Implementing carbon capture technologies and strategies in the cement industry: A complete review

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Implementing carbon capture technologies and strategies in the cement industry: A complete review

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Abstract

The cement industry is one of the main industrial sources of CO_2 emissions globally, it accounted for approximately between 7-8% of total fossil fuel-related CO_2 emissions. There are two carbon-intensive processes in the cement manufacturing: First is Clinker production, the decomposition of limestone into lime. This process is called calcination and is termed process emission, this represents 60%, and the second is Fuel combustion process, the burning of fossil fuel to obtain high temperatures of approximately 1450 °C required in the kiln. This accounted for 40% of total CO2 emissions from cement production, it is termed combustion emission. Decarbonization of cement industry is a necessity because of the global net-zero emissions target of 2050. This review comprehensively examines current and emerging Carbon Capture, Utilization, and Storage (CCUS) technologies in this sector. Post-combustion capture is retrofittable, while calcium looping and oxy-fuel combustion indicated high capture efficiency and compatibility with cement chemistry. The LEILAC is the breakthrough process, producing pure CO_2 without flue-gas contamination. Though, high energy penalties, process complexity, integration challenges linger, and cost of retrofitting. Utilization methods such as mineral carbonation, CO_2 curing in concrete, and enhanced oil recovery offer roadmaps to long-term or value-added CO_2 usage. For permanent sequestration, storage in geological depleted oil fields and saline aquifers is key. Highlighted in this review is the need for all-inclusive integration, economic policy, and digital innovations with AI-driven monitoring and the use of alternative fuels like biomass. Urgent scale-up of CCUS technologies is essential to achieving the 2030-2050 climate targets. infrastructure Investment, Cross-sector collaboration, and supportive regulations are vital for transitioning to a low-carbon and climate-resilient cement industry.

Keywords: Absorbent; Ccementitious materials; CO_2 emissions; Calcium looping; Oxy-fuel combustion; CCS; CCUS; Clinker production

1. Introduction

Globally, the cement industry is one the largest sources of CO_2 emission. Though cement manufacturing's percentage of CO_2 emissions globally is lower in comparison to sectors like power generation and transportation, cement's CO_2

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emission impact is substantial due to the important role of cement in construction and infrastructural development. reducing CO_2 emissions from cement production is critical for achieving Net zero climate goals globally. According to the 2023 global carbon dioxide (CO_2) emissions records by sector, cement production emitted approximately 1.34x10^9 MT (that is; billion metric tons)**,** representing about 4% out of the 9% of total of CO_2 emissions from fossil fuel in industrial processes which includes the cement production, see table 1 below, (Carbon Majors & Global Fossil Fuel and Cement Emissions, 2025).

In global ranking of CO_2 emissions by sector, (Statista, 2025) the cement industry occupied the 5th position, while the power generation stood at 1st position, with transport, industry excluding cement, and fuel production occupied the 2nd, 3rd and 4th positions respectively.

Cement manufacturing is actually highly carbon-intensive process because of two major chemical processes involved, the first is the clinker production chemical process, which is the decomposition of limestone (calcium carbonate, $CaCO_3$) into lime (Calcium Oxide, CaO) and the released CO_2 by addition of heat. This process is call calcination and it is termed process emission**,** this represent 60%**,** chemical reaction is thus: ($CaCO_3 \rightarrow CaO + CO_2$) and the second process is the Fuel combustion process, that is the burning of fossil fuel to obtain high temperatures of approximately ~1450^{o}C required in the kiln section, this accounted for 40% of the total CO_2 emissions from cement production (Open Climate Data, 2023).

Now, there is an urgency for decarbonizing this industry to achieve the Net Zero emission goals. A means to climb down effects of global warming arising from greenhouse gas in the atmosphere. Therefore, the roles of carbon capture, utilization and storage (CCUS) technologies are needed for effective reduction, since these technologies are the only means that permits the continuous use of fossil fuel sources while reducing the CO_2 emitted from them.

The objective of this review work is to comprehensively analyze the implementation of carbon capture, utilization and storage technologies and strategies in cement production, reducing the CO2 emission in this manufacturing sector. Nevertheless, efforts to reduce these emissions include adopting **alternative fuels** (the use of palm kernel shell, rich husk etc.) which are used partly in some Dangote Cement plants across Nigeria. Recall, out of the two major sources of CO_2 emission in the cement production, the alternate fuel is solving the combustion process emission, improving energy efficiency, and utilizing supplementary cementitious materials this is targeted to solve calcination process emissions.

