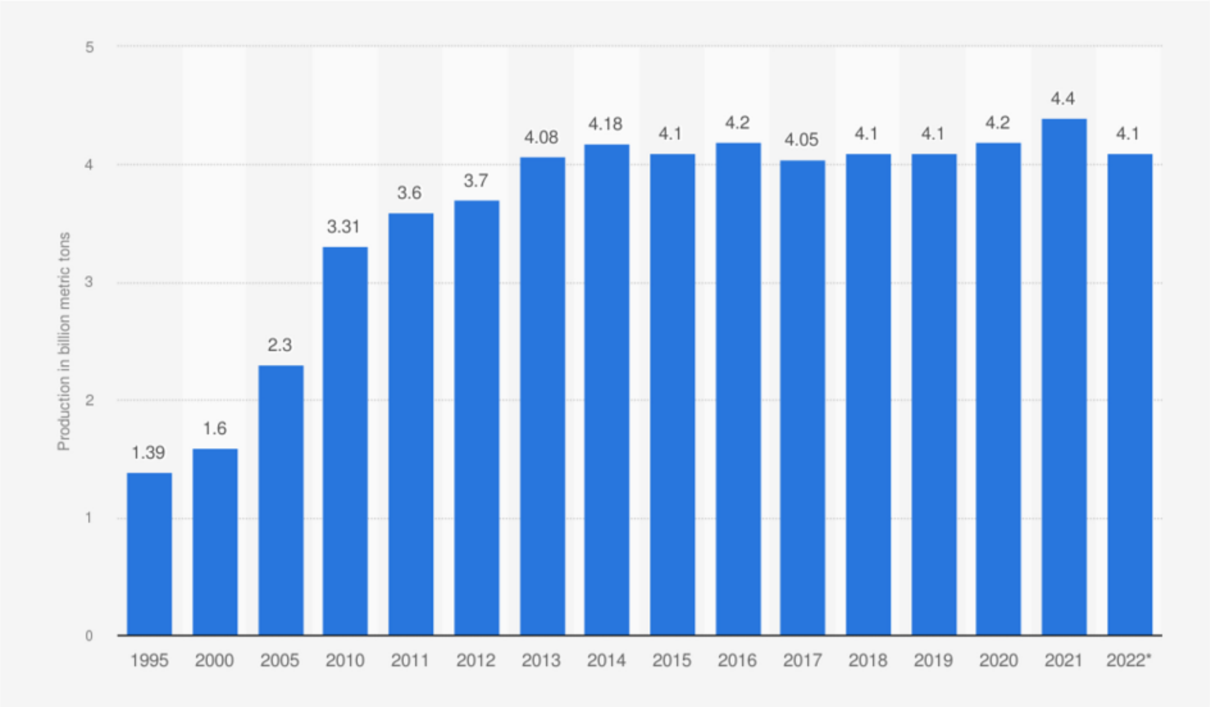


**Fig. 2.** Cement production worldwide from 1995 to 2022 [51].

concrete to gain strength. Curing involves maintaining adequate moisture and temperature conditions for an extended period, typically by covering the concrete with curing blankets, using curing compounds, or applying water.

The properties of the final concrete product depend on factors such as the type and quality of materials used, the water-cement ratio, the presence of additives, the curing conditions and proper construction practices. Concrete production has numerous advantages, including high compressive strength, durability, fire resistance and versatility in forming different shapes and sizes. It is widely used in various construction applications, including buildings, bridges, roads, dams and infrastructure projects. However, it is important to consider the environmental impact of concrete production. The extraction of raw materials, energy consumption during manufacturing and transportation of materials contribute to carbon emissions and resource depletion [66–69]. To address these concerns, efforts are being made to incorporate sustainable practices, such as the use of recycled aggregates, optimising mix designs to reduce cement content and embracing alternative cementitious materials with lower carbon footprints.

### *2.2. Carbon emissions from cement and concrete industry*

The carbon emissions from the concrete industry are a significant environmental concern. While concrete itself does not directly emit carbon dioxide ($CO_2$) during its curing and hardening process, the production of concrete involves the use of cement, which is a major source of CO emissions. The cement industry plays a critical role in global carbon emissions, primarily due to the release of $CO_2$ during the production of cement. The process of cement production involves the transformation of raw materials, such as limestone and clay, into clinker, which is a powdered form of cement. This transformation is achieved through a process called calcination. During calcination, limestone, which contains a significant amount of calcium carbonate, is subjected to high temperatures in a kiln. As a result, the limestone undergoes chemical decomposition, releasing carbon dioxide into the atmosphere [70–72]. This process of calcination is one of the major contributors to carbon emissions in the cement industry. On average, for every ton of clinker produced, approximately 0.5–0.7 tons of $CO_2$ are emitted solely from the calcination process [73–75].

In addition to calcination, the combustion of fossil fuels represents another significant source of carbon emissions in the cement industry. Fossil fuels, including coal, petroleum coke and natural gas, are commonly used as fuel sources to generate the high temperatures required in cement kilns [76,77]. When these fuels are burned, they release carbon dioxide into the atmosphere, contributing to the overall carbon footprint of cement production. The amount of $CO_2$ emissions from fossil fuel combustion in the cement industry depends on several factors, including the type of fuel used, the efficiency of the combustion process and the implementation of emission control measures [78–80].

The carbon emissions resulting from the cement industry have far-reaching environmental implications. Cement production accounts for approximately 7–8 % of global $CO_2$ emissions, making it a significant contributor to the greenhouse effect and climate change [81,82]. The intensity of carbon emissions in cement production can vary depending on various factors, including the type of cement being produced (such as Portland cement or blended cement), the energy sources utilised in the production process (fossil fuels or renewable energy sources) and the overall efficiency of the production facilities. The substantial carbon emissions associated with cement production have raised global concerns and prompted the need for effective mitigation strategies to combat climate change. The $CO_2$ emissions from the manufacture of cement worldwide from 1960 to 2021 is shown in Fig. 3. Global $CO_2$ emissions

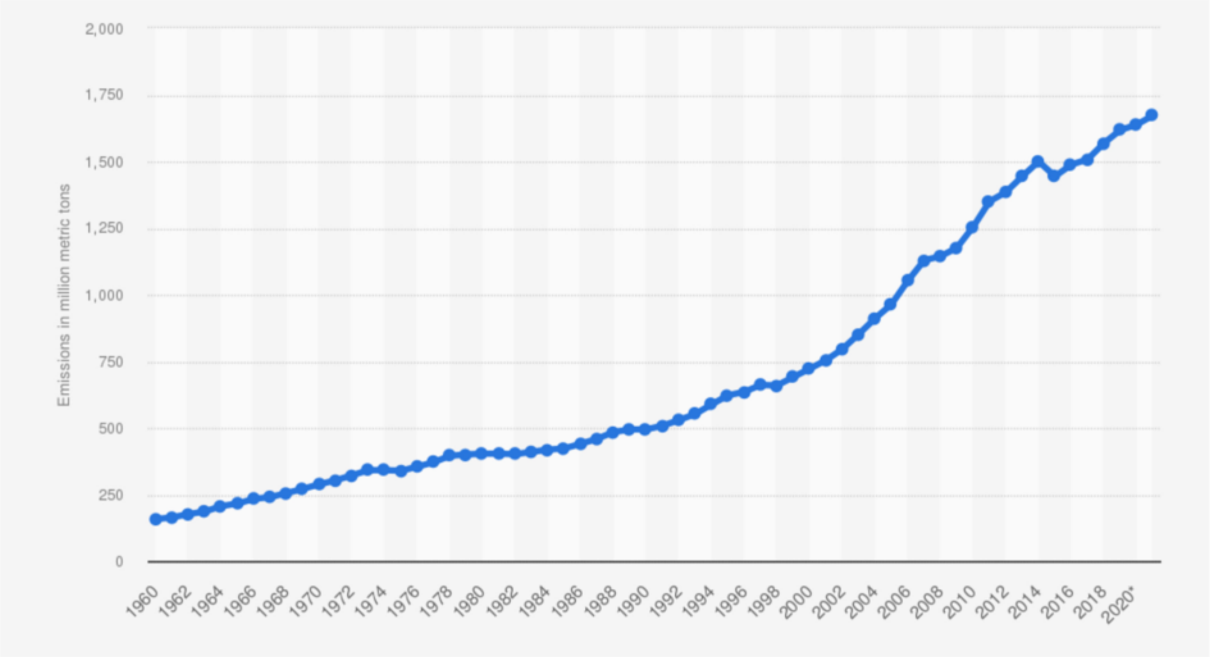


**Fig. 3.** Carbon dioxide emissions from the manufacture of cement worldwide from 1960 to 2021 [51].

from cement production have quadrupled over the past 60 years. These emissions will have to be reduced to almost zero if we are to achieve carbon neutrality.

The direct emissions intensity of cement production in the Net Zero Scenario, 2015–2030 is shown in Fig. 4 [83]. Between 2015 and 2021, the direct $CO_2$ intensity of cement production experienced a yearly increase of approximately 1.5%. However, to align with the Net Zero Emissions by 2050 Scenario, a significant shift is required, with annual declines of 3% until 2030. This necessitates a sharper focus on two key areas: reducing the clinker-to-cement ratio, which includes promoting the use of blended cements and adopting innovative technologies such as carbon capture and storage and clinkers made from alternative raw materials.

### 2.3. Environmental impacts of carbon footprint

The environmental impacts of carbon footprints are wide-ranging and have significant implications for the planet. Carbon footprints represent the total greenhouse gas emissions, particularly carbon dioxide ($CO_2$), associated with an individual, organisation, or activity. These emissions contribute to climate change and have several environmental consequences. One of the primary environmental impacts of carbon footprints is climate change. The excessive release of $CO_2$ and other greenhouse gases into the atmosphere leads to the greenhouse effect, trapping heat and causing global warming. This, in turn, disrupts ecosystems, alters weather patterns, increases the frequency and intensity of extreme weather events and threatens biodiversity. Another significant environmental impact of carbon footprints is ocean acidification. Elevated levels of atmospheric $CO_2$ are absorbed by the oceans, leading to a process called ocean acidification [84]. Increased acidity has detrimental effects on marine ecosystems, including coral reefs, shellfish and other calcifying organisms. It can hinder their ability to build and maintain their calcium carbonate structures, impacting marine biodiversity and ecosystem balance.

Many activities that contribute to carbon footprints also release other harmful pollutants into the air, leading to air pollution. Burning fossil fuels for energy production and transportation, in particular, releases pollutants such as sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$) and particulate matter [85]. Air pollution can harm human health and ecosystems, leading to respiratory issues, reduced visibility and damage to vegetation. High carbon footprints are often linked to land-use changes, particularly deforestation. Deforestation contributes to climate change by releasing carbon stored in trees and reducing the planet's capacity to absorb $CO_2$ through photosynthesis [86]. It also leads to habitat destruction and the loss of biodiversity, as many species rely on forests for their survival.

Climate change, driven by carbon footprints, affects global water resources. Changes in precipitation patterns, melting glaciers and altered river flows impact freshwater availability and quality. Droughts and floods become more frequent, affecting ecosystems, agriculture and human populations that rely on water resources for drinking, irrigation and industrial purposes. Carbon footprints can disrupt ecological balance by altering natural systems [87,88]. Changes in temperature and precipitation patterns impact the distribution and behaviour of plant and animal species, leading to shifts in ecosystems. This can result in reduced biodiversity, as some species struggle to adapt or face habitat loss, while others may proliferate in new conditions. Mitigating the environmental impacts of carbon footprints is essential for sustainable development. Transitioning to renewable energy sources, improving energy efficiency, promoting sustainable transportation, adopting green technologies, implementing nature-based solutions and fostering conservation

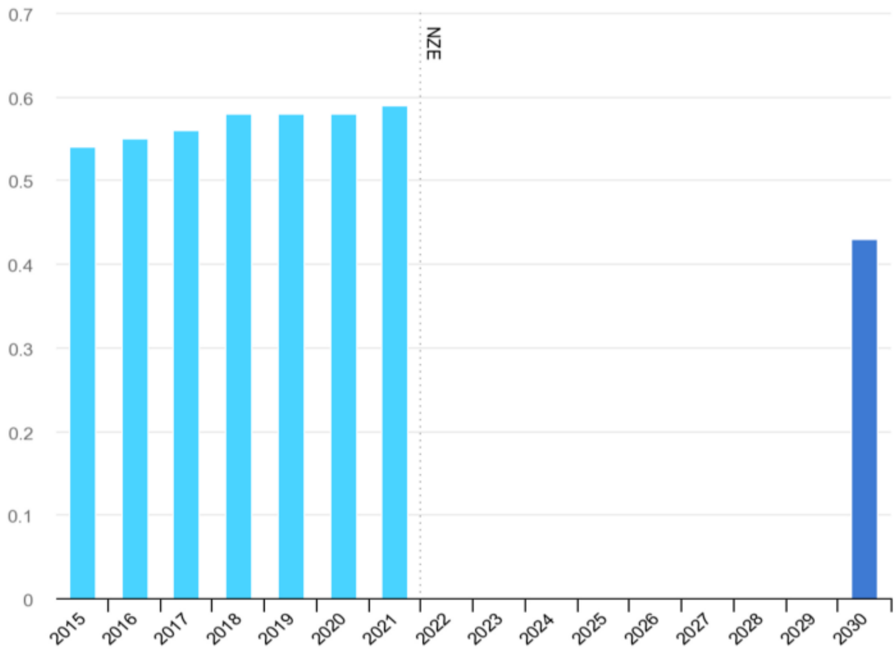


**Fig. 4.** The direct emissions intensity of cement production in the Net Zero Scenario, 2015–2030 (iea.org).

efforts are crucial steps. By reducing carbon footprints and embracing low-carbon lifestyles and practices, we can mitigate the environmental consequences and work towards a more resilient and sustainable future.

## 3. Strategies for decarbonising cement production

Strategies for decarbonising cement production involve a range of approaches aimed at reducing carbon emissions and promoting sustainability. One strategy is the use of alternative cementitious materials, such as fly ash, slag and pozzolans, which can partially replace traditional clinker and reduce carbon intensity. Carbon capture and storage (CCS) technology is another important strategy, capturing $CO_2$ emissions from cement plants and storing them underground. Improving energy efficiency in cement manufacturing through process optimization, waste heat recovery and energy-efficient technologies is also critical. The development of low-carbon cements, including blended cements and novel binders, offers greener alternatives. Circular economy approaches, such as recycling concrete waste and utilising alternative fuels, further contribute to decarbonisation efforts in the cement industry.

### 3.1. Use of alternative clinker technologies

Alternative clinker technologies are innovative approaches aimed at reducing the carbon footprint of cement production. These technologies seek to replace or minimise the use of traditional clinker, which is a major source of $CO_2$ emissions. By exploring and adopting alternative clinker technologies, the cement industry can contribute to global efforts in mitigating climate change and achieving sustainability goals.

One example of an alternative clinker technology is calcined clay-based cements, such as LC3 (Limestone Calcined Clay Cement) [89]. These cements utilise calcined clay as a partial substitute for clinker, resulting in reduced energy consumption and $CO_2$ emissions. Calcined clay is a by-product of various industrial processes and can be readily available, making it an attractive option for sustainable cement production. The incorporation of calcined clay also enhances the properties of the cement, such as improved durability and strength [90–92]. Ongoing research and development efforts are focused on optimising the blend ratios and production techniques to maximise the benefits of calcined clay-based cements. Another approach in alternative clinker technologies is the use of belite-based cements [93]. Belite is a low-temperature phase in cement production that requires less energy during the kiln process compared to traditional clinker. By reducing the clinker content and increasing the proportion of belite, these cements offer a more sustainable alternative to Portland cement. Belite-based cements have shown promising results in terms of reducing $CO_2$ emissions and conserving energy [94–96]. However, further research is needed to optimise the composition and properties of belite-based cements to ensure their commercial viability.

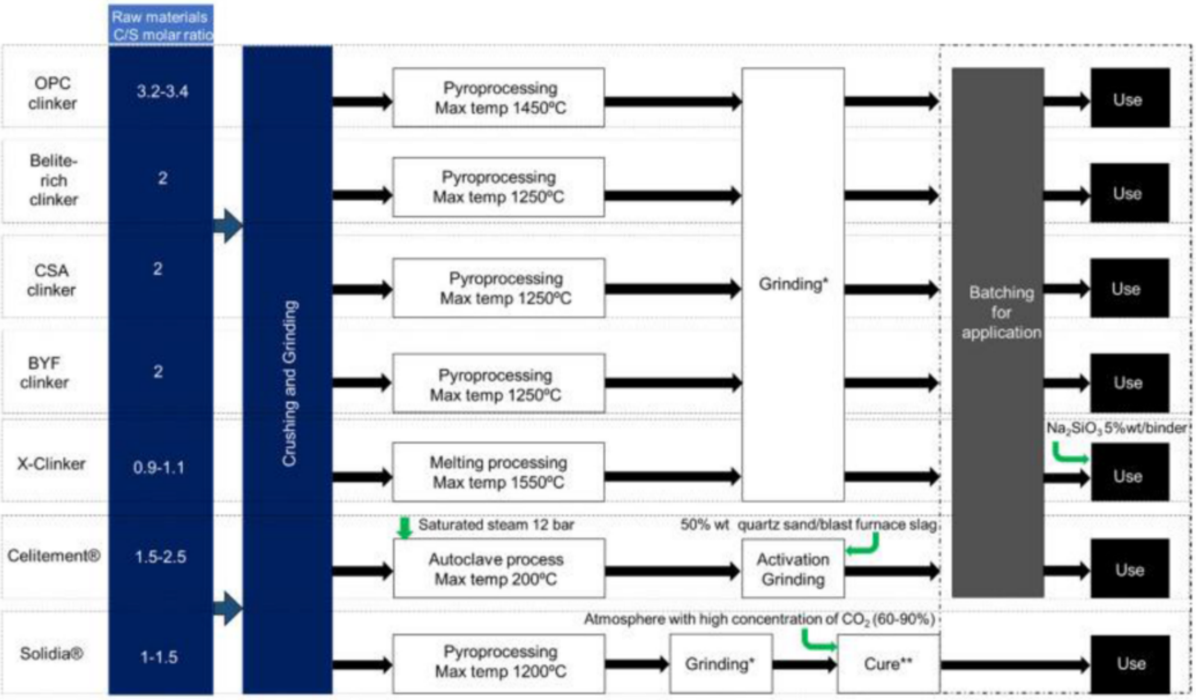
Magnesium-based cements are also emerging as alternative clinker technologies [97,98]. Magnesium oxychloride cement and magnesium phosphate cement are two examples of such technologies. These cements can be produced using magnesium oxide or magnesium silicates, which have lower carbon footprints compared to limestone-based clinker. Magnesium-based cements offer advantages such as faster setting times, high early strength and improved fire resistance [99,100]. However, challenges such as the sourcing of magnesium-rich materials and the need for additional research and development hinder their widespread adoption.