Table 1 Per-capita CO2 emissions By Sector

SN	Sector	Emissions ($GtCO_2e$)	Share of Total Emissions
1	Power Generation	14.9	26%
2	Transport	8.4	15%
3	Industry (excluding cement)	6.5	11%
4	Fuel Production	6.0	10%
5	Industrial Processes (including cement)	5.0	9%
6	Agriculture	6.5	11%
7	Land Use, Land-Use Change, and Forestry	4.0	7%
8	Buildings	3.0	6%
9	Waste and Other	2.0	4%
	Total	**57.1**	**100%**

Source (IEA, Per Capita CO2 Emission By Sector, 2022)

2. Overview of Cement Manufacturing Process

In this section two, we will look at the overview of the cement manufacturing process, involving the raw materials, key process stages, most importantly map out CO_2 emissions sources at each stage (Mattheus Meijssen, 2024).

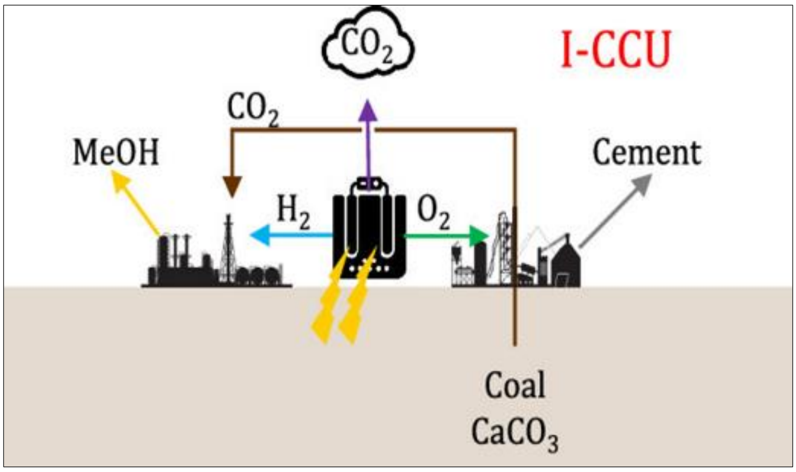

Figure 1 Integrated Carbon Capture and Utilization

2.1. Cement Manufacturing Process

2.1.1. Raw Materials

Cement raw materials include: Limestone, Clay, Iron Ore

- **Limestone ($CaCO_3$):** This is the primary cement production component, representing about **60–70%** of the raw mix. Rich in calcium carbonate, which is crucial for forming clinker minerals like the belite (C_2S) and alite (C_3S)
- **Clay:** This component provides silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). It also balances the chemical composition and contributes to the formation of tricalcium aluminate (C_3A) and tetra-calcium aluminoferrite (C_4AF).
- **Iron Ore (Fe_2O_3):** This component is added to adjust the Fe content in the mix. It enables the fluxing characteristics of the raw mix, helping to reduce the energy needed during clinker production.

2.1.2. Critical Steps in the Cement Manufacturing Process

Raw Material Preparation

This include the Crushing and grinding of limestone and other component into a fine powder called raw meal. Raw materials are chemically mixed to obtain the required composition. Equipment responsible for this process include: crushers, ball mills, vertical roller mills.

Preheating and Calcination

Here, the raw meal is heated in a preheater tower using hot gases from the kiln. calcination this takes place at temperatures of over~850–1000 °C

Chemical reaction of Limestone decomposes:

$$CaCO_3 \rightarrow CaO + CO_2$$

The above calcination process (chemical reaction) releases huge amount of CO_2 as a result, see figure 2 below (Thomas Hills, 2016).

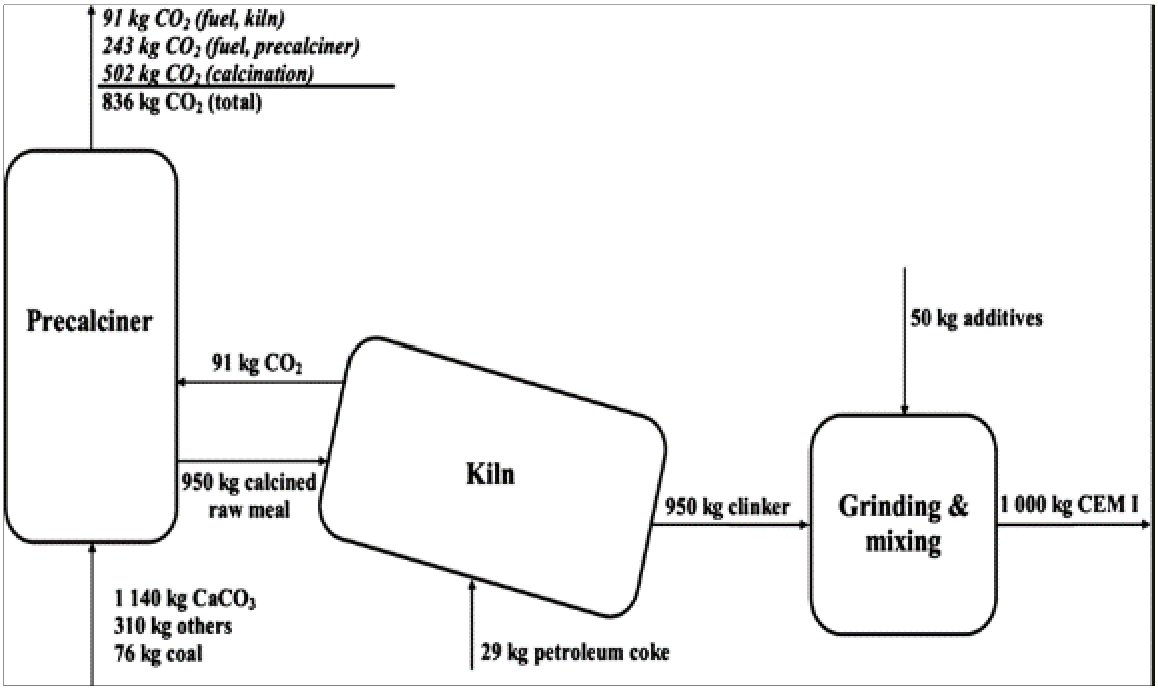

Figure 2 Carbon Capture in the Cement Industry Technologies, Progress and retrofitting

Clinker Production in Rotary Kiln

The heating up to **~1450 °C** in a rotary kiln, caused the major chemical reactions that form clinker nodules like the: Calcium silicates: belite (C_2S), alite (C_3S), aluminate (C_3A), and ferrite (C_4AF). This uses **high thermal energy**, often from **coal, petcoke, or alternative fuels (**palm kernel shell, rice husk etc.), (Andrew, 2019) and (Gartner, 2018).

Grinding and Cement Formation

This clinker is cooled and mixed with additives like the gypsum ($CaSO_4 \cdot 2H_2O$) which primarily is for controlling the cement setting time. Thereafter it is grinded into fine powder in a cement mill. This may include supplementary cementitious materials like fly ash or slag (geopolymers obtained from alumina silica called flay ash). It is an alkali activated material with low CO_2 emission. (Karen L. Scrivener, 2018)

2.2. Sources of CO_2 Emissions Recorded to Each Stage

Table 2 Sources of CO_2 Emissions Recorded to Each Stage

Stage	**Emission Source**	**CO_2 Emissions Contribution**
Raw Material Preparation	Electricity required for crushers and mills	Inconsequential (<5%)
Calcination process (Preheater/Kiln)	Chemical disintegration of limestone into ($CaCO_3 \rightarrow CaO + CO_2$)	~50–60%
Clinker formation	Burning of fossil fuels for heating the kiln (~1450°C)	~30–35%
Grinding and Cement Milling	Electricity for mills and air compressors	~5–10%
Transport and Packing	Indirect emissions from logistics and auxiliary power	Negligible

Key Note: from the table above (Ellis Gartner, 2018), we realized that more than 90% of CO_2 emissions from cement manufacturing come from calcination and fuel combustion processes during clinker production (Habert, 2020).

3. Carbon capture technologies in cement industry

In this section we will look as the potent technologies for CCUS in cement industry, we will consider their mechanisms, maturity levels, benefits and limitations (IEA, Technology Roadmap – Low-Carbon Transition in the Cement Industry, 2020).

3.1. Post-Combustion CO_2 Capture in the Cement industry

3.1.1. Description

This Post-combustion CO_2 capture technology involves the **separation of CO_2 from flue gases** (gaseous by-products of combustion, CO_2 N_2, H_2O vapor, O_2, CO, NO_x, SO_2, and particulate matter) *from* fuel combustion in the cement kiln.

- The flue gas from clinker production in cement plants contains approximately 14–33% CO_2, making it an achievable target for capture.
- Giving it a retrofittable viable option, meaning the existing cement plants can adapt to the technology without completely changing their equipment or infrastructure.