Alkali-activated binders are another category of alternative clinker technologies [101]. These binders are produced by activating industrial by-products, such as fly ash or slag, with alkali activators. By utilising these by-products, alkali-activated binders reduce the dependence on clinker production and contribute to the circular economy. These binders offer similar or even superior mechanical properties compared to traditional cement and have demonstrated durability in various applications [102–104]. Ongoing research aims to optimise the formulation, improve long-term performance and enhance the cost-effectiveness of alkali-activated binders for commercial use.

Carbon-negative clinker technologies represent an advanced approach in alternative clinker technologies. These technologies not only aim to reduce carbon emissions but also achieve carbon-negative cement production. Carbon-negative clinker technologies capture $CO_2$ from the atmosphere or industrial flue gases and incorporate it into the cementitious material. This results in a net removal of $CO_2$ from the environment. These technologies hold great promise for the cement industry to actively contribute to climate change mitigation efforts. However, further research, development and large-scale implementation are required to ensure their technical feasibility, economic viability and environmental benefits.

Fig. 5 provides a simplified flow chart illustrating the different stages involved in the production of alternative binders discussed in this review, highlighting the variations in the processes across various alternative clinker technologies [96]. The figure emphasises the need for continued research and development in all of the proposed solutions. It is evident from Fig. 5 that only the Celitement® and X-Clinker approaches currently consider a scenario of complete process electrification, whereas the other approaches primarily rely on fuel combustion, similar to the existing Best Available Technology (BAT). While being close to BAT in terms of clinker production is advantageous for the industrial implementation of certain alternative binders, it is the author's perspective that a shift towards electricity-based technology, either fully or partially, should occur in the coming decades for the decarbonisation of the cement industry. This transition would align with the broader goals of reducing carbon emissions and achieving sustainability in cement production.

The development and adoption of alternative clinker technologies face challenges such as cost-effectiveness, scalability and market acceptance. The transition from traditional clinker production to alternative technologies requires significant investments in research and development, as well as the modification or construction of new production facilities. The availability and sourcing of suitable raw materials, the compatibility of alternative clinker technologies with existing infrastructure and the willingness of stakeholders to embrace change are also important considerations. Furthermore, standards and regulations need to evolve to incorporate alternative clinker technologies and provide a level playing field for sustainable cement producers. However, ongoing research and devel-



*The grinding stage is considered to be similar in all the cases presented

**Mortar and concrete curing should be performed under controlled conditions

**Fig. 5.** Simplified schematic representation of the stages considered within the production processes of the alternative binders [96].

opment efforts, supportive policies and collaboration between stakeholders are helping to overcome these barriers and accelerate the transition toward sustainable and low-carbon cement production. Continuous innovation and knowledge sharing among researchers, industry players and policymakers are crucial for advancing alternative clinker technologies. Partnerships and collaborations between academia, government bodies, cement manufacturers and technology providers facilitate the exchange of expertise, resources and best practices. By collectively addressing the challenges and seizing the opportunities, alternative clinker technologies can play a vital role in decarbonising the cement industry and shaping a more sustainable future.

### *3.2. Carbon capture and storage (CCS) in cement plants*

Carbon Capture and Storage (CCS) is a promising technology for reducing carbon emissions in cement plants, which are significant contributors to greenhouse gas emissions. Cement production involves the combustion of fossil fuels and the calcination of limestone, leading to the release of large amounts of carbon dioxide ($CO_2$) into the atmosphere. CCS aims to capture this $CO_2$ and prevent it from being released, thus mitigating climate change. In the context of cement plants, CCS can be implemented through various methods to reduce carbon emissions. One common approach is post-combustion capture, which involves capturing $CO_2$ from the flue gases generated during cement production [105,106]. This process typically employs chemical solvents or sorbents that selectively capture $CO_2$ from the flue gas stream. The flue gases are passed through an absorber where the $CO_2$ reacts with the solvent, forming a solution of $CO_2$-rich solvent. The solvent is then regenerated by heating, releasing the captured $CO_2$, which can be further purified and compressed for transport and storage.

Voldsund et al. [107] presented the chilled ammonia process (CAP) as a post-combustion technology for $CO_2$ capture in cement plants. CAP utilises chilled ammonia as a solvent to selectively remove $CO_2$ from the flue gas (Fig. 6). The process involves several steps, starting with the conditioning of the flue gas in a Direct Contact Cooler (DCC) to lower its temperature and remove sulphur oxides ($SO_x$) through scrubbing with ammonia. The conditioned flue gas then enters an absorption column, where $CO_2$ is separated by an ammonia solution. To control the temperature, a solvent pump-around system chills the absorber down to around 12–13 °C. Ammonia is recovered from the flue gas in a water wash section, while the purified flue gas is released into the atmosphere. The desorption column allows for ammonia recovery from the wash water, which is then recycled in the process. The $CO_2$-rich ammonia solvent is regenerated in a $CO_2$ desorber operating at approximately 25 bar. The resulting high-purity $CO_2$ stream requires further pressurization to meet transportation specifications. The CAP process necessitates heat for solvent regeneration and ammonia recovery, as well as power for chilling, pumping and compression. Utilising waste heat can partially fulfil the heat demand, accounting for about 7–8% of the total heat demand in a reference cement plant.

Another method is pre-combustion capture, where $CO_2$ is captured from the fuel before it is combusted [108,109]. In cement plants, this can be achieved by reforming the fuel, such as coal or natural gas, to produce a hydrogen-rich gas stream. The fuel is re-

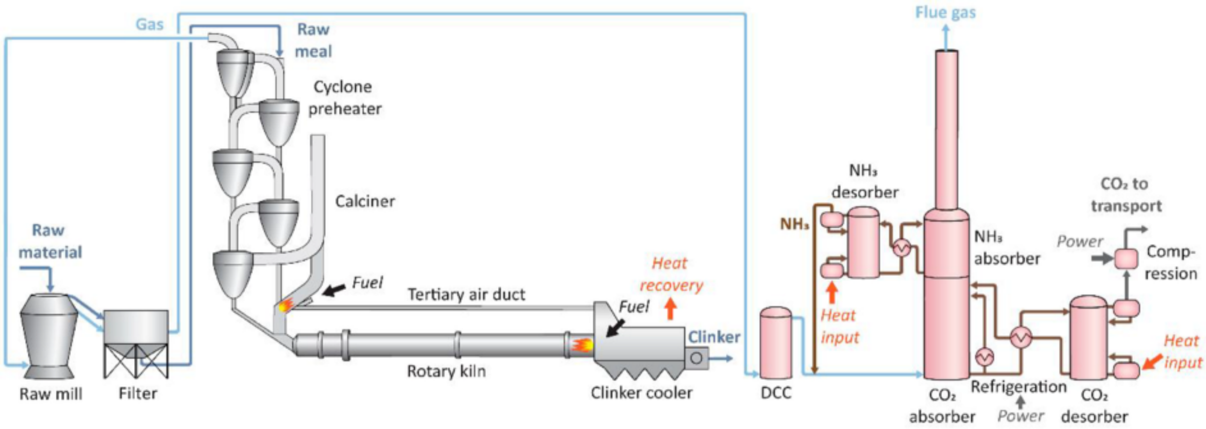


Fig. 6. Reference clinker burning line with CAP $CO_2$ capture [107].

acted with steam in a process called steam methane reforming or coal gasification, resulting in the production of a gas stream containing hydrogen and $CO_2$. The $CO_2$ is then separated from this gas stream using processes like pressure swing adsorption or membranes, producing a concentrated $CO_2$ stream that can be transported and stored.

The pre-combustion process is similar for coal, oil and natural gas, although additional purification stages are required when using coal or oil to remove impurities such as ash, sulphur compounds and other minor contaminants. The process for pre-combustion capture in power generation is illustrated in Fig. 7 [110]. In both coal and natural gas applications, the overall plant can be divided into five sections: the syngas island, $CO_2$ separation, $CO_2$ compression, power island and optionally, the oxygen island (for natural gas cases). These sections work together to facilitate the capture of $CO_2$ and generate power. The syngas island produces a synthesis gas mix, which undergoes $CO_2$ separation to extract the $CO_2$. The separated $CO_2$ is then compressed for storage or utilisation purposes. The power island generates electricity and in natural gas cases, the oxygen island provides the required oxygen for combustion.

Both post-combustion capture and pre-combustion capture have their advantages and challenges. Post-combustion capture can be retrofitted to existing cement plants, allowing for the reduction of carbon emissions without significant modifications to the existing infrastructure [111,112]. However, it requires a large amount of energy for the capture and regeneration processes, which can impact the overall energy efficiency of the plant. Pre-combustion capture, on the other hand, offers the advantage of higher $CO_2$ capture efficiency and potential co-production of hydrogen, which has its own industrial applications [113]. However, it requires additional processing units and may necessitate changes in the fuel supply and combustion systems.

Oxy-combustion systems are a carbon capture technology that can be applied in cement plants to reduce $CO_2$ emissions [114,115]. This approach involves replacing air with pure oxygen in the combustion process, resulting in a flue gas stream primarily composed of

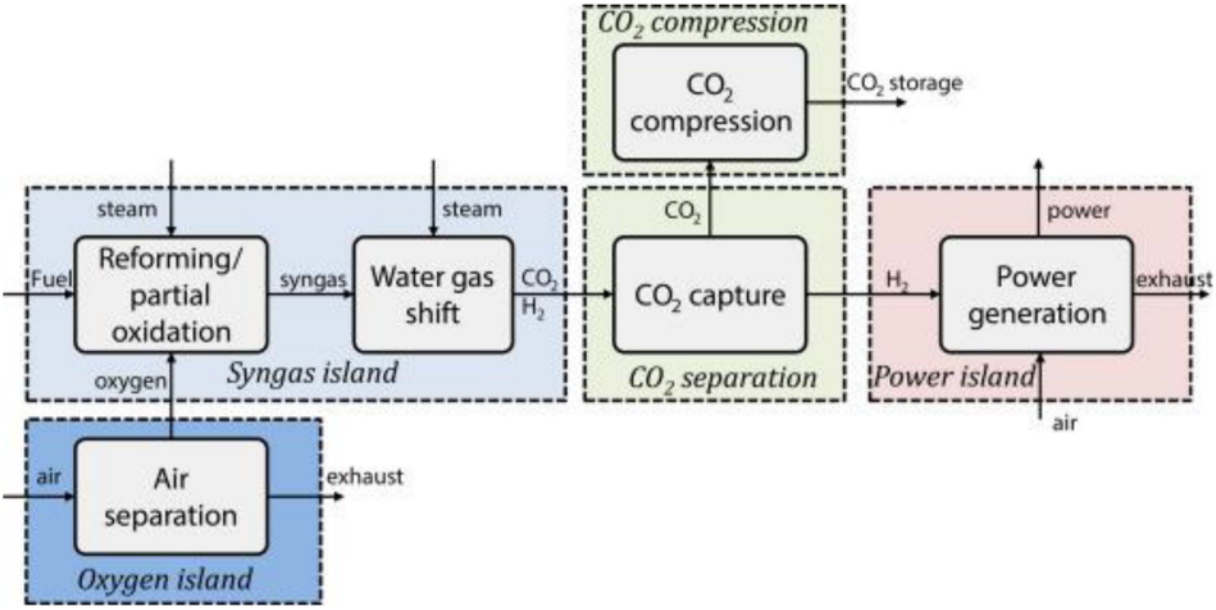


Fig. 7. Schematic of pre-combustion capture for power generation [110].

$CO_2$ and water vapor. By separating and capturing the $CO_2$ from this stream, it can be stored or utilised for other purposes. Oxy-combustion offers several advantages, including high $CO_2$ capture efficiency and the potential for near-zero emissions. However, it also presents challenges, such as the high energy requirements for oxygen production and the need for $CO_2$ transportation and storage infrastructure. Nonetheless, oxy-combustion systems hold promise for mitigating $CO_2$ emissions in cement plants and contributing to sustainable cement production.

In their study, Ellis et al. [116] introduced an innovative electrochemical process for decarbonating $CaCO_3$ in the cement industry (Fig. 8). Their proposed method involved the use of an ambient-temperature electrolyser, where $CaCO_3$ undergoes electrochemical reactions. The process resulted in the production of solid $Ca(OH)_2$, which served as the precursor for synthesizing desired calcium silicates. Additionally, the electrochemical process generated concentrated gas streams of $H_2$ and $O_2 + CO_2$, which could be utilised for $CO_2$ capture and sequestration or for other value-added processes. The authors demonstrated a proof of concept for this approach, highlighting its potential for decarbonising cement production and producing valuable gas streams.

Once carbon dioxide ($CO_2$) is captured from cement plants, it must be transported to suitable storage sites. The transportation method depends on factors such as the distance to the storage site and the volume of $CO_2$ to be transported [117–119]. The most common transportation options are pipelines, ships and trucks. Pipelines are often preferred for long-distance transport of large volumes of $CO_2$. Dedicated pipelines can be constructed to connect the capture facility to the storage site, ensuring a continuous and efficient flow of $CO_2$. Pipelines offer a secure and cost-effective means of transportation and they are widely used in existing $CO_2$ capture and storage projects. For shorter distances or when pipeline infrastructure is not available, ships and trucks can be used for $CO_2$ transportation. $CO_2$ can be transported in specially designed containers on ships or in pressurised tanks on trucks. This mode of transportation is more flexible and suitable for smaller volumes of $CO_2$ or when the storage site is located near a waterway or roadway.

The storage sites for $CO_2$ are typically deep underground geological formations [120–122]. These formations provide secure and permanent storage for the captured $CO_2$, preventing it from entering the atmosphere and contributing to climate change. The most common storage sites include depleted oil and gas reservoirs, saline aquifers and unmineable coal seams [123–125]. Depleted oil and gas reservoirs are considered ideal storage sites due to their geological characteristics. These reservoirs have been previously used to extract oil and gas and once they are depleted, they can be repurposed for $CO_2$ storage. The existing infrastructure, such as wells and infrastructure for oil and gas extraction, can be utilised for $CO_2$ injection. Saline aquifers are porous rock formations that contain salty water. They have large storage capacities and can potentially store significant amounts of $CO_2$. The $CO_2$ is injected into the saline aquifers, where it is trapped in the pore spaces of the rock formation.

Unmineable coal seams, which are coal deposits that cannot be economically extracted, can also serve as storage sites for $CO_2$ [126,127]. The $CO_2$ is injected into the coal seams, where it is adsorbed onto the coal matrix. This process, known as enhanced coalbed methane recovery, not only stores the $CO_2$ but also enhances the recovery of methane from the coal seams. To ensure the safe and effective storage of $CO_2$, extensive site characterization and monitoring are conducted. This involves assessing the geological properties of the storage site, such as permeability and porosity, to ensure the suitability for $CO_2$ storage. Monitoring techniques, including seismic imaging, pressure monitoring and geochemical analysis, are employed to detect any potential leakage and ensure the integrity of the storage site [128–131]. The storage of $CO_2$ in deep underground geological formations offers a long-term solution for reducing carbon emissions from cement plants. It provides a way to permanently remove $CO_2$ from the atmosphere, contributing to

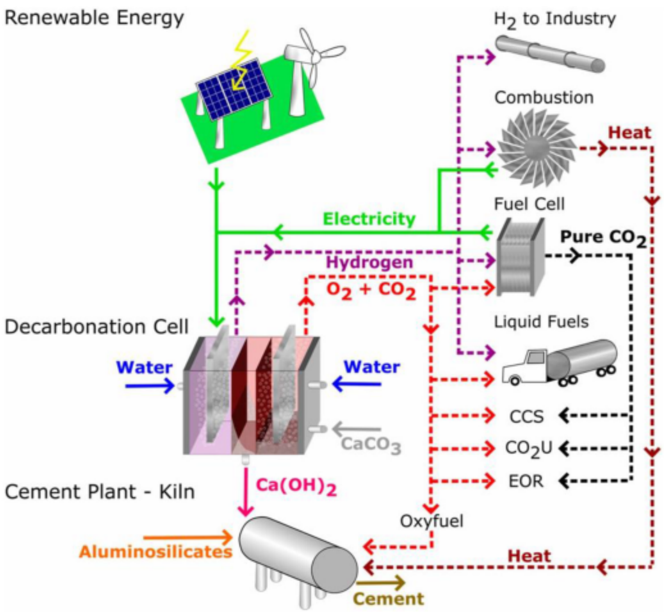


**Fig. 8.** Electrochemical process for decarbonating $CaCO_3$ in the cement industry [116].

the mitigation of climate change. However, it is essential to implement proper regulatory frameworks and monitoring protocols to ensure the safety and effectiveness of $CO_2$ storage operations.