3.1.2. Technologies for post-combustion co_2 capture

Amine-based chemical absorption

- **These include:** Diethanolamine (DEA), Methyldiethanolamine (MDEA), Monoethanolamine (MEA) see figure 3 below (Voldsund M. G.-C.-F., 2019),

Working principle

- The exhaust gas (Flue gas) passes through an absorber tower where **amines chemically bind to CO_2.**
- Then the CO_2-rich amine is forwarded or sent to a **regenerator (stripper)**, there heat is used to release pure CO_2.
- Regenerated amine is then recycled back to the absorber.

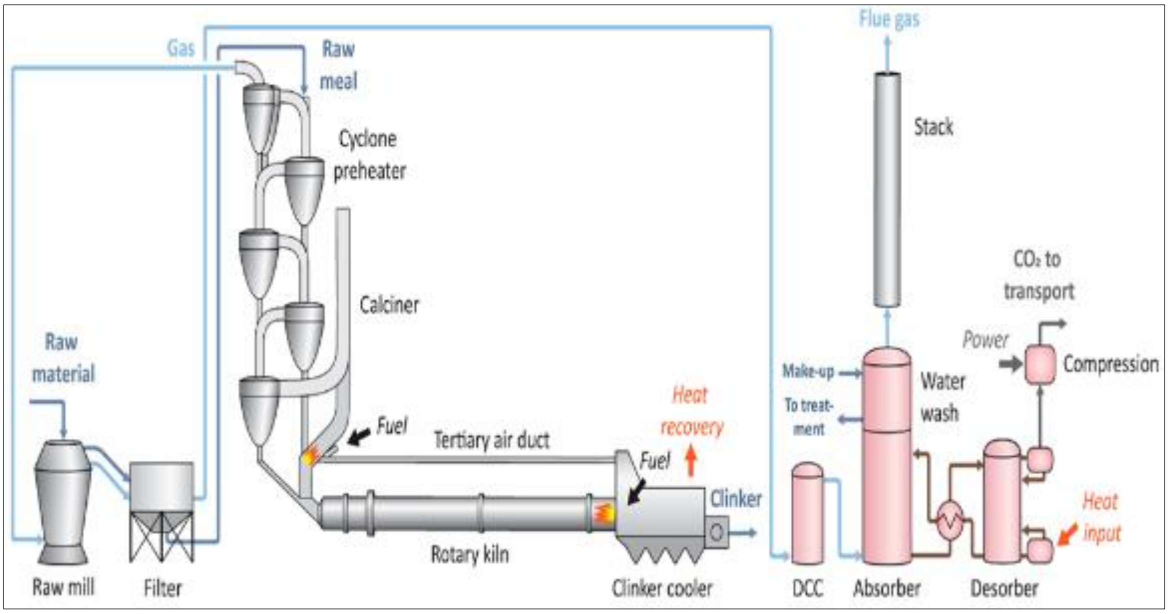

Figure 3 Post Combustion: Clinker burning line with MEA Absorption

Advantages

- This technology is mature and proven: Often used in power generation, natural gas, and ammonia industries.
- It is highly selected for CO_2 capture.
- It has the capacity to capture up to 90% of CO_2 from a particular facility

Challenges

- It is energy-intensive: this is especially for regeneration (reboiler duty with capture rate of 3.5–4 GJ/ton CO_2).
- The Amine corrosiveness and degradation nature
- It also requires a large cooling system due to the heating solvent.

Practical applicable example

The Norcem (Heidelberg Materials) in Norway is on record as the first ever pilot full-scale MEA capture as part of its Carbon Capture and Storage project.

3.1.3. Solid absorbents

- This include: Activated Carbon, Metal-Organic Frameworks (MOFs) and Zeolites,

Working principle

- The CO_2 is captured by means of adsorption on the surface or pores of solid materials.
- The Regeneration is achieved by means of Temperature Swing Adsorption (TSA) or Pressure Swing Adsorption (PSA).

Advantages

- Lower energy consumption than amines in some designs.
- Regeneration often does not require boiling solvents.
- Less corrosion, non-toxic, and reusable materials.

Challenges

- It is moisture sensitive (especially zeolites).
- It has lower CO_2 capture capability compared to chemical absorption.
- The scalability challenges for full cement plant emissions.

3.1.4. The membrane separation

Working principle

- The Flue gas passes through dedicated gas-selective membranes which allow CO_2 to pass through faster than other flue gases, N_2 or O_2.
- Using of partial pressure gradients to separate gases.

Advantages

- It has a compact, modular, and scalable design.
- No chemical solvents required and it requires lower maintenance.

Challenges

- The performance of the membrane declines at low CO_2 concentrations.
- The Purity and recovery trade-offs.
- Increasing operational cost may result for high pressure may be needed.

Ongoing Research

- There is ongoing research that explores project with hybrid systems: membrane + absorption or membrane + cryogenics.

3.1.5. Cryogenic separation

Working principle

- The carbon iv oxide (CO_2) is separated by cooling the flue gases to very low temperatures of about 78.5°C, where the CO_2 condenses or de-sublimates into liquid or solid form.

Advantages

- This method produces high-purified CO_2 suitable for storage or industrial use.
- No chemicals are involved.

Challenges

- Though it is extremely energy-intensive for cooling large volume of gas but it can be overcome with ongoing research.
- It is typically viable in high CO_2 concentration settings only.

Current area of application

- It is more commonly used in natural gas processing or in liquefied CO_2 production, but R &D is underway for cement applications.

Table 3 Comparative Summary

Technology	**Maturity**	**CO_2 Capture Efficiency**	**Energy Demand**	**Pros**	**Cons**
Amine Absorption	Commercial	High (85–90%)	High	Proven, high efficiency	Costly regeneration, corrosive
Solid Sorbents	Emerging	Moderate	Moderate	Non-toxic, reusable	Moisture sensitivity, less mature
Membranes	Pilot-stage	Moderate	Low–Moderate	Compact, no solvents	Limited at low CO_2, purity tradeoffs
Cryogenic	Lab/pilot	High	Very High	High purity CO_2	Expensive, energy intensive

3.2. Oxy-fuel combustion in the cement industry

3.2.1. Fuel Burned in Pure Oxygen Instead of Air

Description

- The traditional combustion process involves air which contains ~78% nitrogen and ~21% oxygen is used to combust fuel in rotary cement kilns. (Zhi, 2023)
- For oxy-fuel combustion technology, the air is substituted with almost pure oxygen which represent more than 95% O_2 to avoid nitrogen dilution in the combustion process.

Process in cement kilns:

This is aimed to reduces the **nitrogen content** in flue gases, enabling for easier CO_2 concentrations and capture.

It might require **recirculation of concentration of high CO_2 flue gas** to maintain flame temperatures and clinker quality see figure 4 below.

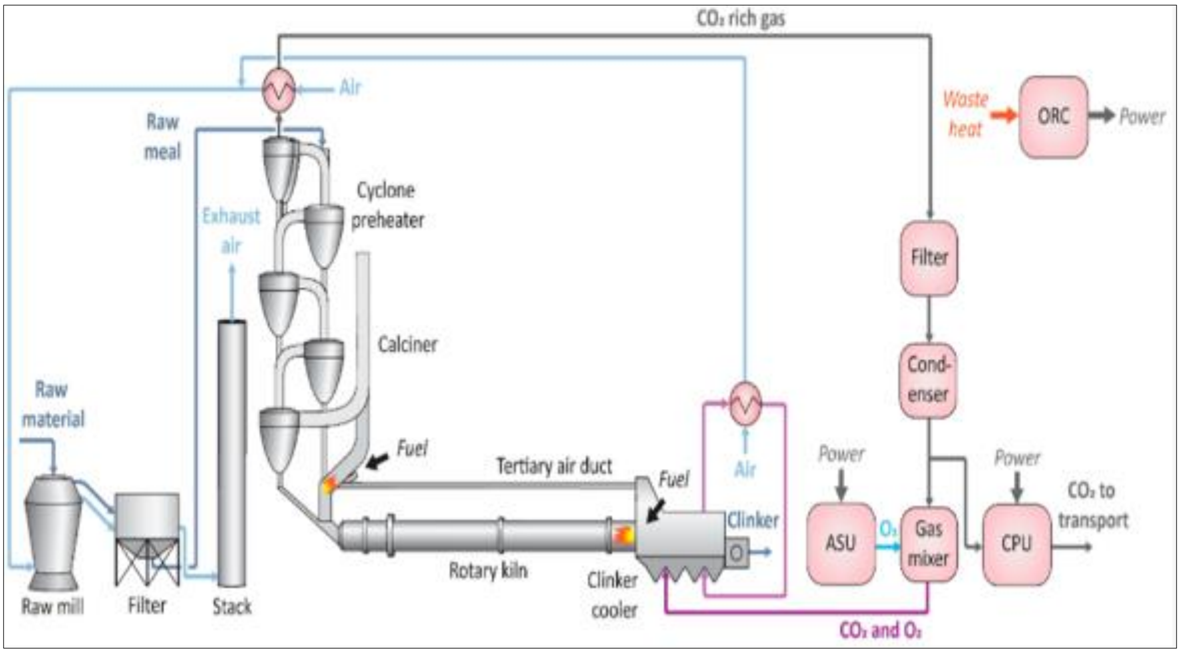

Figure 4 Reference clinker burning line with Oxyfuel CO2 capture

3.2.2. Produces Flue Gas with High CO_2 Concentration (~80%)

Description

By removing nitrogen from combustion air, the forming flue gas mainly consists of: CO_2 (~70–90%), Water vapor (H_2O). This pure CO_2 makes carbon capture and purification easier and more energy-efficient than in conventional systems (Kumar, 2025).