Normann et al. (2019) discussed the application of Carbon Capture and Storage (CCS) in cement plants in their study (Fig. 9). The authors emphasised the importance of CCS in mitigating $CO_2$ emissions from the cement industry and reducing its carbon footprint. The study explores various strategies to lower the cost of CCS implementation, such as optimising the capture process, improving solvent performance and utilising waste heat integration. Additionally, the authors highlighted the potential of utilising the captured $CO_2$ for enhanced oil recovery or other industrial applications, which can contribute to the economic viability of CCS projects. The findings of the study provide valuable insights for cement plant operators and policymakers in their efforts to implement cost-effective CCS technologies.

The implementation of Carbon Capture and Storage (CCS) in cement plants offers numerous benefits for the industry and the environment. One of the key advantages is the significant reduction of $CO_2$ emissions. By capturing and storing $CO_2$ emissions, cement plants can contribute to global efforts to mitigate climate change and meet emissions reduction targets set by international agreements [132,133]. CCS technology enables cement plants to reduce their carbon footprint and operate more sustainably. It allows for the separation and capture of $CO_2$ from flue gases or fuel combustion processes, preventing the release of a substantial amount of $CO_2$ into the atmosphere [134,135]. This reduction in emissions helps to minimise the environmental impact of cement production, which is known for its high carbon intensity.

Implementing CCS in cement plants also provides a viable pathway for the industry to transition towards more environmentally friendly and low-carbon cement production. By capturing and storing $CO_2$, cement plants can continue producing this essential construction material while significantly reducing their environmental impact. This is crucial as the demand for cement continues to grow with global urbanization and infrastructure development. Furthermore, the adoption of CCS technology in cement plants can contribute to the development of a sustainable and circular economy. The stored $CO_2$ can potentially be utilised for other industrial applications or in carbon utilisation projects, further reducing the overall carbon footprint. Additionally, the availability of CCS technology in cement plants can encourage the development of carbon offset markets, where the captured $CO_2$ can be traded or sold to industries seeking to offset their emissions. From a business perspective, implementing CCS can enhance the reputation of cement companies as environmentally responsible and forward-thinking organisations. It can provide a competitive advantage in an increasingly carbon-constrained world, where sustainability and environmental performance are valued by stakeholders, including investors, customers and regulatory bodies.

Implementing CCS technologies in cement plants is not without challenges. One of the primary obstacles is the high cost associated with the entire CCS process, from capture to transport and storage [136–138]. The construction and operation of capture facilities, such as installing carbon capture equipment in cement plants, require substantial capital investment. These capture technologies, such as chemical solvents or sorbents, add additional complexity and operating costs to the cement production process. Transporting captured $CO_2$ to suitable storage sites also poses a challenge [119,139]. Building the necessary infrastructure, such as pipelines or storage vessels, involves considerable expenses. The distance and volume of $CO_2$ to be transported influence the feasibility and cost-effectiveness of different transportation methods. Pipelines are generally considered the most efficient means of $CO_2$ transport, but their construction and maintenance require substantial investment. Ensuring the long-term integrity and safety of the storage sites is of utmost importance. Storage sites, typically deep underground geological formations, must be carefully selected and monitored to

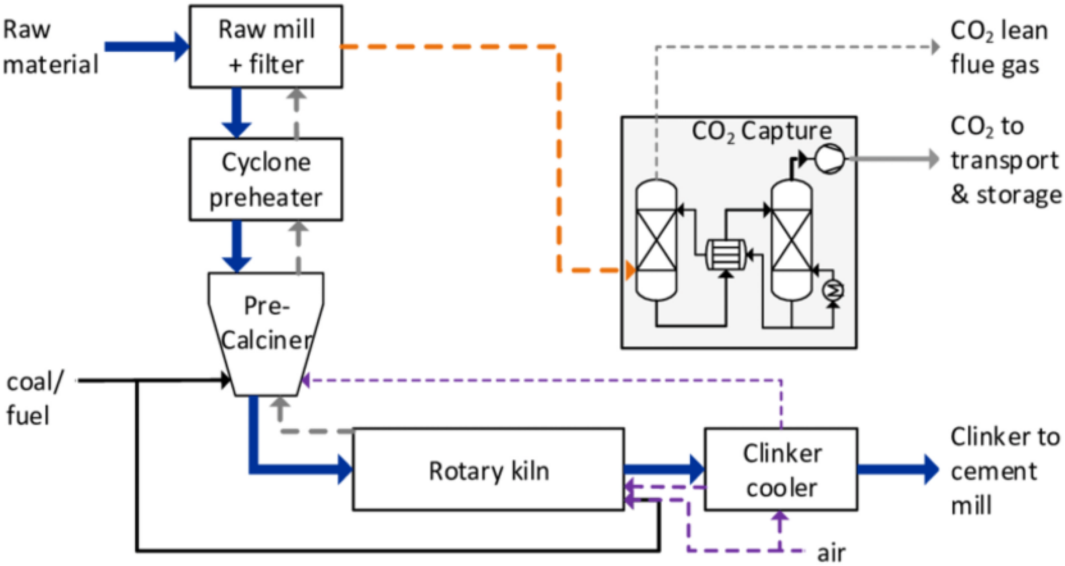


Fig. 9. Process overview of the Norcem cement plant including the integration of a $CO_2$ capture plant (Normann et al., 2019).

prevent $CO_2$ leakage. The potential risks associated with $CO_2$ migration or unintended release into the atmosphere must be assessed and mitigated through rigorous monitoring and well-designed storage operations.

To address the challenges associated with implementing CCS technologies in cement plants, extensive research and development efforts are underway. These initiatives aim to enhance the efficiency and cost-effectiveness of CCS technologies, making them more viable for widespread adoption. One area of focus is the development of advanced capture technologies. Researchers are working on improving the performance of chemical solvents and sorbents used in post-combustion capture systems [140–142]. This involves enhancing their $CO_2$ capture capacity, reducing energy requirements and optimising the regeneration process for continuous operation. Innovations in capture technologies, such as the development of novel materials and processes, can contribute to the overall efficiency and economic viability of CCS in cement plants.

Efforts are also directed towards optimising the transport and storage systems for captured $CO_2$. Research is being conducted to identify the most efficient and cost-effective means of transporting $CO_2$, taking into account factors like distance, volume and infrastructure requirements [143,144]. Innovations in pipeline design and materials, as well as advancements in compression and transportation technologies, can help minimise costs and ensure safe and reliable $CO_2$ transport. In addition to technological advancements, exploring innovative financing mechanisms is crucial to overcome the high upfront costs associated with CCS implementation. Governments and industry stakeholders are exploring various financial models, including carbon pricing mechanisms, grants, tax incentives and carbon offset programs, to incentivize cement plants to invest in CCS technologies. Public-private partnerships and international collaborations are being fostered to facilitate knowledge sharing, resource mobilisation and technology transfer, accelerating the deployment of CCS in the cement industry.

Government support and incentives are key drivers in advancing CCS deployment in cement plants and other industrial sectors. Many governments have introduced policies and regulations to incentivize the adoption of low-carbon technologies, including CCS [145,146]. These measures may include financial support for research and development, subsidies for CCS projects, carbon pricing mechanism and regulatory frameworks that support CCS deployment. International collaborations, such as the sharing of best practices and lessons learned, can also facilitate the development and deployment of CCS technologies on a global scale.

### *3.3. Improved energy efficiency in cement manufacturing*

Improved energy efficiency in cement manufacturing is vital for reducing the carbon footprint of the industry and achieving sustainability goals. Cement production is known for its high energy consumption, which occurs during various processes such as raw material preparation, clinker production and grinding. Enhancing energy efficiency not only helps to minimise greenhouse gas emissions but also improves the overall competitiveness and economic viability of cement manufacturing.

One of the primary approaches to improving energy efficiency in cement manufacturing is optimising kiln operations [147–150]. This involves the implementation of advanced control systems to monitor and regulate kiln parameters such as temperature, airflow and fuel-to-air ratios. By fine-tuning these parameters, the energy efficiency of the process can be maximised, resulting in reduced energy consumption and lower carbon emissions. Additionally, efficient heat recovery systems can be implemented to capture and utilise waste heat generated during the manufacturing process, further enhancing energy efficiency.

The use of alternative fuels and raw materials is another important aspect of improving energy efficiency in cement manufacturing [151–155]. By substituting fossil fuels with renewable or low-carbon alternatives such as biomass, waste-derived fuels, or non-recyclable plastics, the dependence on traditional fossil fuels can be reduced. This not only reduces carbon emissions but also diversifies the energy sources used in cement production. Incorporating alternative raw materials, such as industrial by-products like slag or fly ash, not only helps in utilising waste materials but also optimises the cement production process, resulting in reduced energy consumption and lower environmental impact.

Investments in energy-efficient technologies and equipment are crucial for improving energy efficiency in cement plants. Upgrading machinery, such as modernising grinding systems or installing high-efficiency separators, can significantly improve the energy performance of the plant (Madllol et al., 2013 [156]). Utilising advanced technologies like preheaters and calciners can help maximise the utilisation of heat and reduce energy losses. Efficient dust collection systems can also contribute to energy savings by minimising material loss and optimising process efficiency [157–159]. Energy management systems and regular energy audits are effective tools for identifying energy-saving opportunities and optimising energy use in cement plants. Conducting energy audits helps assess the energy performance of the plant, identify areas for improvement and set targets for energy reduction. Implementing energy management systems allows for continuous monitoring and optimization of energy consumption, while adopting energy-saving practices such as optimising lighting, improving insulation and promoting employee awareness can contribute to long-term energy efficiency gains.

Collaboration and knowledge sharing among industry stakeholders are essential for promoting improved energy efficiency in cement manufacturing. Cement manufacturers can learn from each other's best practices and experiences, exchange information on successful energy-saving initiatives and participate in industry forums and associations focused on sustainability and energy management. Governments and regulatory bodies can play a crucial role by establishing energy efficiency standards, providing incentives for energy-saving investments and promoting research and development in energy-efficient technologies. Such collaboration and support facilitate the adoption of energy-efficient practices across the industry, accelerating the transition towards a more sustainable cement manufacturing sector.

### *3.4. Development of low-carbon cements*

The imperative to address environmental challenges in the construction industry has propelled the development of low-carbon cements. Traditional cement production, notably in the case of Portland cement, releases substantial $CO_2$ during the calcination of limestone, contributing significantly to climate change. Researchers are actively exploring innovative strategies to mitigate these emissions, such as optimising processes to reduce clinker content and incorporating supplementary materials like fly ash [76,160]. Alternative binders, including calcium sulphoaluminate and magnesium-based cement, offer lower carbon emissions, diversifying the industry's material options [161–163].

Carbon capture and utilisation (CCU) technologies, exemplified by carbonation, play a vital role by capturing $CO_2$ emissions from cement plants and integrating them into cementitious materials, thereby reducing both emissions and environmental impact [164–167]. Collaboration among stakeholders, government support, and awareness initiatives are essential for scaling up production processes and fostering the widespread adoption of low-carbon cements. Financial incentives, tax benefits, and green certifications further incentivize the construction industry to embrace sustainable practices, ultimately contributing to global efforts in mitigating climate change. By prioritizing the development and adoption of low-carbon cements, the industry can significantly reduce its environmental footprint while meeting the rising demand for infrastructure in a sustainable manner.

### *3.5. Circular economy approaches in cement production*

Circular economy approaches in cement production are gaining momentum as a means to enhance sustainability and resource efficiency. The traditional linear model of production, consumption and disposal is being replaced by a circular approach that aims to close the resource loop and minimise waste generation. In the context of cement production, circular economy principles are applied to reduce the environmental impact of cement manufacturing and promote a more sustainable industry (Soe et al., 2021 [168]). One key aspect of circular economy approaches in cement production is the use of alternative raw materials. Instead of solely relying on virgin materials, such as limestone and clay, cement manufacturers can incorporate recycled materials and industrial by-products into their production processes. This not only reduces the need for extracting and processing new raw materials but also diverts waste from landfills. For example, using waste materials like slag from steel production or fly ash from coal-fired power plants as SCMs can significantly reduce the environmental impact of cement production while promoting the efficient use of resources. The concept of circular economy in cement and concrete production is shown in Fig. 10.

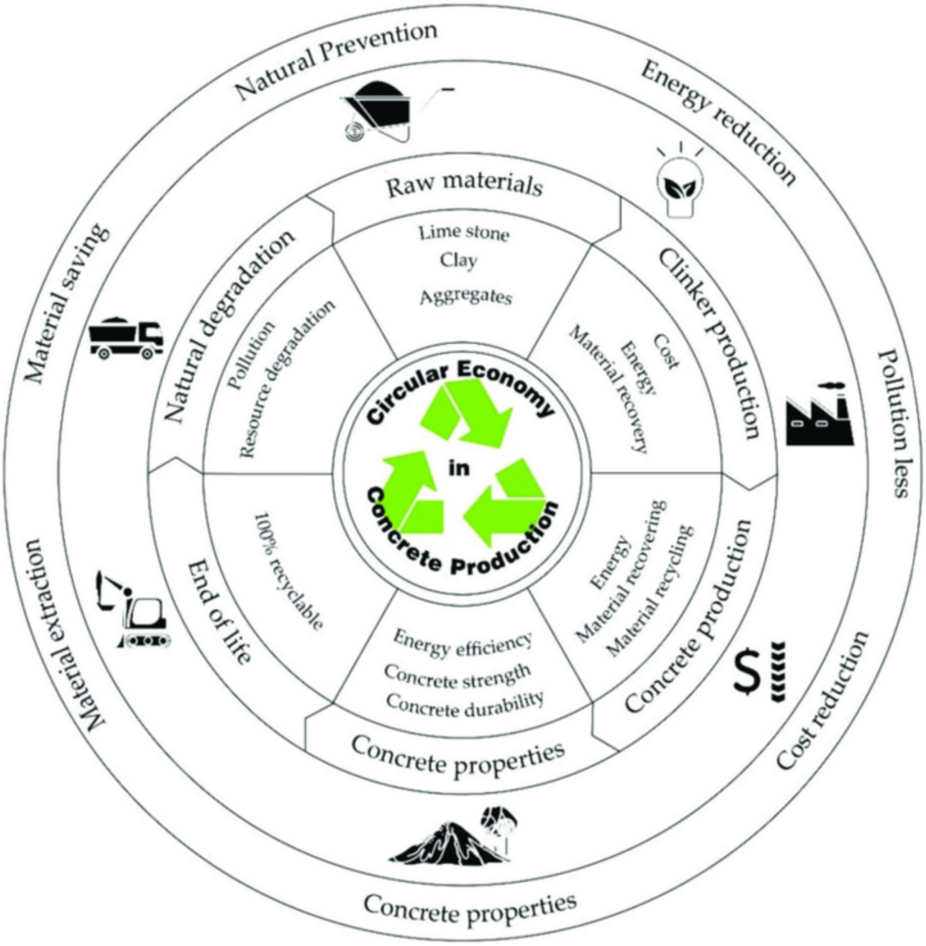


**Fig. 10.** The Concept of circular economy in cement and concrete production [169].

Another important circular economy approach is the promotion of industrial symbiosis [170]. Cement plants can collaborate with other industries, such as steel, glass, or chemical manufacturing, to exchange materials, energy, or by-products. This symbiotic relationship helps to optimise resource utilisation, reduce waste and create a closed-loop system within the industrial ecosystem. For instance, waste heat from cement kilns can be utilised by neighbouring industries, reducing the need for additional energy sources. In return, cement plants can receive secondary raw materials or alternative fuels, reducing their reliance on primary resources. Recycling and reusing concrete waste are another key aspect of circular economy approaches in cement production [171,172]. Demolished concrete structures or concrete waste from construction sites can be crushed, processed and used as aggregates for new concrete production. This practice not only conserves natural resources but also minimises the amount of waste sent to landfills. Additionally, incorporating recycled concrete aggregates into new concrete can contribute to improved performance and reduce the overall carbon footprint of the cement industry.

Beyond the production phase, circular economy approaches also encompass extending the lifespan and value of cement-based products [173,174]. Designing for durability, adaptability and easy disassembly promotes the reuse and recycling of cement-based materials. By considering the end-of-life stage of products, cement manufacturers can facilitate the efficient recovery of materials and promote circularity. For example, designing modular concrete elements that can be easily disassembled and reused in other applications reduces waste generation and supports a circular approach [29,175,176]. To support and encourage circular economy approaches in cement production, collaboration among stakeholders is crucial. Governments can establish policies and regulations that promote resource efficiency, waste management and the use of recycled materials. These policies can incentivize cement manufacturers to adopt circular practices and invest in the necessary infrastructure. Industry associations and research institutions can play a significant role in facilitating knowledge sharing, innovation and the development of best practices. Additionally, fostering partnerships between cement manufacturers, waste management companies and recycling industries can create a closed-loop system that maximises the circularity of materials and drives the transition towards a more sustainable cement industry.

Circular economy approaches in cement production offer significant benefits, including reduced resource consumption, minimised waste generation and decreased environmental impact. By embracing these approaches, the cement industry can transition towards a more sustainable and circular model, contributing to the overall goal of achieving a low-carbon and resource-efficient future. This shift not only addresses environmental concerns but also presents economic opportunities by creating new markets for recycled materials and promoting innovation in cement production. Embracing circular economy principles in cement manufacturing is a vital step towards building a more sustainable and resilient construction industry.

## 4. Technologies for decarbonising concrete production

Technologies for decarbonising concrete production offer promising solutions to reduce the environmental impact of this widely used construction material. One key technology is the use of Supplementary Cementitious Materials (SCMs) such as fly ash, slag and silica fume, which can replace a portion of cement in concrete mixes, lowering carbon emissions. Another approach involves the carbonation of concrete and Carbon Capture and Utilisation (CCU), where $CO_2$ is captured and stored in concrete during its curing process. The development of low-carbon concrete mixes, incorporating alternative binders and aggregates, helps reduce carbon intensity. Recycling and reusing concrete waste as aggregates and employing novel manufacturing processes that require less energy and emit fewer emissions are also crucial for decarbonisation efforts in concrete production.