Advantages

- Reduced volume of flue gases.
- This simplifies CO_2 separation for compression, storage, or utilization (CCS/CCUS).
- Flue gas is suitable for pipeline transport or direct use in industries (e.g., enhanced oil recovery).

3.2.3. Easier CO_2 Separation, Lower Volume of Flue Gas:

Benefits

- Simplified carbon capture: No need for chemical solvents (like amines) to separate CO_2 from nitrogen.
- Lower energy consumption in the downstream CO_2 separation and purification process.
- Smaller exhaust gas treatment systems due to reduced flue gas volume (~75% less than conventional systems).
- Facilitates CO_2 purity levels above 95%, which is suitable for geological storage or utilization.

3.2.4. Challenges of Oxy-Fuel Combustion

- It is capital and energy intensive to produce pure oxygen (via air separation units – ASUs).
- It actually will require cryogenic distillation, pressure swing adsorption (PSA), or membrane separation. Oxygen production accounts for 10–15% of plant energy use in oxy-fuel retrofits.

Retrofitting Existing Kilns

Existing cement kilns are designed for air combustion and may not handle the thermal and flow dynamics of oxy-fuel combustion. Retrofitting involves:

- Redesigning burners and combustion chambers
- Adding flue gas recirculation (FGR) systems to control flame temperature

- Integrating air separation and CO_2 compression systems

Implementation Challenges

- Capital-intensive upgrades
- Process complexity
- Operational risks in clinker quality and kiln stability during transition (Carrasco-Maldonado, 2016).

Current Pilots Schemes and Development Efforts

- European Cement Research Academy (ECRA) The following Cement Manufacturer like: Lafarge Holcim, and Heidelberg Materials are exploring oxy-fuel kiln pilot projects.
- Research on integrated oxy-fuel + Carbon Capture and Storage systems is underway; the targeted timeline is by 2030-2040 for cost reduction and commercialization actualization.

3.3. Pre-Combustion Capture

3.3.1. Gasify the fuel to get Syngas (CO + H_2)

In pre-combustion capture, the process commence before fuel combustion. Fossil fuels (coal, petcoke, or natural gas) are gasified in the presence of oxygen and steam to produce syngas:

Chemical reaction $C + H_2O + O_2 \rightarrow CO + H_2$

A mix of carbon monoxide (CO) and hydrogen (H_2) is called syngas. It is a clean-burning fuel that can be further treated to isolate CO_2.

- CO_2 capturing process

The water-gas shift reaction is used to convert CO to CO_2:

$CO + H_2O \rightarrow CO_2 + H_2$. The CO_2 is then separated and captured, while H_2 is combusted as the energy source for the process. Summarily, the CO Converted to CO_2 and Captured Before Combustion

Advantage

Because, CO_2 is separated at high pressure and high concentration, capture is: More energy-efficient and Less chemically complex than post-combustion separation from flue gases

- High CO_2 capture efficiency (>90%)
- H_2-rich gas used for combustion is clean and does not produce further CO_2.
- The process is well-suited for integrated gasification combined cycle (IGCC) power plants.

Limitation in cement plant (process due to incompatibility)

- The thermal requirements and direct contact between fuel and raw materials make it difficult to integrate syngas combustion.
- Cement kilns depend on solid fuels and do operate under open-loop high-temperature process for calcination and clinkering.

Why Pre-combustion will not fit for retrofitting

- Syngas combustion does not produce the same thermal profile required for proper clinker formation.
- Gasification units are capital intensive and complex to integrate with cement kilns.
- High retrofit cost and limited scalability for existing plants.

3.4. Calcium Looping (CaL)

3.4.1. Cyclic Carbonation/Calcination Using CaO from Limestone

Description

A cyclic process called Calcium Looping is based on the reversible reaction of calcium oxide (CaO) and carbon dioxide (CO_2):

Carbonation (CO_2 capture):

$$CaO\ (s) + CO_2\ (g) \rightarrow CaCO_3\ (s)\ \text{at 600–700°C)}$$

Calcination (regeneration):

$$CaCO_3\ (s) \rightarrow CaO\ (s) + CO_2\ (g)\text{(at 900°C)}$$

Here the CaO to act as a sorbent for CO_2 over multiple cycles.

CaO captures CO_2 from flue gases to form calcium carbonate ($CaCO_3$).

While the $CaCO_3$ then is heated in a calciner to regenerate CaO, removing a pure stream of CO_2 ready for storage or utilization. This is actually a decomposition reaction of CaCO3, where CO2 react with CaO to form CaCO3 (Zhou, 2019)

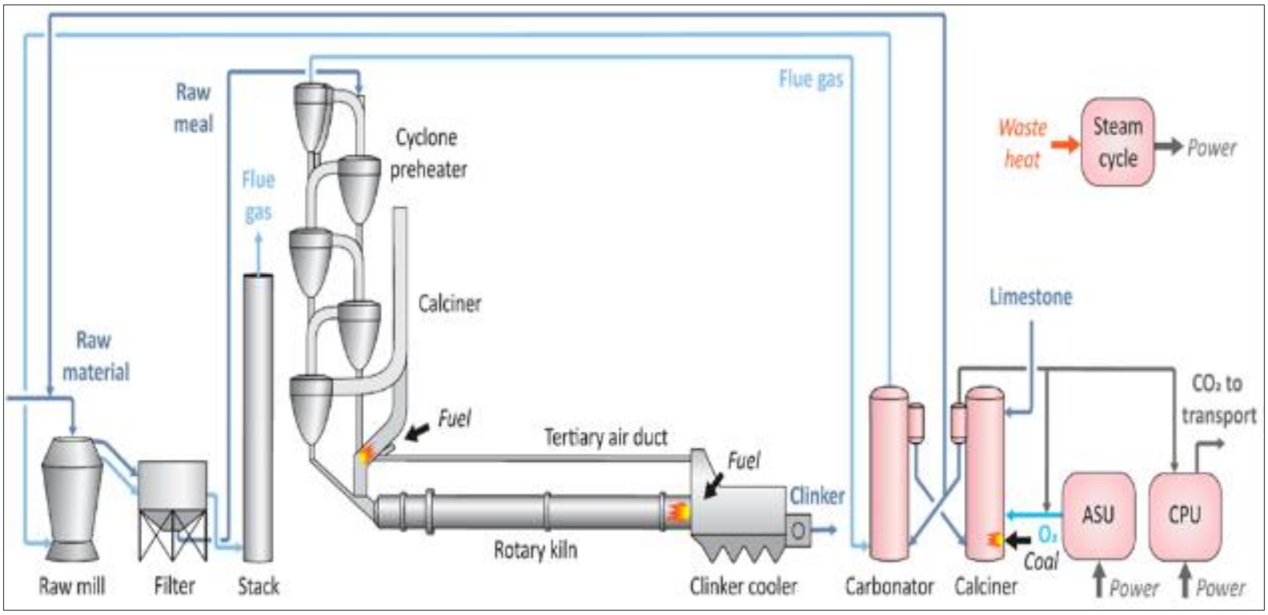

Figure 5 Calcium looping CO2 capture: Integrated configuration (Voldsund M. G.-C.-F., 2019)

Step 1: Capture

- Flue gases pass through a carbonator where CaO captures CO_2.

Step 2: Regeneration

- The resulting $CaCO_3$ is sent to a calciner, where it's heated to decompose back into CaO and release concentrated CO_2.

Advantages

- CaO can be reused for multiple cycles.
- High purity (>95%) CO_2 is captured from the gas stream.

- Avoids the use of chemical solvents like amines.

Calcium Looping is achieved using a dual fluidized bed reactor system:

- Carbonator Bed: Where CO_2 capture occurs ($CaO \rightarrow CaCO_3$)
- Calciner Bed: Where $CaCO_3$ is decomposed ($CaCO_3 \rightarrow CaO + CO_2$)
- Solids loop: Circulates sorbent material ($CaO/CaCO_3$) between the two reactors (al. B. e., 2010).

Benefits

- There is efficient heat exchange and continuous circulation of materials.
- High contact efficiency between solids and gases in the Fluidized beds.
- Waste heat or renewable sources are used to power to reduce net CO_2 emissions.

Well suited for Cement Kilns because of Ca cycle compatibility

- Clinker production in cement kilns needs CaO, the same material used in CaL
- So CaL is chemically and thermally compatible because cement process already involves calcination of limestone ($CaCO_3$) to form CaO.

Pros.