### *4.1. Use of supplementary cementitious materials (SCMs)*

Utilising Supplementary Cementitious Materials (SCMs) is a pivotal strategy in the construction industry's endeavour to decarbonize concrete production, aiming to mitigate its environmental impact [177]. However, particular emphasis should be placed on substitution in the binder, which includes cement and its constituents (as depicted in Fig. 11). SCMs, comprising fly ash, slag cement, silica fume, and natural pozzolans, offer the potential to replace portions of Portland cement in concrete mixes, thereby reducing the overall carbon footprint associated with cement production [76,160]. Notably, SCMs enhance concrete performance while diminishing the need for cement. This dual benefit contributes to the sustainability of the construction sector by reducing both environmental impact and the demand for the resource-intensive material.

The substitution of cement constituents, especially in the binder, emerges as a key focus for environmental improvement in cement and concrete production [178]. This emphasis addresses the significant environmental impact linked to clinker production, providing an avenue to decrease carbon emissions. Additionally, it opens opportunities to incorporate industrial by-products into the binder matrix, promoting resource efficiency and minimising waste [179]. While the global substitution of cement with non-cementitious materials remains challenging, prioritizing the substitution of cement constituents in the binder proves a practical approach to achieving sustainability goals without compromising essential construction properties.

SCMs offer various benefits, including improved durability, reduced cracking risk, increased resistance to chemical attack, and enhanced permeability properties [180–183]. However, challenges such as SCM variability and regional availability must be addressed. Rigorous testing, quality control measures, and regional-specific strategies are crucial [23,184]. To foster the widespread adoption of SCMs, supportive policies, standards, and government interventions are vital, encouraging the construction industry to prioritise low-carbon materials. Collaborative efforts between researchers, industry stakeholders, and policymakers are imperative to optimise SCM performance, explore new sources, and accelerate the adoption of these materials, ensuring a sustainable future for concrete production.

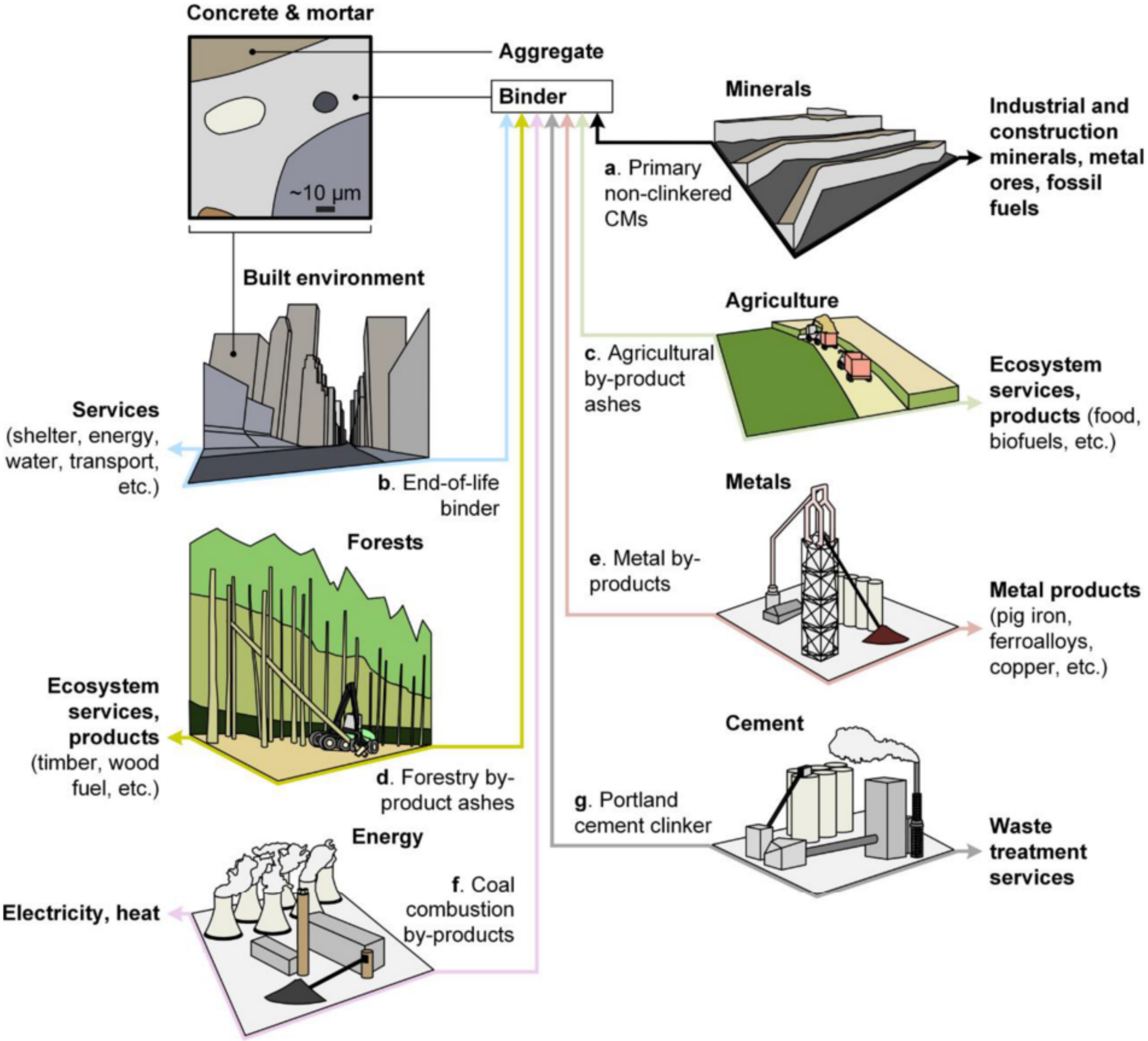


**Fig. 11.** Conceptual representation of clinker and cement substitution [177].

### *4.2. Carbon capture and utilisation (CCU)*

Carbon Capture and Utilisation (CCU) offers innovative solutions to reduce the carbon impact of concrete production and enhance its sustainability. One approach to CCU in concrete production is the capture and utilisation of $CO_2$ emissions from industrial sources. By capturing $CO_2$ from power plants, cement factories, or other emission-intensive processes, the greenhouse gas is diverted from the atmosphere and prevented from contributing to climate change. This captured $CO_2$ can then be utilised in several ways. One application of CCU is the incorporation of captured $CO_2$ into the concrete mix itself [185–187]. This can be achieved by chemically converting $CO_2$ into mineralized carbonates, which can act as a SCM. These carbonates can be used as a mineral admixture in concrete, partially replacing traditional cement. By utilising $CO_2$ in this manner, the carbonation process is enhanced, leading to increased carbon sequestration within the concrete and reducing the overall carbon footprint of the material.

Another CCU approach in concrete production involves the production of alternative binders or aggregates using captured $CO_2$ [188–190]. Through chemical reactions, $CO_2$ can be bound with certain materials to produce cementitious products with reduced carbon footprints. These alternative binders can be used as substitutes for traditional cement in concrete production, further reducing $CO_2$ emissions associated with the manufacturing process. CCU technologies in concrete production not only help to mitigate $CO_2$ emissions but also contribute to the circular economy by transforming waste $CO_2$ into a valuable resource. By capturing and utilising $CO_2$, concrete producers can transition towards a more sustainable and environmentally friendly manufacturing process. Both carbonation and CCU face challenges that need to be addressed for widespread implementation. The slow nature of natural carbonation requires extended periods for significant carbon sequestration. Accelerated carbonation techniques must be optimised to ensure consistent and efficient carbonation throughout the concrete matrix. Additionally, CCU requires efficient and cost-effective technologies for capturing and purifying $CO_2$ from industrial emissions.

Implementing CCU in concrete production requires collaboration between industry, researchers and policymakers. Challenges such as the scalability of CCU technologies, the availability of suitable carbon capture infrastructure and ensuring the long-term durability and performance of CCU-enhanced concrete need to be addressed. However, the potential benefits of CCU in decarbonising concrete production make it a promising avenue for reducing the environmental impact of this essential construction material. To promote the adoption of carbonation and CCU in concrete production, further research and development efforts are necessary. This includes optimising carbonation processes, developing new materials and binders that incorporate captured $CO_2$ and advancing technologies for efficient $CO_2$ capture and purification. Collaboration between researchers, industry stakeholders and policymakers is essential to drive innovation and facilitate the transition to more sustainable concrete production practices.

### 4.3. *Development of low-carbon concrete mixes*

The evolution of low-carbon concrete involves a strategic approach to mitigate its environmental impact while sustaining or elevating performance characteristics. Utilising alternative cementitious materials like fly ash, slag, silica fume, and calcined clays offers a pathway to reduce the carbon footprint by replacing or complementing Portland cement. Rigorous research and testing, as emphasised by Shubbar et al. [191] and Jalaei et al. [192], are instrumental in determining optimal combinations and proportions of these materials within the concrete mix. The integration of Supplementary Cementitious Materials (SCMs), showcased in blended cements, not only decreases clinker content but also enhances concrete durability, as noted by Kim et al. [193] and Knight et al. [194].

Simultaneously, optimising aggregate selection, a substantial portion of concrete volume, involves choosing materials with lower embodied carbon. Recycled aggregates, sourced from demolished structures, offer an eco-friendly alternative, while locally obtained aggregates reduce transportation distances, further diminishing environmental impact [195,196]. Innovations in concrete technology, leveraging chemical admixtures and additives, result in high-performance mixes requiring less cement content, thereby reducing the overall carbon footprint. Collaboration among researchers, engineers, material suppliers, and concrete producers is crucial for the advancement of low-carbon concrete, fostering knowledge exchange and innovation in the field.

### 4.4. *Recycling and reuse of concrete waste*

The recycling and reuse of concrete waste play a vital role in promoting sustainable construction practices and reducing the environmental impact of concrete production. Concrete waste can be generated from various activities such as construction, demolition and renovation. Instead of simply discarding this waste, it can be processed and utilised in a beneficial manner. One commonly used method for recycling concrete waste is through the process of crushing and screening [192,197]. The waste concrete is broken down into smaller pieces and sorted based on their size. The resulting material, known as recycled concrete aggregate (RCA), can be used as a substitute for natural aggregates in the production of new concrete. RCA retains the structural properties of conventional aggregates while significantly reducing the need for virgin materials and minimising the extraction of new aggregates. The simplified flow of the concrete recycling process is depicted in Fig. 12.

Recycled concrete can also serve as a sustainable base material for constructing roads, pavements and foundations. By using recycled concrete as a substitute for traditional granular materials, the consumption of natural resources can be reduced, leading to a decrease in the carbon footprint associated with the transportation of construction materials. Furthermore, recycled concrete can be processed into smaller particles called recycled concrete fines. These fines can be employed as a replacement for sand in specific applications, such as road sub-base layers and pipe bedding. The utilisation of recycled concrete fines helps to diminish the demand for virgin sand, which is often obtained from riverbeds and contributes to environmental degradation.

Another approach to concrete waste management is in-situ recycling [199]. This method involves crushing and reusing the demolished concrete directly at the construction site, eliminating the need for transportation and reducing costs. In-situ recycling is particularly advantageous for large-scale demolition projects, where the crushed concrete can be utilised as fill material or for constructing temporary roads and pathways. To effectively promote the recycling and reuse of concrete waste, it is crucial to implement proper waste management practices and establish recycling facilities. Construction companies and contractors should adopt strategies to separate and collect concrete waste on-site, ensuring that it is appropriately sorted and processed for recycling purposes. Collaborative efforts among stakeholders, including contractors, waste management companies and recycling facilities, are essential in establishing efficient and sustainable concrete waste management systems.

## 5. Policy considerations for decarbonisation

Policy considerations play a vital role in driving decarbonisation efforts in the cement and concrete industry. National and international climate change policies, such as carbon pricing mechanisms and emission reduction targets, provide a regulatory framework and a clear signal for the industry to transition towards low-carbon practices. Governments can further support decarbonisation through incentives, grants and subsidies that encourage investments in clean technologies and sustainable practices. Collaborative initiatives and partnerships between governments, industry stakeholders and research institutions facilitate knowledge sharing, research and development of innovative solutions. Standards and certifications, such as green building codes and sustainability labels, promote the adoption of sustainable cement and concrete practices, ensuring transparency and accountability in the industry's environmental performance. Effective policy frameworks are essential in creating an enabling environment for decarbonisation and driving the transition towards a more sustainable cement and concrete sector.

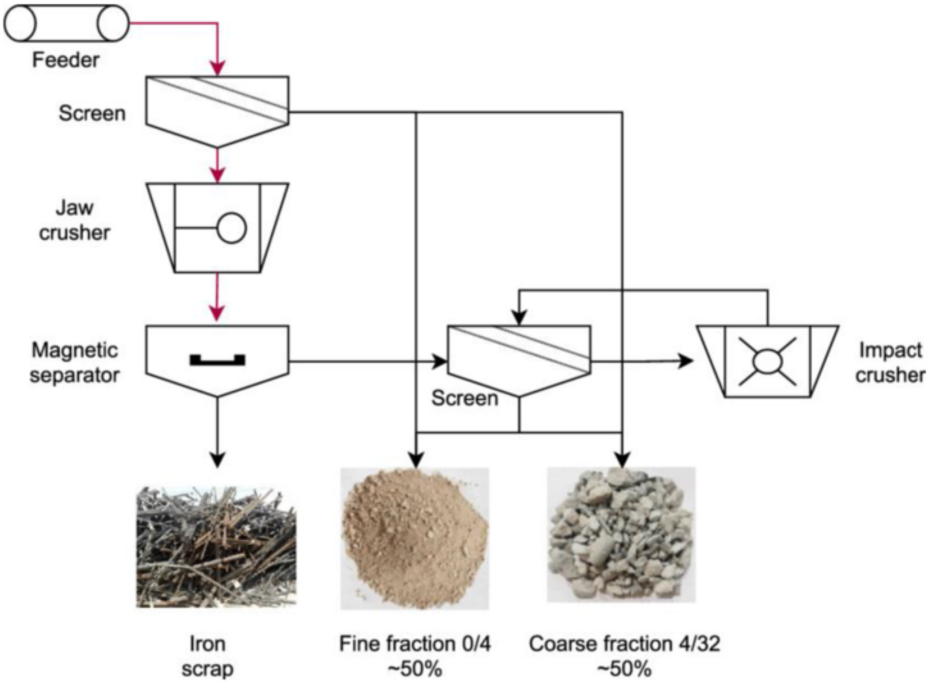


**Fig. 12.** Simplified flow of the concrete recycling process [198].

### 5.1. *National and international climate change policies*

Policy considerations for decarbonisation in the cement industry involve the implementation of national and international climate change policies to tackle the environmental challenges associated with carbon emissions from cement production. At the national level, governments have a range of policy measures at their disposal to incentivize and regulate the reduction of greenhouse gas emissions.

One commonly used policy tool is carbon pricing, which involves putting a price on carbon emissions [200–202]. This can be done through carbon taxes, where cement manufacturers are required to pay a certain amount for each ton of $CO_2$ emitted, or through emissions trading systems, where companies are allocated a certain number of emission allowances that they can buy or sell in a marketplace. Carbon pricing mechanisms create economic incentives for cement manufacturers to reduce their emissions by adopting low-carbon technologies and practices. By putting a price on carbon, the true cost of emissions is internalized, encouraging companies to invest in cleaner and more sustainable production methods. In addition to carbon pricing, governments can also implement regulatory standards and emission limits for the cement industry. These standards set mandatory targets for emissions reductions and impose regulations on cement manufacturers to comply with these targets. By setting specific requirements for emissions from the entire cement production process, including raw material extraction, fuel combustion and clinker production, governments can ensure that cement manufacturers adopt cleaner and more efficient technologies and practices to minimise their carbon footprint.

At the international level, climate change policies, particularly the Paris Agreement, play a vital role in providing a global framework for countries to collectively address climate change [203–205]. The Paris Agreement aims to limit global temperature rise well below 2 °C and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. To achieve these goals, countries are required to develop their own climate action plans, known as nationally determined contributions (NDCs). NDCs outline each country's targets, strategies and policies for reducing greenhouse gas emissions. Cement-producing countries have the opportunity to include specific targets and measures in their NDCs that address emissions from the cement sector. This can involve setting emission reduction targets, implementing regulations and standards and promoting the deployment of low-carbon technologies in cement production.

According to the recently released 2020 Climate Change Performance Index by the NewClimate Institute, the Climate Action Network and Germanwatch, 57 countries were ranked on their national climate change action (statista.com). The index evaluated various categories including emissions, renewable energy, energy use and policy. Shockingly, Australia ranked at the bottom of the index in terms of policy. Unsurprisingly, the United States also received a poor score, only slightly better than Australia (Fig. 13). On a more positive note, Portugal was recognized as the best-performing country for climate change policy. This report emphasises the need for urgent and comprehensive climate change action on a global scale. It raises concerns about the lack of progress and regression demonstrated by certain countries, while highlighting the positive efforts made by others. The rankings serve as a reminder of the importance of strong and effective climate change policies in addressing this critical global issue.

By including specific targets and measures in their NDCs, cement-producing countries can demonstrate their commitment to reducing emissions from the cement sector and contribute to the global effort in combating climate change ([82]; Patidar et al., 2023).

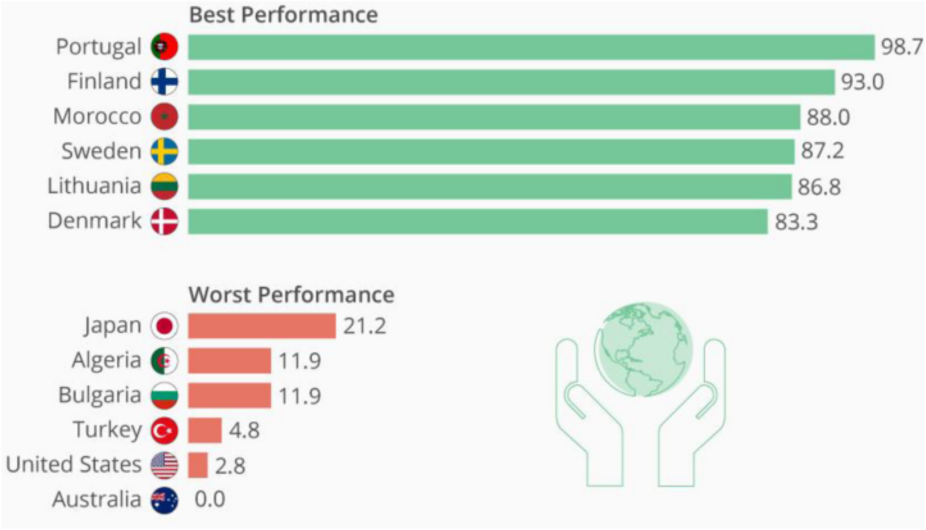


**Fig. 13.** The best & worst countries for climate change policy (statista.com).

This can involve implementing energy efficiency measures, adopting alternative cementitious materials, promoting carbon capture and storage technologies and improving overall sustainability in cement production. Furthermore, the Paris Agreement encourages collaboration among countries in sharing best practices and technologies. Cement-producing countries can take advantage of this collaborative platform to exchange knowledge and experiences, learn from successful initiatives implemented by other countries and foster international cooperation in the development and deployment of low-carbon technologies in the cement sector.

To ensure the success of climate change policies, robust monitoring, reporting and verification (MRV) systems are necessary. MRV systems enable governments to track emissions reduction progress, ensure regulatory compliance and provide transparency in emissions reporting. Establishing standardized methodologies for emissions accounting in the cement sector facilitates accurate measurement and comparison of performance across different companies and countries, supporting effective monitoring of policy outcomes.

### 5.2. *Government incentives and regulations*

Government incentives and regulations play a significant role in driving the decarbonisation of the cement industry. By providing incentives and implementing regulations, governments can encourage cement manufacturers to adopt sustainable practices and reduce their carbon emissions. One common form of government incentive is financial support in the form of grants, subsidies, or tax incentives. These incentives can help offset the costs of implementing low-carbon technologies and infrastructure upgrades. Governments may offer funding programs specifically designed to support research and development in sustainable cement production, promote the use of alternative fuels and raw materials, or encourage the adoption of carbon capture and storage technologies.

Additionally, governments can establish regulatory frameworks and standards that require cement manufacturers to meet specific environmental targets. These regulations can include emissions limits, energy efficiency requirements, or the use of certain percentages of alternative cementitious materials. By implementing such regulations, governments provide clear guidance to the industry and create a level playing field for all cement manufacturers. Government regulations can also include mandatory reporting and disclosure requirements for carbon emissions. By mandating the measurement and reporting of emissions, governments can track industry progress, identify areas for improvement and hold cement manufacturers accountable for their environmental performance. Publicly disclosing emissions data can also enhance transparency and allow stakeholders to make informed decisions regarding sustainable construction practices.

Government procurement policies can also drive the adoption of low-carbon cement. By incorporating sustainability criteria into public infrastructure projects, governments can create a market demand for environmentally friendly cement products. This, in turn, encourages cement manufacturers to innovate and produce low-carbon cement options to compete for government contracts. Furthermore, governments can support the industry by providing research and development funding, promoting collaboration between academia and industry and facilitating knowledge sharing. By investing in research and development, governments can accelerate the development and commercialisation of new technologies and solutions that reduce the carbon footprint of cement production.

### 5.3. *Collaborative initiatives and partnerships*

Collaborative initiatives and partnerships are essential for achieving effective decarbonisation in the cement industry. By bringing together governments, industry stakeholders and civil society organisations, these collaborations create a platform for knowledge exchange, shared learning and coordinated action. One notable organisation in the cement industry is the Global Cement and Concrete Association (GCCA). The GCCA serves as a platform for cement manufacturers from around the world to come together and address sustainability challenges. Through the GCCA, industry players can share their experiences, successes and challenges, fostering a collaborative environment where best practices can be identified and shared.

Collaborative initiatives like the GCCA provide a valuable opportunity for cement manufacturers to learn from one another and develop sustainable solutions. Through collaborative research and development efforts, industry stakeholders can collectively work towards identifying and implementing innovative technologies and practices that reduce the carbon footprint of cement production. Moreover, partnerships with governments, research institutions and civil society organisations contribute to the acceleration of technology transfer in the cement industry. Such partnerships help bridge the gap between research and implementation by facilitating the adoption of proven low-carbon technologies in cement plants. This allows for a more rapid and widespread deployment of sustainable practices throughout the industry.

Collaboration also enables industry stakeholders to advocate for policy changes that support decarbonisation efforts. By working collectively, organisations like the GCCA can engage with policymakers, raise awareness about the need for sustainable cement production and advocate for the development of supportive policies and regulations. These policy changes can range from incentivizing the use of low-carbon technologies to establishing regulatory frameworks that promote sustainability and carbon reduction in the cement industry. Civil society organisations and consumer groups also play an important role in collaborative efforts. Their involvement helps ensure that decarbonisation initiatives align with societal and environmental priorities. By engaging with these stakeholders, industry players can gain insights into public concerns, incorporate social considerations into their sustainability strategies and build trust and credibility with the broader community.

### 5.4. *Standards and certifications for sustainable cement and concrete*

Standards and certifications play a crucial role in promoting sustainable cement and concrete production by providing guidelines, criteria and verification processes to ensure environmental performance and social responsibility. They help stakeholders, including manufacturers, builders and consumers, make informed choices and drive the adoption of sustainable practices in the industry. One widely recognized standard for sustainable cement and concrete is the Leadership in Energy and Environmental Design (LEED) certification. LEED is a globally recognized rating system developed by the U.S. Green Building Council (USGBC) that assesses the sustainability performance of buildings and infrastructure. Within the LEED framework, specific credits and points are allocated for the use of environmentally friendly cement and concrete, such as those with reduced carbon emissions, recycled content, or sourced from responsible suppliers.

Another prominent certification is the Concrete Sustainability Council (CSC) certification, which focuses specifically on the sustainability of concrete production. The CSC certification evaluates various aspects of concrete manufacturing, including responsible sourcing of materials, social and environmental impacts and the implementation of sustainable management practices. The CSC provides a comprehensive framework that covers the entire concrete supply chain, ensuring transparency and accountability throughout the process.

The International Organisation for Standardisation (ISO) has also developed standards related to cement and concrete sustainability. For instance, ISO 14001 sets the criteria for environmental management systems, while ISO 9001 addresses quality management systems. These standards help cement manufacturers establish processes and practices that minimise environmental impacts, ensure product quality and continually improve sustainability performance.

Regional and national organisations also contribute to the development of standards and certifications for sustainable cement and concrete. For example, the European Committee for Standardisation (CEN) has developed the European Standards for cement (EN 197) and concrete (EN 206) to ensure their conformity and performance. These standards cover various aspects, including composition, properties and durability requirements, with an emphasis on sustainability considerations. Furthermore, organisations such as the Global Cement and Concrete Association (GCCA) and the World Business Council for Sustainable Development (WBCSD) work collaboratively with industry stakeholders to establish sustainability frameworks and guidelines. These initiatives promote the use of alternative materials, encourage carbon reduction strategies and prioritise circular economy principles in cement and concrete production.

By adhering to recognized standards and certifications, cement and concrete manufacturers demonstrate their commitment to sustainability and provide assurance to customers and stakeholders. These certifications help differentiate products in the market, enhance credibility and foster a culture of continuous improvement. Additionally, they contribute to the broader goal of achieving sustainable development by reducing environmental impacts, conserving resources and improving the overall performance of the built environment. It is important to note that standards and certifications are constantly evolving to align with the latest scientific knowledge and industry best practices. As the understanding of sustainable practices deepens and technology advances, these frameworks will continue to evolve to drive further improvements in the sustainability of cement and concrete production.

## 6. Case studies and best practices

### 6.1. *Successful examples of decarbonisation in cement and concrete industry*

There are several successful examples of decarbonisation in the cement and concrete industry that showcase the industry's commitment to reducing its carbon footprint and transitioning towards more sustainable practices. These examples highlight innovative technologies, collaborations and initiatives that have achieved significant emissions reductions and demonstrate the feasibility of decarbonisation.

1. The LEILAC (Low Emissions Intensity Lime and Cement) project, led by the European Cement Research Academy, exemplifies the success of carbon capture technology in cement production [53]. Employing Calix's Direct Separation Process, the initiative selectively captured $CO_2$ from cement kiln flue gases, utilising it in the creation of synthetic limestone through mineral

carbonation [206]. This dual benefit not only significantly reduced $CO_2$ emissions from cement production but also produced a valuable by-product with applications across industries. The LEILAC project serves as a pivotal milestone in advancing CCU, highlighting its potential as a sustainable solution for the cement industry's decarbonisation and transition to a low-carbon future.
2. In response to the imperative to reduce carbon emissions in cement production, global cement producer LafargeHolcim has proactively embraced sustainability measures, notably substituting fossil fuels with alternative fuels [207,208]. This strategy includes integrating biomass, waste-derived fuels, and non-recyclable plastics into manufacturing processes. By diversifying fuel sources, LafargeHolcim curtails reliance on fossil fuels, diminishing carbon emissions tied to energy consumption. Importantly, using non-recyclable plastics as an alternative fuel aligns with waste management principles, diverting plastics from landfills and incineration. This circular economy approach promotes resource efficiency, contributing to a sustainable waste management paradigm. LafargeHolcim's commitment to innovation and sustainable solutions is evident through ongoing research and development, optimising alternative fuel utilisation for maximal environmental benefits in the cement industry.
3. The Global Cement and Concrete Association (GCCA) plays a pivotal role in uniting industry stakeholders for concerted efforts in decarbonisation and sustainable practices. Serving as a unifying platform, GCCA fosters collaboration and knowledge sharing among members to accelerate the shift towards a low-carbon and sustainable future. Through initiatives like the “2050 Climate Ambition,” GCCA commits its members to actively reduce $CO_2$ emissions and promote sustainability throughout the value chain, aligning with global climate goals. This collaborative approach allows the pooling of resources, expertise, and technological advancements, contributing to more efficient decarbonisation. GCCA's engagement with policymakers and industry stakeholders further shapes supportive regulations, fostering the adoption of low-carbon technologies and circular economy principles, addressing sustainability challenges beyond emissions reduction. The association's collaborative efforts drive positive change, promoting a more resilient cement and concrete industry.
4. In 2021, several major cement companies, including HeidelbergCement, LafargeHolcim, and Cemex, made a significant commitment to combat climate change by joining the Race to Zero campaign [209]. This campaign, led by the United Nations Framework Convention on Climate Change (UNFCCC), aims to mobilise businesses, cities, regions, and other stakeholders to achieve net-zero carbon emissions by 2050 [210]. The participation of these cement industry giants in the Race to Zero campaign demonstrates their strong determination and proactive approach to decarbonisation. By setting the goal of achieving net-zero CO2 emissions by 2050, these companies are making a clear statement about their commitment to sustainability and aligning their efforts with global climate objectives. To achieve this ambitious target, cement companies are embracing a holistic approach that encompasses various strategies and actions. One key aspect is the adoption of low-carbon technologies throughout the cement production process. This includes the use of alternative fuels, such as biomass and waste-derived fuels, to replace fossil fuels, which significantly reduces the carbon intensity of cement production.
5. Certification systems like LEED, BREEAM, and DGNB offer comprehensive frameworks for assessing building sustainability [211,212]. Evaluating aspects like energy efficiency and the use of eco-friendly materials, these certifications highlight the importance of low-carbon materials, urging builders to choose those with reduced footprints. This fosters a market demand for sustainable cement and concrete, prompting manufacturers to innovate. Green certifications also raise awareness among industry professionals, guiding them on carbon reduction, waste management, and sustainable practices. Encouraging the adoption of low-carbon materials, these certifications contribute to the industry's decarbonisation, aligning with international climate targets and enhancing the market value of certified buildings.

These successful examples demonstrate that decarbonisation in the cement and concrete industry is not only feasible but also economically viable. They showcase the industry's commitment to sustainable development, innovation and collaboration to address the environmental challenges posed by carbon emissions. By leveraging these successes and continuing to invest in research, technology and policy frameworks, the industry can accelerate its transition towards a low-carbon future.

### 6.2. *Lessons learned and transferability of best practices*

Lessons from successful decarbonisation initiatives in the cement and concrete industry offer crucial guidance for broader adoption in diverse sectors. Clear and supportive policy frameworks, coupled with long-term commitment, are vital drivers for industry players to embrace sustainable strategies. Collaboration among stakeholders fosters knowledge exchange, accelerating the deployment of effective decarbonisation efforts. Continuous investment in research and development is key to advancing low-carbon technologies and processes. Financial incentives from governments and financial institutions encourage widespread adoption. Adopting a life cycle perspective and embracing circular economy principles are crucial for reducing environmental impact. Consumer awareness and demand, supported by green certifications, drive market transformation. Scalability, replicability, and adaptability to local conditions enhance the effectiveness of decarbonisation strategies. Robust monitoring and reporting systems ensure transparency and accountability, tracking progress toward decarbonisation goals. Applying these lessons globally accelerates the transition to a low-carbon cement and concrete industry, contributing significantly to climate change mitigation.

## 7. Economic and market implications

Decarbonising cement and concrete production have significant economic and market implications. One key consideration is the cost of decarbonisation technologies, as transitioning to low-carbon practices may involve upfront investments and operational adjustments. However, as the demand for sustainable construction materials and practices grows, market opportunities for low-carbon cement and concrete emerge. Companies that embrace decarbonisation can gain a competitive edge by offering environmentally friendly products and meeting the evolving preferences of environmentally conscious consumers. Economic incentives, such as tax incentives or grants, can further encourage businesses to adopt sustainable construction practices. The development of new business models focused on sustainability, such as green building certifications and circular economy approaches, creates economic opportunities and drives market transformation towards a more sustainable and resilient construction industry.

### 7.1. *Cost considerations of decarbonisation technologies*

Decarbonisation technologies face a crucial hurdle in economic feasibility, shaping their adoption across industries. Capital investment, covering upfront costs for equipment and infrastructure modifications, demands careful scrutiny of returns on investment. Government support through grants and subsidies becomes essential to incentivize widespread adoption. Operational costs, including maintenance and energy consumption, must be balanced against potential savings from reduced emissions. Scalability and economies of scale play pivotal roles in influencing cost-effectiveness, with large-scale deployment leading to significant reductions. Integration costs for retrofitting existing infrastructure and workforce training represent additional considerations. The dynamic cost landscape of decarbonisation technologies, influenced by research, technological advancements, and market competition, may see substantial reductions over time. Supportive policies, carbon pricing, and government initiatives play crucial roles in creating a conducive environment. Balancing cost considerations with long-term benefits is key to driving an effective transition to a sustainable, low-carbon future.

### 7.2. *Market opportunities for low-carbon cement and concrete*

The escalating demand for sustainable construction materials propels market opportunities for low-carbon cement and concrete. Heightened awareness of traditional cement's environmental impact induces governments, construction firms, and consumers to embrace eco-friendly alternatives. Stringent regulations and sustainability standards further drive demand, incentivizing or mandating the adoption of environmentally responsible building materials. Governments' carbon neutrality targets reinforce the need for low-carbon construction in public projects. Consumer and corporate preferences for sustainability amplify demand, making low-carbon cement and concrete pivotal. Green certifications like LEED enhance market prospects, endorsing sustainable construction practices. Collaborations within the construction industry facilitate knowledge and resource-sharing, driving market penetration for low-carbon solutions. Export opportunities arise as global regions with significant infrastructure development seek sustainable construction materials. To capitalize, companies must ensure product availability, affordability, quality, invest in R&D, and conduct effective marketing campaigns, aligning with the growing focus on sustainability, regulatory support, and global infrastructure development.

### 7.3. *Economic incentives and business models for sustainable construction*

Economic incentives and evolving business models are pivotal drivers for widespread adoption of sustainable construction practices. Green building certifications like LEED and BREEAM not only offer market recognition but also financial benefits, encouraging sustainable design. Energy efficiency incentives, such as grants and tax credits, promote cost-effective technologies like LED lighting. Financial support, expedited permitting, and regulatory flexibility incentivize net zero and zero-energy buildings, emphasizing long-term cost savings.

Green financing options, such as loans and bonds, offset upfront costs and enable investments in energy-efficient technologies. Carbon pricing mechanisms and trading systems create financial motivations for low-carbon technologies. Performance-based contracts ensure accountability and shared risks in sustainable construction. Embracing circular economy principles minimises waste and boosts innovative business models. Sustainable supply chain practices enhance reputation and meet rising demand for eco-friendly construction. Collectively, these economic incentives drive the economic viability of sustainable construction, fostering a transition to an environmentally friendly and economically sustainable built environment.

## 8. Challenges and barriers to decarbonisation

Decarbonising cement and concrete production face several challenges and barriers that hinder the transition to low-carbon practices. Technological challenges and research gaps exist, as developing and scaling up innovative technologies for carbon capture, alternative materials and energy-efficient processes requires further research and development. Investment and financing constraints pose another barrier, as the upfront costs of adopting decarbonisation technologies and implementing sustainable practices can be substantial. Resistance to change and industry practices rooted in traditional methods and established norms can impede the adoption of new technologies and practices. Additionally, a lack of awareness and education among industry stakeholders about the benefits and feasibility of decarbonisation can slow down progress. Overcoming these challenges requires collaborative efforts, increased research funding, supportive policies and educational campaigns to drive the necessary transformation in the cement and concrete industry.

### 8.1. *Technological challenges and research gaps*

Sustainable construction has made significant progress, yet enduring technological challenges persist. Innovations are sought in energy-efficient building systems, requiring research into advanced HVAC, lighting, and building envelope technologies. Integrating renewables demands optimization in design, installation, and management, while sustainable materials and techniques necessitate evaluating performance, durability, and life-cycle impacts of alternatives like low-carbon cements. Challenges in smart and connected buildings involve data management, interoperability, and cybersecurity, requiring scalable, privacy-focused solutions.

Refining life-cycle assessments for accurate environmental impact evaluations, addressing climate change with resilient designs, and overcoming hurdles in digitalization and Building Information Modelling (BIM) also demand attention. Collaboration among researchers, industry, policymakers, and funding agencies is pivotal. Investment in research, knowledge sharing, and interdisciplinary collaboration is vital to accelerate the adoption of sustainable technologies and practices in construction.

### 8.2. *Investment and financing constraints*

Overcoming investment and financing constraints is crucial for the widespread adoption of sustainable construction practices. Challenges arise from the higher initial costs of sustainable projects, dissuading short-term-focused investors. Limited access to capital, especially for small and medium-sized enterprises (SMEs) and startups, stems from traditional financiers' unfamiliarity with sustainable practices. Lack of awareness and education regarding the economic benefits of sustainable construction creates barriers to securing financing. Perceived risks associated with new technologies and materials in sustainable projects further hinder investment. The inadequacy of traditional financial instruments necessitates innovative options aligned with the long-term nature of sustainability investments.

Inconsistent policy frameworks contribute to uncertainty for investors, emphasizing the need for clear, supportive policies and financial incentives. The limited track record of sustainable construction projects requires data dissemination on their financial returns and operational benefits to build investor confidence. Addressing these challenges involves collaborative efforts among financial stakeholders, industry players, and governments. Developing incentivizing financial mechanisms, improving access to capital, promoting knowledge sharing, and establishing supportive policy frameworks can collectively propel the transition towards a more sustainable and resilient built environment.

### 8.3. *Resistance to change and industry practices*

Overcoming resistance to change and entrenched industry practices is pivotal for the widespread adoption of sustainable construction methods. Resistance is rooted in established norms, where professionals, accustomed to traditional methods, may be hesitant to embrace new approaches or technologies. Limited awareness of the benefits and feasibility of sustainable practices further impedes transformation. Cost considerations, though crucial, often focus on upfront expenses, disregarding long-term cost savings, energy efficiency, and environmental benefits associated with sustainability.

A shortage of expertise in sustainable design, energy-efficient technologies, and green building certifications hampers full adoption. The fragmented construction supply chain, involving various stakeholders, poses coordination challenges. Regulatory environments, not universally prioritizing sustainable practices, may discourage investment in regions with inadequate or outdated regulations. Risk aversion, driven by concerns about performance issues and liability, adds to the resistance. To address these challenges, multifaceted approaches involving education, awareness initiatives, collaboration, financial incentives, regulatory reforms, and skill development programs are essential. Transforming entrenched practices in the construction industry towards sustainability requires a concerted effort to build awareness, knowledge, and support for change.

## 9. Future outlook and recommendations

The future outlook for decarbonising cement and concrete production holds great promise, but it requires concerted efforts and strategic actions. Pathways for achieving deep decarbonisation involve a combination of technological advancements, policy frameworks and industry collaboration. Recommendations include setting ambitious emission reduction targets, implementing carbon pricing mechanisms and incentivizing the adoption of low-carbon technologies and practices. Research and development priorities should focus on developing breakthrough technologies, alternative materials and energy-efficient processes. Collaboration and knowledge sharing among industry stakeholders, research institutions and policymakers are essential for sharing best practices, accelerating innovation and driving sector-wide transformation. By pursuing these recommendations, the cement and concrete industry can contribute significantly to global climate goals and foster a more sustainable and resilient built environment.

### 9.1. *Pathways for achieving deep decarbonisation*

Achieving deep decarbonisation, the substantial reduction of greenhouse gas emissions, demands a multifaceted strategy spanning energy, transportation, industry, and buildings. Key pathways include transitioning to renewable energy sources like solar, wind, hydro, and geothermal power, thereby diminishing emissions from power generation. Electrifying sectors such as transportation and heating through the adoption of electric vehicles (EVs) and electric heating systems further decreases reliance on fossil fuels, contingent upon an expanded renewable energy capacity.

Energy efficiency is pivotal, with the implementation of energy-saving technologies and practices in buildings, industries, and transportation. Decentralized energy systems, incorporating small-scale solar panels, wind turbines, and smart grid technologies, enhance energy efficiency and resilience. Carbon Capture and Storage (CCS) technologies become crucial for challenging-to-electrify industries. Sustainable land use practices, circular economy models, and promoting behavioural changes, including sustainable consumption patterns, contribute significantly to emissions reduction. To achieve deep decarbonisation, a tailored combination of these pathways is necessary, considering the specific context of each sector and region. Collaboration among governments, businesses, communities, and individuals is essential for the effective implementation of these pathways, driving systemic changes toward a low-carbon future. This holistic approach underscores the urgency of a unified effort in the global pursuit of sustainability.

### 9.2. *Policy recommendations for promoting sustainable cement and concrete*

Promoting sustainable cement and concrete production requires a multifaceted policy approach. Carbon pricing mechanisms, like taxes or emissions trading, create economic incentives for manufacturers to invest in low-carbon technologies. Regulatory standards, including emission reduction targets, drive cleaner practices. Financial support for research and development initiatives, focusing on low-carbon technologies, is essential. Sustainable procurement policies, prioritizing eco-friendly materials in public projects, incentivize manufacturers to adopt green practices. Educational programs raise awareness about sustainable construction methods. Collaboration among governments, industry stakeholders, and research institutions facilitates knowledge exchange and innovation. Certification schemes, endorsed by governments, recognize and promote environmentally-friendly products. Financial incentives, such as tax breaks, encourage the adoption of sustainable technologies. Life cycle assessments, supported by standardized methods, evaluate environmental impacts. International cooperation is vital for establishing common sustainability standards. Agreements and frameworks guide collaborative efforts, fostering global progress in sustainable construction.

### *9.3. Research and development priorities*

Research and Development (R&D) are pivotal for advancing sustainable cement and concrete production. Focused efforts in low-carbon technologies, alternative cementitious materials, process optimization, and circular economy approaches can significantly reduce carbon emissions. R&D must also advance life cycle assessment methodologies and explore the potential of digital technologies like artificial intelligence and automation to enhance efficiency. Knowledge dissemination and collaboration among academia, industry, and stakeholders are crucial, facilitated by platforms and networks. Adequate funding from governments, research institutions, and industry stakeholders is essential, with public-private partnerships accelerating the development and implementation of sustainable technologies in the cement and concrete sector. These comprehensive R&D initiatives are vital for achieving environmental goals and fostering a more sustainable future in construction materials.

### *9.4. Collaboration and knowledge sharing*

Collaboration and knowledge sharing are paramount for fostering sustainability in the cement and concrete industry. Through partnerships and information exchange, stakeholders can collectively confront environmental challenges and expedite the adoption of sustainable solutions. Industry collaborations, involving manufacturers, suppliers, and contractors, enable the pooling of expertise and resources, fostering joint research and addressing common challenges. Research networks formed by academic institutions and industry associations promote collaboration on sustainable cement and concrete, facilitating the sharing of research findings and methodologies.

Dedicated online platforms and databases serve as centralized hubs for sharing best practices, case studies, and technical reports, keeping stakeholders informed about the latest developments. Knowledge transfer programs, including workshops and mentoring initiatives, empower smaller companies and emerging markets with insights from industry leaders. International cooperation on a global scale allows diverse perspectives to address sustainability challenges, while policy alignment and transparent reporting enhance collaboration. By actively participating in these initiatives, stakeholders can drive innovation and collectively tackle environmental issues, hastening the transition to sustainable practices in the cement and concrete industry.

## 10. Concluding remarks

Decarbonising cement and concrete production is a complex but crucial endeavour in the fight against climate change. By implementing a combination of strategies, technologies, policy considerations and future pathways, we can significantly reduce the carbon footprint of these industries. The adoption of low-carbon technologies, such as alternative fuels, energy-efficient processes and carbon capture, can play a vital role in reducing emissions. These technologies need to be further developed and deployed at scale to ensure their effectiveness and economic viability.

Policy considerations, both at the national and international levels, are essential in driving decarbonisation efforts. Carbon pricing mechanisms, regulatory standards and financial incentives can provide the necessary framework for sustainable practices and investments. International collaboration, as exemplified by the Paris Agreement, facilitates knowledge exchange and coordinated actions towards common climate goals. However, decarbonising cement and concrete production also requires addressing technological challenges, research gaps, investment constraints and resistance to change within the industry. Continued research and development, collaboration and knowledge sharing will be vital in overcoming these obstacles.

Looking to the future, it is crucial to prioritise the development of innovative technologies, explore new materials and promote circular economy approaches. This includes reducing the clinker-to-cement ratio, utilising alternative raw materials and exploring carbon capture and utilisation. Additionally, a focus on sustainable business models, market opportunities and consumer awareness will drive the adoption of low-carbon cement and concrete. By combining these strategies and considering the interplay between technology, policy and market forces, we can pave the way for a sustainable and low-carbon future in cement and concrete production. The collective efforts of governments, industry stakeholders, researchers and society at large will be pivotal in achieving the ambitious goal of decarbonisation and creating a more sustainable built environment.

## CRediT authorship contribution statement

**Salim Barbhuiya:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Fragkoulis Kanavaris:** Writing – review & editing. **Bibhuti Bhusan Das:** Writing – review & editing. **Maria Idrees:** Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## References

[1] G. Habert, N. Roussel, Study of two concrete mix-design strategies to reach carbon mitigation objectives, Cement Concr. Compos. 31 (6) (2009) 397–402.
[2] G. Habert, C. Billard, P. Rossi, C. Chen, N. Roussel, Cement production technology improvement compared to factor 4 objectives, Cement Concr. Res. 40 (5) (2010) 820–826.
[3] D. Xu, Y. Cui, H. Li, K. Yang, W. Xu, Y. Chen, On the future of Chinese cement industry, Cement Concr. Res. 78 (2015) 2–13.
[4] T. Watari, Z. Cao, S. Hata, K. Nansai, Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions, Nat. Commun. 13 (1) (2022) 4158.
[5] S. Griffiths, B.K. Sovacool, D.D.F. Del Rio, A.M. Foley, M.D. Bazilian, J. Kim, J.M. Uratani, Decarbonizing the cement and concrete industry: a systematic review of socio-technical systems, technological innovations, and policy options, Renew. Sustain. Energy Rev. 180 (2023) 113291.
[6] N. Mahasenan, S. Smith, K. Humphreys, The cement industry and global climate change: current and potential future cement industry CO2 emissions, in: Greenhouse Gas Control Technologies-6th International Conference, Pergamon, 2003, January, pp. 995–1000.
[7] R. Rehan, M. Nehdi, Carbon dioxide emissions and climate change: policy implications for the cement industry, Environ. Sci. Pol. 8 (2) (2005) 105–114.
[8] V. Sousa, J.A. Bogas, S. Real, I. Meireles, Industrial production of recycled cement: energy consumption and carbon dioxide emission estimation, Environ. Sci. Pollut. Control Ser. 30 (4) (2023) 8778–8789.
[9] C. Bataille, H. Waisman, M. Colombier, L. Segafredo, J. Williams, F. Jotzo, The need for national deep decarbonization pathways for effective climate policy, Clim. Pol. 16 (sup1) (2016) S7–S26.
[10] F. Johnsson, I. Karlsson, J. Rootzén, A. Ahlbäck, M. Gustavsson, The framing of a sustainable development goals assessment in decarbonizing the construction industry–Avoiding "Greenwashing", Renew. Sustain. Energy Rev. 131 (2020) 110029.
[11] R.J. Brecha, G. Ganti, R.D. Lamboll, Z. Nicholls, B. Hare, J. Lewis, M.J. Gidden, Institutional decarbonization scenarios evaluated against the Paris Agreement 1.5 C goal, Nat. Commun. 13 (1) (2022) 4304.
[12] O. Manoliadis, I. Tsolas, A. Nakou, Sustainable construction and drivers of change in Greece: a Delphi study, Construct. Manag. Econ. 24 (2) (2006) 113–120.
[13] P.O. Akadiri, E.A. Chinyio, P.O. Olomolaiye, Design of a sustainable building: a conceptual framework for implementing sustainability in the building sector, Buildings 2 (2) (2012) 126–152.
[14] J.M. Hussin, I.A. Rahman, A.H. Memon, The way forward in sustainable construction: issues and challenges, Int. J. Adv. Appl. Sci. 2 (1) (2013) 15–24.
[15] A. Revell, D. Stokes, H. Chen, Small businesses and the environment: turning over a new leaf? Bus. Strat. Environ. 19 (5) (2010) 273–288.
[16] J. Giesekam, J.R. Barrett, P. Taylor, Construction sector views on low carbon building materials, Build. Res. Inf. 44 (4) (2016) 423–444.
[17] A. Adesina, Recent advances in the concrete industry to reduce its carbon dioxide emissions, Environmental Challenges 1 (2020) 100004.
[18] J. Rissman, C. Bataille, E. Masanet, N. Aden, W.R. Morrow III, N. Zhou, J. Cresko, Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070, Appl. Energy 266 (2020) 114848.
[19] P. Morseletto, Targets for a circular economy, Resour. Conserv. Recycl. 153 (2020) 104553.
[20] Ö. Çimen, Construction and built environment in circular economy: a comprehensive literature review, J. Clean. Prod. 305 (2021) 127180.
[21] S. Kanagaraj, H. Thiyagarajan, A. Vasudevan, M. Moghul, Road map for implementing circular construction practices in India: an overview, Proceedings of the Institution of Civil Engineers-Management, Procurement and Law 40 (XXXX) (2022) 1–10.
[22] M.S. Imbabi, C. Carrigan, S. McKenna, Trends and developments in green cement and concrete technology, Int. J. Sustainable Built Environ. 1 (2) (2012) 194–216.
[23] M.C. Juenger, R. Snellings, S.A. Bernal, Supplementary cementitious materials: new sources, characterization, and performance insights, Cement Concr. Res. 122 (2019) 257–273.
[24] A. Arrigoni, D.K. Panesar, M. Duhamel, T. Opher, S. Saxe, I.D. Posen, H.L. MacLean, Life cycle greenhouse gas emissions of concrete containing supplementary cementitious materials: cut-off vs. substitution, J. Clean. Prod. 263 (2020) 121465.
[25] S.M. Benson, F.M. Orr, Carbon dioxide capture and storage, MRS Bull. 33 (4) (2008) 303–305.
[26] M.B. Ali, R. Saidur, M.S. Hossain, A review on emission analysis in cement industries, Renew. Sustain. Energy Rev. 15 (5) (2011) 2252–2261.
[27] Y. Izumi, A. Iizuka, H.J. Ho, Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry, J. Clean. Prod. 312 (2021) 127618.
[28] J.L. Gálvez-Martos, D. Styles, H. Schoenberger, B. Zeschmar-Lahl, Construction and demolition waste best management practice in Europe, Resour. Conserv. Recycl. 136 (2018) 166–178.
[29] M.U. Hossain, S.T. Ng, P. Antwi-Afari, B. Amor, Circular economy and the construction industry: existing trends, challenges and prospective framework for sustainable construction, Renew. Sustain. Energy Rev. 130 (2020) 109948.
[30] A. Hasan, A. Elmualim, Entire concrete waste reuse model, in: Multi-Functional Concrete with Recycled Aggregates, Woodhead Publishing, 2023, pp. 363–379.
[31] N. Lippiatt, T.C. Ling, S.Y. Pan, Towards carbon-neutral construction materials: carbonation of cement-based materials and the future perspective, J. Build. Eng. 28 (2020) 101062.
[32] S. Bhattacherjee, A.S. Basavaraj, A.V. Rahul, M. Santhanam, R. Gettu, B. Panda, E. Schlangen, Sustainable materials for 3D concrete printing, Cement Concr. Compos. 122 (2021) 104156.
[33] J.X. Lu, P. Shen, H.A. Ali, C.S. Poon, Mix design and performance of lightweight ultra high-performance concrete, Mater. Des. 216 (2022) 110553.
[34] A.K. Chatterjee, Cement Production Technology: Principles and Practice, CRC Press, 2018.
[35] M. Schneider, M. Romer, M. Tschudin, H. Bolio, Sustainable cement production—present and future, Cement Concr. Res. 41 (7) (2011) 642–650.
[36] S.A. Abdul-Wahab, H. Al-Dhamri, G. Ram, V.P. Chatterjee, An overview of alternative raw materials used in cement and clinker manufacturing, Int. J. Sustain. Eng. 14 (4) (2021) 743–760.
[37] S. Khurana, R. Banerjee, U. Gaitonde, Energy balance and cogeneration for a cement plant, Appl. Therm. Eng. 22 (5) (2002) 485–494.
[38] H.M. Ludwig, W. Zhang, Research review of cement clinker chemistry, Cement Concr. Res. 78 (2015) 24–37.
[39] X. Yao, S. Yang, H. Dong, S. Wu, X. Liang, W. Wang, Effect of CaO content in raw material on the mineral composition of ferric-rich sulfoaluminate clinker, Construct. Build. Mater. 263 (2020) 120431.
[40] M. Amin, D.C. Birawidha, M.A. Muttaqii, K. Isnugroho, Y. Hendronursito, The effect of combustion temperature on the characteristic of clinker, AIP Conf. Proc. 2232 (1) (2020, April), 040010 AIP Publishing LLC.
[41] F. Winnefeld, L.H. Martin, C.J. Müller, B. Lothenbach, Using gypsum to control hydration kinetics of CSA cements, Construct. Build. Mater. 155 (2017) 154–163.
[42] R.K. Gupta, D. Majumdar, J.V. Trivedi, A.D. Bhanarkar, Particulate matter and elemental emissions from a cement kiln, Fuel Process. Technol. 104 (2012) 343–351.
[43] H. Mikulčić, M. Vujanović, N. Duić, Reducing the CO2 emissions in Croatian cement industry, Appl. Energy 101 (2013) 41–48.
[44] E. Benhelal, G. Zahedi, E. Shamsaei, A. Bahadori, Global strategies and potentials to curb CO2 emissions in cement industry, J. Clean. Prod. 51 (2013) 142–161.

[45] M. Schneider, Process technology for efficient and sustainable cement production, Cement Concr. Res. 78 (2015) 14–23.
[46] Y.H. Huang, J.H. Wu, Bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials in the cement industry for energy transition: an application of extended marginal abatement cost curves, J. Clean. Prod. 296 (2021) 126619.
[47] M. Thomas, L. Barcelo, B. Blair, K. Cail, A. Delagrave, K. Kazanis, Lowering the carbon footprint of concrete by reducing clinker content of cement, Transport. Res. Rec. 2290 (1) (2012) 99–104.
[48] K.S. Lauch, V. Dieryck, V. Pollet, The use of ternary cements to reduce the environmental impact of concrete, RILEM Technical Letters 1 (2016) 88–93.
[49] D. Song, J. Yang, B. Chen, T. Hayat, A. Alsaedi, Life-cycle environmental impact analysis of a typical cement production chain, Appl. Energy 164 (2016) 916–923.
[50] Z. Giergiczny, Fly ash and slag, Cement Concr. Res. 124 (2019) 105826.
[51] www.statista.com.
[52] S. Shagñay, A. Bautista, F. Velasco, M. Torres-Carrasco, Hybrid cements: towards their use as alternative and durable materials against wear, Construct. Build. Mater. 312 (2021) 125397.
[53] Y. Guo, L. Luo, T. Liu, L. Hao, Y. Li, P. Liu, T. Zhu, A review of low-carbon technologies and projects for the global cement industry, J. Environ. Sci. 136 (2023) 682–697.
[54] E. Yaşar, Y. Erdoğan, A. Kılıç, Effect of limestone aggregate type and water–cement ratio on concrete strength, Mater. Lett. 58 (5) (2004) 772–777.
[55] D. Sari, A.G. Pasamehmetoglu, The effects of gradation and admixture on the pumice lightweight aggregate concrete, Cement Concr. Res. 35 (5) (2005) 936–942.
[56] B.A. Warda, A.N. Munaz, Effects of aggregate gradation on water permeability of concrete, Adv. Mater. Res. 488 (2012) 248–252 Trans Tech Publications Ltd.
[57] M.J. McGinnis, M. Davis, A. de la Rosa, B.D. Weldon, Y.C. Kurama, Strength and stiffness of concrete with recycled concrete aggregates, Construct. Build. Mater. 154 (2017) 258–269.
[58] D.C. Ukala, Effects of combined aggregate gradation on the compression strength and workability of concrete using fineness modulus, J. Appl. Sci. Environ. Manag. 23 (5) (2019) 851–856.
[59] H. Yiğiter, H. Yazıcı, S. Aydın, Effects of cement type, water/cement ratio and cement content on sea water resistance of concrete, Build. Environ. 42 (4) (2007) 1770–1776.
[60] S.B. Singh, P. Munjal, N. Thammishetti, Role of water/cement ratio on strength development of cement mortar, J. Build. Eng. 4 (2015) 94–100.
[61] N. Diamantonis, I. Marinos, M.S. Katsiotis, A. Sakellariou, A. Papathanasiou, V. Kaloidas, M. Katsioti, Investigations about the influence of fine additives on the viscosity of cement paste for self-compacting concrete, Construct. Build. Mater. 24 (8) (2010) 1518–1522.
[62] M. Uysal, Self-compacting concrete incorporating filler additives: performance at high temperatures, Construct. Build. Mater. 26 (1) (2012) 701–706.
[63] A.P. Svintsov, E.L. Shchesnyak, V.V. Galishnikova, R.S. Fediuk, N.A. Stashevskaya, Effect of nano-modified additives on properties of concrete mixtures during winter season, Construct. Build. Mater. 237 (2020) 117527.
[64] T.C. Ling, Effects of compaction method and rubber content on the properties of concrete paving blocks, Construct. Build. Mater. 28 (1) (2012) 164–175.
[65] E. Şengün, B. Alam, R. Shabani, I.O. Yaman, The effects of compaction methods and mix parameters on the properties of roller compacted concrete mixtures, Construct. Build. Mater. 228 (2019) 116807.
[66] J. Zhang, J.C. Cheng, I.M. Lo, Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong, Int. J. Life Cycle Assess. 19 (2014) 745–757.
[67] F.N. Stafford, F. Raupp-Pereira, J.A. Labrincha, D. Hotza, Life cycle assessment of the production of cement: a Brazilian case study, J. Clean. Prod. 137 (2016) 1293–1299.
[68] M. Dabaieh, J. Heinonen, D. El-Mahdy, D.M. Hassan, A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks, J. Clean. Prod. 275 (2020) 122998.
[69] N. Mohamad, K. Muthusamy, R. Embong, A. Kusbiantoro, M.H. Hashim, Environmental impact of cement production and Solutions: a review, Mater. Today: Proc. 48 (2022) 741–746.
[70] G.S. Kumar, A. Ramakrishnan, Y.T. Hung, Lime Calcination. Advanced Physicochemical Treatment Technologies, 2007, pp. 611–633.
[71] A. Bosoaga, O. Masek, J.E. Oakey, CO2 capture technologies for cement industry, Energy Proc. 1 (1) (2009) 133–140.
[72] L.X. Hao, F.Q. Zhao, P.X. Zhao, Measures to reduce carbon dioxide emission of China cement industry, Adv. Mater. Res. 233 (2011) 412–415 Trans Tech Publications Ltd.
[73] E. Worrell, N. Martin, L. Price, Potentials for energy efficiency improvement in the US cement industry, Energy 25 (12) (2000) 1189–1214.
[74] E. Worrell, L. Price, N. Martin, C. Hendriks, L.O. Meida, Carbon dioxide emissions from the global cement industry, Annu. Rev. Energy Environ. 26 (1) (2001) 303–329.
[75] H.G. Van Oss, A.C. Padovani, Cement manufacture and the environment part II: environmental challenges and opportunities, J. Ind. Ecol. 7 (1) (2003) 93–126.
[76] D.N. Huntzinger, T.D. Eatmon, A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies, J. Clean. Prod. 17 (7) (2009) 668–675.
[77] M. Georgiopoulou, G. Lyberatos, Life cycle assessment of the use of alternative fuels in cement kilns: a case study, J. Environ. Manag. 216 (2018) 224–234.
[78] J.S. Gregg, R.J. Andres, G. Marland, China: emissions pattern of the world leader in CO2 emissions from fossil fuel consumption and cement production, Geophys. Res. Lett. 35 (8) (2008).
[79] Z. Liu, D. Guan, W. Wei, S.J. Davis, P. Ciais, J. Bai, S. Peng, Q. Zhang, K. Hubacek, G. Marland, R.J. Andres, Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature 524 (7565) (2015) 335–338.
[80] Z. Liu, P. Ciais, Z. Deng, S.J. Davis, B. Zheng, Y. Wang, D. Cui, B. Zhu, X. Dou, P. Ke, T. Sun, Carbon Monitor, a near-real-time daily dataset of global CO2 emission from fossil fuel and cement production, Sci. Data 7 (1) (2020) 392.
[81] L. Proaño, A.T. Sarmiento, M. Figueredo, M. Cobo, Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: a system dynamics approach, J. Clean. Prod. 263 (2020) 121457.
[82] M. Amran, N. Makul, R. Fediuk, Y.H. Lee, N.I. Vatin, Y.Y. Lee, K. Mohammed, Global carbon recoverability experiences from the cement industry, Case Stud. Constr. Mater. 17 (2022) e01439.
[83] www.iea.org.
[84] U. Riebesell, J.P. Gattuso, Lessons learned from ocean acidification research, Nat. Clim. Change 5 (1) (2015) 12–14.
[85] E. Rokni, A. Panahi, X. Ren, Y.A. Levendis, Curtailing the generation of sulfur dioxide and nitrogen oxide emissions by blending and oxy-combustion of coals, Fuel 181 (2016) 772–784.
[86] E.T. Mitchard, The tropical forest carbon cycle and climate change, Nature 559 (7715) (2018) 527–534.
[87] J. Venetoulis, J. Talberth, Refining the ecological footprint, Environ. Dev. Sustain. 10 (4) (2008) 441–469.
[88] B. Ozcan, S. Bozoklu, Dynamics of ecological balance in OECD countries: sustainable or unsustainable? Sustain. Prod. Consum. 26 (2021) 638–647.
[89] M. Sharma, S. Bishnoi, F. Martirena, K. Scrivener, Limestone calcined clay cement and concrete: a state-of-the-art review, Cement Concr. Res. 149 (2021) 106564.
[90] L. Wang, N.U. Rehman, I. Curosu, Z. Zhu, M.A.B. Beigh, M. Liebscher, L. Chen, D.C. Tsang, S. Hempel, V. Mechtcherine, On the use of limestone calcined clay cement (LC3) in high-strength strain-hardening cement-based composites (HS-SHCC), Cement Concr. Res. 144 (2021) 106421.
[91] A. Zolfagharnasab, A.A. Ramezanianpour, F. Bahman-Zadeh, Investigating the potential of low-grade calcined clays to produce durable LC3 binders against chloride ions attack, Construct. Build. Mater. 303 (2021) 124541.
[92] A. Ejbouh, A. Ech-chebab, S. Hassi, M. Galai, H. Benqlilou, M.E. Touhami, Durability assessment of LC3-based reinforced concrete under combined chloride-sulfate environment via the EIS technique, Construct. Build. Mater. 366 (2023) 130194.
[93] A. Cuesta, A. Ayuela, M.A. Aranda, Belite cements and their activation, Cement Concr. Res. 140 (2021) 106319.
[94] J.W. Phair, Green chemistry for sustainable cement production and use, Green Chem. 8 (9) (2006) 763–780.
[95] T. Staněk, P. Sulovský, Active low-energy belite cement, Cement Concr. Res. 68 (2015) 203–210.

[96] M. Antunes, R.L. Santos, J. Pereira, P. Rocha, R.B. Horta, R. Colaço, Alternative clinker technologies for reducing carbon emissions in cement industry: a critical review, Materials 15 (1) (2022) 209.

[97] J. Morrison, G. Jauffret, J.L. Galvez-Martos, F.P. Glasser, Magnesium-based cements for CO2 capture and utilisation, Cement Concr. Res. 85 (2016) 183–191.

[98] D. Meng, C. Unluer, E.H. Yang, S. Qian, Recent advances in magnesium-based materials: CO2 sequestration and utilization, mechanical properties and environmental impact, Cement Concr. Compos. (2023) 104983.

[99] M.A. Haque, B. Chen, Research progresses on magnesium phosphate cement: a review, Construct. Build. Mater. 211 (2019) 885–898.

[100] W. Ruan, J. Liao, F. Li, X. Gu, A. Zhou, Y. Xie, Effects of water purifying material waste and red mud on performance of magnesium phosphate cement, Construct. Build. Mater. 303 (2021) 124563.

[101] J.L. Provis, Alkali-activated materials, Cement Concr. Res. 114 (2018) 40–48.

[102] F.G. Collins, J.G. Sanjayan, Workability and mechanical properties of alkali activated slag concrete, Cement Concr. Res. 29 (3) (1999) 455–458.

[103] Y. Ding, J.G. Dai, C.J. Shi, Mechanical properties of alkali-activated concrete: a state-of-the-art review, Construct. Build. Mater. 127 (2016) 68–79.

[104] K. Behfarnia, M. Rostami, Mechanical properties and durability of fiber reinforced alkali activated slag concrete, J. Mater. Civ. Eng. 29 (12) (2017) 04017231.

[105] S. Laribi, L. Dubois, G. De Weireld, D. Thomas, Study of the post-combustion CO2 capture process by absorption-regeneration using amine solvents applied to cement plant flue gases with high CO2 contents, Int. J. Greenh. Gas Control 90 (2019) 102799.

[106] S. Cloete, A. Giuffrida, M.C. Romano, A. Zaabout, The swing adsorption reactor cluster for post-combustion CO2 capture from cement plants, J. Clean. Prod. 223 (2019) 692–703.

[107] M. Voldsund, S.O. Gardarsdottir, E. De Lena, J.-F. Pérez-Calvo, A. Jamali, D. Berstad, C. Fu, M. Romano, S. Roussanaly, R. Anantharaman, et al., Comparison of technologies for CO2 capture from cement production—Part 1: technical evaluation, Energies 12 (3) (2019) 559.

[108] A. Padurean, C.C. Cormos, P.S. Agachi, Pre-combustion carbon dioxide capture by gas-liquid absorption for Integrated Gasification Combined Cycle power plants, Int. J. Greenh. Gas Control 7 (2012) 1–11.

[109] S. Park, S. Lee, Y. Lee, Y. Lee, Y. Seo, Hydrate-based pre-combustion capture of carbon dioxide in the presence of a thermodynamic promoter and porous silica gels, Int. J. Greenh. Gas Control 14 (2013) 193–199.

[110] D. Jansen, M. Gazzani, G. Manzolini, E. van Dijk, M. Carbo, Pre-combustion CO2 capture, Int. J. Greenh. Gas Control 40 (2015) 167–187.

[111] C. Bruce, S. Giannaris, B. Jacobs, D. Janowczyk, W. Srisang, Post combustion CO2 capture retrofit of Saskpower's shand power station: capital and operating cost reduction of a 2nd generation capture facility, in: 14th Greenhouse Gas Control Technologies Conference Melbourne, 2018, October, pp. 21–26.

[112] F. Raganati, F. Miccio, P. Ammendola, Adsorption of carbon dioxide for post-combustion capture: a review, Energy Fuels 35 (16) (2021) 12845–12868.

[113] D.K. Moon, Y. Park, H.T. Oh, S.H. Kim, M. Oh, C.H. Lee, Performance analysis of an eight-layered bed PSA process for H2 recovery from IGCC with pre-combustion carbon capture, Energy Convers. Manag. 156 (2018) 202–214.

[114] D.J. Dillon, R.S. Panesar, R.A. Wall, R.J. Allam, V. White, J. Gibbins, M.R. Haines, Oxy-combustion processes for CO2 capture from advanced supercritical PF and NGCC power plant, Greenhouse Gas Control Technologies 7 (2005) 211–220 Elsevier Science Ltd.

[115] A. Gopan, B.M. Kumfer, J. Phillips, D. Thimsen, R. Smith, R.L. Axelbaum, Process design and performance analysis of a Staged, Pressurized Oxy-Combustion (SPOC) power plant for carbon capture, Appl. Energy 125 (2014) 179–188.

[116] L.D. Ellis, A.F. Badel, M.L. Chiang, Y.M. Chiang, Toward electrochemical synthesis of cement—an electrolyzer-based process for decarbonating CaCO3 while producing useful gas streams, Proc. Natl. Acad. Sci. USA 117 (23) (2020) 12584–12591.

[117] R. Svensson, M. Odenberger, F. Johnsson, L. Strömberg, Transportation systems for CO2 – application to carbon capture and storage, Energy Convers. Manag. 45 (15–16) (2004) 2343–2353.

[118] S.T. McCoy, E.S. Rubin, An engineering-economic model of pipeline transport of CO2 with application to carbon capture and storage, Int. J. Greenh. Gas Control 2 (2) (2008) 219–229.

[119] V.E. Onyebuchi, A. Kolios, D.P. Hanak, C. Biliyok, V. Manovic, A systematic review of key challenges of CO2 transport via pipelines, Renew. Sustain. Energy Rev. 81 (2018) 2563–2583.

[120] S.M. Benson, T. Surles, Carbon dioxide capture and storage: an overview with emphasis on capture and storage in deep geological formations, Proc. IEEE 94 (10) (2006) 1795–1805.

[121] Z. Ziabakhsh-Ganji, H. Kooi, Sensitivity of the CO2 storage capacity of underground geological structures to the presence of SO2 and other impurities, Appl. Energy 135 (2014) 43–52.

[122] T. Ajayi, J.S. Gomes, A. Bera, A review of CO2 storage in geological formations emphasizing modeling, monitoring and capacity estimation approaches, Petrol. Sci. 16 (2019) 1028–1063.

[123] R. Martínez, I. Suárez, M.A. Zapatero, B. Saftic, I. Kolenkovic, M. Car, S. Persoglia, F. Donda, The EU GeoCapacity project—saline aquifers storage capacity in group south countries, Energy Proc. 1 (1) (2009) 2733–2740.

[124] M. Jafari, S.C. Cao, J. Jung, Geological CO2 sequestration in saline aquifers: implication on potential solutions of China's power sector, Resour. Conserv. Recycl. 121 (2017) 137–155.

[125] K. War, D.N. Arnepalli, A review on coupled phenomena in aquifers from the perspective of geological storage of carbon dioxide with ecological significance, Building Materials for Sustainable and Ecological Environment (2021) 135–149.

[126] C.M. White, D.H. Smith, K.L. Jones, A.L. Goodman, S.A. Jikich, R.B. LaCount, S.B. DuBose, E. Ozdemir, B.I. Morsi, K.T. Schroeder, Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery: a review, Energy Fuels 19 (3) (2005) 659–724.

[127] D. Yang, N. Koukouzas, M. Green, Y. Sheng, Recent development on underground coal gasification and subsequent CO2 storage, J. Energy Inst. 89 (4) (2016) 469–484.

[128] B. Mayer, P. Humez, V. Becker, C. Dalkhaa, L. Rock, A. Myrttinen, J.A.C. Barth, Assessing the usefulness of the isotopic composition of CO2 for leakage monitoring at CO2 storage sites: a review, Int. J. Greenh. Gas Control 37 (2015) 46–60.

[129] W. Harbert, T.M. Daley, G. Bromhal, C. Sullivan, L. Huang, Progress in monitoring strategies for risk reduction in geologic CO2 storage, Int. J. Greenh. Gas Control 51 (2016) 260–275.

[130] T. Zhang, W. Zhang, R. Yang, Y. Liu, M. Jafari, CO2 capture and storage monitoring based on remote sensing techniques: a review, J. Clean. Prod. 281 (2021) 124409.

[131] R. Gholami, A. Raza, S. Iglauer, Leakage risk assessment of a CO2 storage site: a review, Earth Sci. Rev. 223 (2021) 103849.

[132] R. Wennersten, Q. Sun, H. Li, The future potential for Carbon Capture and Storage in climate change mitigation–an overview from perspectives of technology, economy and risk, J. Clean. Prod. 103 (2015) 724–736.

[133] K.O. Yoro, M.O. Daramola, CO2 emission sources, greenhouse gases, and the global warming effect, in: Advances in Carbon Capture, Woodhead Publishing, 2020, pp. 3–28.

[134] D.Y. Leung, G. Caramanna, M.M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, Renew. Sustain. Energy Rev. 39 (2014) 426–443.

[135] N. Bahman, M. Al-Khalifa, S. Al Baharna, Z. Abdulmohsen, E. Khan, Review of carbon capture and storage technologies in selected industries: potentials and challenges, Rev. Environ. Sci. Biotechnol. (2023) 1–20.

[136] S. Budinis, S. Krevor, N. Mac Dowell, N. Brandon, A. Hawkes, An assessment of CCS costs, barriers and potential, Energy Strategy Rev. 22 (2018) 61–81.

[137] T. Wilberforce, A. Baroutaji, B. Soudan, A.H. Al-Alami, A.G. Olabi, Outlook of carbon capture technology and challenges, Sci. Total Environ. 657 (2019) 56–72.

[138] M.I. Rashid, E. Benhelal, S. Rafiq, Reduction of greenhouse gas emissions from gas, oil, and coal power plants in Pakistan by carbon capture and storage (CCS): a Review, Chem. Eng. Technol. 43 (11) (2020) 2140–2148.

[139] S. Bachu, CO2 storage in geological media: role, means, status and barriers to deployment, Prog. Energy Combust. Sci. 34 (2) (2008) 254–273.

[140] Y. Wu, X. Chen, J. Ma, Y. Wu, D. Liu, J. Mi, W. Xie, System integration for coal-fired power plant with post combustion CO2 capture: comparative study for different solid dry sorbents, Fuel 280 (2020) 118561.

[141] O. Akeeb, L. Wang, W. Xie, R. Davis, M. Alkasrawi, S. Toan, Post-combustion CO2 capture via a variety of temperature ranges and material adsorption process: a review, J. Environ. Manag. 313 (2022) 115026.

[142] T.E. Akinola, P.L.B. Prado, M. Wang, Experimental studies, molecular simulation and process modelling\simulation of adsorption-based post-combustion carbon capture for power plants: a state-of-the-art review, Appl. Energy 317 (2022) 119156.
[143] V. Becattini, P. Gabrielli, C. Antonini, J. Campos, A. Acquilino, G. Sansavini, M. Mazzotti, Carbon dioxide capture, transport and storage supply chains: optimal economic and environmental performance of infrastructure rollout, Int. J. Greenh. Gas Control 117 (2022) 103635.
[144] P. Balcombe, D.A. Heggo, M. Harrison, Total methane and CO2 emissions from liquefied natural gas carrier ships: the first primary measurements, Environ. Sci. Technol. 56 (13) (2022) 9632–9640.
[145] M. Shen, F. Kong, L. Tong, Y. Luo, S. Yin, C. Liu, P. Zhang, L. Wang, P.K. Chu, Y. Ding, Carbon capture and storage (CCS): development path based on carbon neutrality and economic policy, Carbon Neutrality 1 (1) (2022) 37.
[146] S.C. Gowd, P. Ganeshan, V.S. Vigneswaran, M.S. Hossain, D. Kumar, K. Rajendran, H.H. Ngo, A. Pugazhendhi, Economic Perspectives and Policy Insights on Carbon Capture, Storage, and Utilization for Sustainable Development, Science of The Total Environment, 2023 163656.
[147] A.I. Okoji, A.N. Anozie, J.A. Omoleye, A.E. Taiwo, F.N. Osuolale, Energetic assessment of a precalcining rotary kiln in a cement plant using process simulator and neural networks, Alex. Eng. J. 61 (7) (2022) 5097–5109.
[148] A.M. Ali, J.D. Tabares, M.W. McGinley, A machine learning approach for clinker quality prediction and nonlinear model predictive control design for a rotary cement kiln, J. Adv. Manuf. Process. 4 (4) (2022) e10137.
[149] M.Z. Sogut, T.H. Karakoc, Investigation of energy efficiency strategies in production processes based on operational management, Int. J. Glob. Warming 29 (1–2) (2023) 139–158.
[150] V. Ramasamy, R. Kannan, G. Muralidharan, R.K. Sidharthan, G. Veerasamy, S. Venkatesh, R. Amirtharajan, A comprehensive review on Advanced Process Control of cement kiln process with the focus on MPC tuning strategies, J. Process Control 121 (2023) 85–102.
[151] A.A. Usón, A.M. López-Sabirón, G. Ferreira, E.L. Sastresa, Uses of alternative fuels and raw materials in the cement industry as sustainable waste management options, Renew. Sustain. Energy Rev. 23 (2013) 242–260.
[152] F.B. Juangsa, A.S. Cezeliano, P.S. Darmanto, M. Aziz, Thermodynamic analysis of hydrogen utilization as alternative fuel in cement production, S. Afr. J. Chem. Eng. 42 (2022) 23–31.
[153] R.T. Kusuma, R.B. Hiremath, P. Rajesh, B. Kumar, S. Renukappa, Sustainable transition towards biomass-based cement industry: a review, Renew. Sustain. Energy Rev. 163 (2022) 112503.
[154] C. Tan, X. Yu, Y. Guan, A technology-driven pathway to net-zero carbon emissions for China's cement industry, Appl. Energy 325 (2022) 119804.
[155] A.C. Kahawalage, M.C. Melaeen, L.A. Tokheim, Opportunities and challenges of using SRF as an alternative fuel in the cement industry, Cleaner Waste Systems (2022) 100072.
[156] S. Fellaou, T. Bounahmidi, Evaluation of energy efficiency opportunities of a typical Moroccan cement plant: Part I. Energy analysis, Appl. Therm. Eng. 115 (2017) 1161–1172.
[157] J.D. Bapat, Application of ESP for gas cleaning in cement industry—with reference to India, J. Hazard Mater. 81 (3) (2001) 285–308.
[158] A.M. Radwan, Different possible ways for saving energy in the cement production, Adv. Appl. Sci. Res. 3 (2) (2012) 1162–1174.
[159] C. Ciobanu, I.A. Istrate, P. Tudor, G. Voicu, Dust emission monitoring in cement plant mills: a case study in Romania, Int. J. Environ. Res. Publ. Health 18 (17) (2021) 9096.
[160] W. Zhang, A. Maleki, M.G. Khajeh, Y. Zhang, S.M. Mortazavi, A. Vasel-Be-Hagh, A novel framework for integrated energy optimization of a cement plant: an industrial case study, Sustain. Energy Technol. Assessments 35 (2019) 245–256.
[161] E. Gartner, K. Quillin, Low-CO2 cements based on calcium sulfoaluminates, Sustainability in the Cement and Concrete Industry, Norwegian Cement Association 16 (2007) 95–105 September.
[162] M.C.G. Juenger, F. Winnefeld, J.L. Provis, J.H. Ideker, Advances in alternative cementitious binders, Cement Concr. Res. 41 (12) (2011) 1232–1243.
[163] Y. Tao, A.V. Rahul, M.K. Mohan, G. De Schutter, K. Van Tittelboom, Recent progress and technical challenges in using calcium sulfoaluminate (CSA) cement, Cement Concr. Compos. (2022) 104908.
[164] S.A. Ishak, H. Hashim, Low carbon measures for cement plant–a review, J. Clean. Prod. 103 (2015) 260–274.
[165] L. Mo, F. Zhang, D.K. Panesar, M. Deng, Development of low-carbon cementitious materials via carbonating Portland cement–fly ash–magnesia blends under various curing scenarios: a comparative study, J. Clean. Prod. 163 (2017) 252–261.
[166] C. Shi, B. Qu, J.L. Provis, Recent progress in low-carbon binders, Cement Concr. Res. 122 (2019) 227–250.
[167] T. Jiang, K. Cui, J. Chang, Development of low-carbon cement: carbonation of compounded C2S by β-C2S and γ-C2S, Cement Concr. Compos. 139 (2023) 105071.
[168] A.T. Marsh, A.P. Velenturf, S.A. Bernal, Circular Economy strategies for concrete: implementation and integration, J. Clean. Prod. (2022) 132486.
[169] R. Martínez-García, P. Jagadesh, F.J. Fraile-Fernández, J.M. Morán-del Pozo, A. Juan-Valdés, Influence of design parameters on fresh properties of self-compacting concrete with recycled aggregate—a review, Materials 13 (24) (2020) 5749.
[170] M.L. Tseng, R.R. Tan, A.S. Chiu, C.F. Chien, T.C. Kuo, Circular economy meets industry 4.0: can big data drive industrial symbiosis? Resour. Conserv. Recycl. 131 (2018) 146–147.
[171] T. Joensuu, H. Edelman, A. Saari, Circular economy practices in the built environment, J. Clean. Prod. 276 (2020) 124215.
[172] Y. Yu, D.M. Yazan, S. Bhochhibhoya, L. Volker, Towards Circular Economy through Industrial Symbiosis in the Dutch construction industry: a case of recycled concrete aggregates, J. Clean. Prod. 293 (2021) 126083.
[173] D.K. Mishra, J. Yu, Circular economy in construction: an overview with examples from materials research, Circular Economy in the Construction Industry (2021) 11–21.
[174] Q. Chen, H. Feng, B.G. de Soto, Revamping construction supply chain processes with circular economy strategies: a systematic literature review, J. Clean. Prod. 335 (2022) 130240.
[175] R. Minunno, T. O'Grady, G.M. Morrison, R.L. Gruner, Exploring environmental benefits of reuse and recycle practices: a circular economy case study of a modular building, Resour. Conserv. Recycl. 160 (2020) 104855.
[176] I.Y. Wuni, G.Q. Shen, Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong, Sustain. Prod. Consum. 29 (2022) 574–587.
[177] I.H. Shah, S.A. Miller, D. Jiang, et al., Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons, Nat. Commun. 13 (2022) 5758.
[178] S. Pamenter, R.J. Myers, Decarbonizing the cementitious materials cycle: a whole-systems review of measures to decarbonize the cement supply chain in the UK and European contexts, J. Ind. Ecol. 25 (2021) 359–376.
[179] J.S.J. van Deventer, C.E. White, R.J. Myers, A roadmap for production of cement and concrete with low-CO2 emissions, Waste and Biomass Valorization 12 (2021) 4745–4775.
[180] M.H. Shehata, G. Adhikari, S. Radomski, Long-term durability of blended cement against sulfate attack, ACI Mater. J. 105 (6) (2008) 594.
[181] M.M. Johari, J.J. Brooks, S. Kabir, P. Rivard, Influence of supplementary cementitious materials on engineering properties of high strength concrete, Construct. Build. Mater. 25 (5) (2011) 2639–2648.
[182] A. Borosnyói, Long term durability performance and mechanical properties of high performance concretes with combined use of supplementary cementing materials, Construct. Build. Mater. 112 (2016) 307–324.
[183] I.Y. Hakeem, F. Althoey, A. Hosen, Mechanical and durability performance of ultra-high-performance concrete incorporating SCMs, Construct. Build. Mater. 359 (2022) 129430.
[184] M. Thomas, Supplementary Cementing Materials in Concrete, CRC press, 2013.
[185] W. Gao, S. Liang, R. Wang, Q. Jiang, Y. Zhang, Q. Zheng, B. Xie, C.Y. Toe, X. Zhu, J. Wang, L. Huang, Industrial carbon dioxide capture and utilization: state of the art and future challenges, Chem. Soc. Rev. 49 (23) (2020) 8584–8686.
[186] S.Y.W. Chai, L.H. Ngu, B.S. How, M.Y. Chin, K. Abdouka, M.J.B.A. Adini, A.M. Kassim, Review of CO2 capture in construction-related industry and their utilization, Int. J. Greenh. Gas Control 119 (2022) 103727.

[187] T. Strunge, P. Renforth, M. Van der Spek, Towards a business case for CO2 mineralisation in the cement industry, Communications earth & environment 3 (1) (2022) 59.
[188] D. Ravikumar, D. Zhang, G. Keoleian, S. Miller, V. Sick, V. Li, Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit, Nat. Commun. 12 (1) (2021) 855.
[189] M. Zajac, J. Skocek, J. Skibsted, M.B. Haha, CO2 mineralization of demolished concrete wastes into a supplementary cementitious material–a new CCU approach for the cement industry, RILEM Technical Letters 6 (2021) 53–60.
[190] I. Ghiat, T. Al-Ansari, A review of carbon capture and utilisation as a CO2 abatement opportunity within the EWF nexus, J. CO2 Util. 45 (2021) 101432.
[191] A.A. Shubbar, H. Jafer, A. Dulaimi, K. Hashim, W. Atherton, M. Sadique, The development of a low carbon binder produced from the ternary blending of cement, ground granulated blast furnace slag and high calcium fly ash: An experimental and statistical approach, Construct. Build. Mater. 187 (2018) 1051–1060.
[192] F. Jalaei, R. Masoudi, G. Guest, A framework for specifying low-carbon construction materials in government procurement: A case study for concrete in a new building investment, J. Clean. Produ. 345 (2022) 131056.
[193] Y. Kim, A. Hanif, M. Usman, M.J. Munir, S.M.S. Kazmi, S. Kim, Slag waste incorporation in high early strength concrete as cement replacement: Environmental impact and influence on hydration & durability attributes, J. Clean. Prod. 172 (2018) 3056–3065.
[194] K.A. Knight, P.R. Cunningham, S.A. Miller, Optimizing supplementary cementitious material replacement to minimize the environmental impacts of concrete, Cement Concr. Compos. 139 (2023) 105049.
[195] S.C. Bostanci, M. Limbachiya, H. Kew, Use of recycled aggregates for low carbon and cost effective concrete construction, J. Clean. Prod. 189 (2018) 176–196.
[196] C.S Karadumpa, R.K. Pancharathi, Developing a novel mix design methodology for slow hardening composite cement concretes through packing density approach, Construct. Build. Mater. 303 (2021) 124391.
[197] C.H. Lee, J.C. Du, D.H. Shen, Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt, Construct. Build. Mater. 28 (1) (2012) 66–71.
[198] Y.A. Villagrán-Zaccardi, A.T.M. Marsh, M.E. Sosa, C.J. Zega, N. De Belie, S.A. Bernal, Complete re-utilization of waste concretes–Valorisation pathways and research needs, Resour. Conserv. Recycl. 177 (2022) 105955.
[199] F. Xie, J. Li, G. Zhao, P. Zhou, H. Zheng, Experimental study on performance of cast-in-situ recycled aggregate concrete under different sulfate attack exposures, Construct. Build. Mater. 253 (2020) 119144.
[200] J.K. Boyce, Carbon pricing: effectiveness and equity, Ecol.Econ. 150 (2018) 52–61.
[201] E. Tvinnereim, M. Mehling, Carbon pricing and deep decarbonisation, Energy pol. 121 (2018) 185–189.
[202] D. Klenert, L. Mattauch, E. Combet, O. Edenhofer, C. Hepburn, R. Rafaty, N. Stern, Making carbon pricing work for citizens, Nat. Clim. Change 8 (8) (2018) 669–677.
[203] D. Bodansky, The legal character of the Paris Agreement, Rev. Eur. Community Int. Environ. Law 25 (2) (2016) 142–150.
[204] R. Falkner, The Paris Agreement and the new logic of international climate politics, Int. Aff. 92 (5) (2016) 1107–1125.
[205] C.F. Schleussner, G. Ganti, J. Rogelj, M.J. Gidden, An emission pathway classification reflecting the Paris Agreement climate objectives, Commun. Earth Environ. 3 (1) (2022) 135.
[206] M. Simoni, M.D. Wilkes, S. Brown, J.L. Provis, H. Kinoshita, T. Hanein, Decarbonising the lime industry: state-of-the-art, Renew. Sustain. Energy Rev. 168 (2022) 112765.
[207] A. Rahman, M.G. Rasul, M.M.K. Khan, S. Sharma, Recent development on the uses of alternative fuels in cement manufacturing process, Fuel 145 (2015) 84–99.
[208] P.S. Fennell, S.J. Davis, A. Mohammed, Decarbonizing cement production, Joule 5 (6) (2021) 1305–1311.
[209] A. Sevil, G. Muñoz, A. Godoy-Faúndez, Aligning global efforts for a carbon neutral world: the Race to zero campaign, J. Appl. Behav. Sci. 58 (4) (2022) 779–783.
[210] T. Hale, S.M. Smith, R. Black, K. Cullen, B. Fay, J. Lang, S. Mahmood, Assessing the rapidly-emerging landscape of net zero targets, Clim. Pol. 22 (1) (2022) 18–29.
[211] E. Giama, A.M. Papadopoulos, Sustainable building management: overview of certification schemes and standards, Adv. Build. Energy Res. 6 (2) (2012) 242–258.
[212] D.T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey, A critical comparison of green building rating systems, Build. Environ. 123 (2017) 243–260.