- The CO_2 captured is then routed for compression and storage.
- The regenerated CaO from CaL can be fed directly into the cement kiln, reducing the need for fresh limestone.
- Provided cost-effectiveness in CO_2 capture with minimal disruption to clinker chemistry or kiln operation, there is pilot plant called the cleanker project in Italy with full scale operating CaL (IEA., Technology Roadmap – Low-Carbon Transition in the Cement Industry, 2020).

3.5. Direct Separation (LEILAC Technology)

3.5.1. Indirect Heating of Limestone in Calciner, see figure 6.

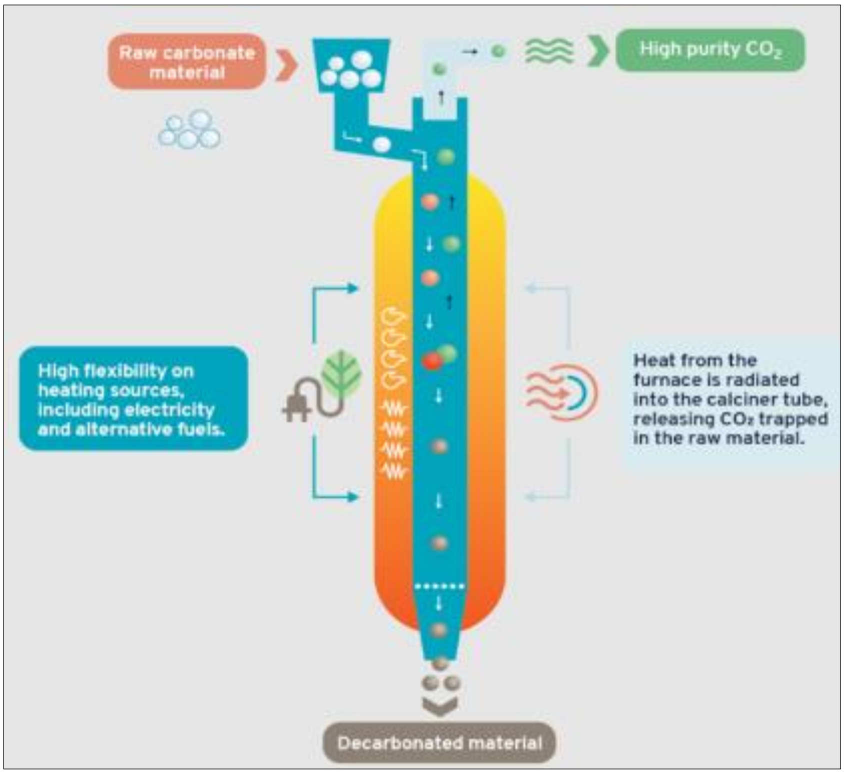

Figure 6 LEILACS-Direct-Separator-Reactor (Norster., 2024)

- Low Emissions Intensity Lime and Cement (LEILAC) uses a novel design where limestone is heated indirectly via a steel or refractory-lined reactor wall. (al. D. e., 2022)
- In conventional cement production, limestone ($CaCO_3$) is directly heated with combustion gases, the flue gas mixture is rich in CO_2, N_2, and other by-products with the CO_2 released from calcination (IEA., Technology Roadmap – Low-Carbon Transition in the Cement Industry, 2020).

Working Principle

- The heat source (from burning fuel or electricity) does not come in direct contact with the limestone.
- The calciner acts like a radiant tube: CO_2 released from calcination remains uncontaminated by combustion gases.

Chemical Reaction

$$CaCO_3\ (s) \frac{900oC}{CaO\ (s)\ +\ CO_2\ (g)}$$

Advantage

- Because CO_2 from limestone is not mixed with combustion products, it is released as a pure stream from calcination (no dilution with flue gas, almost 100% of pure CO_2).
- This method eliminates the need for complex separation technologies like amines or membranes
- Tremendously reduce energy demand for CO2 purification
- The CO2 is simply compressed, stores and utilized (CCUS)
- Enhances cement quality when the using existing feedstock chemistry (CaO remains compatible for clinker).

3.5.2. Pilot projects

LEILAC I (2016–2020)

- Funded by the European Union's Horizon 2020 program.
- Demonstration plant built at Heidelberg Materials' plant in Lixhe, Belgium.
- Successfully validated the direct separation concept at a scale of 25,000 t/year of CO_2.

LEILAC II (2020–2025):

- Projected aim to Scale up to 100,000 t/year CO_2 capture.
- This will include integration with carbon transport and storage infrastructure.
- Located mapped Germany: Heidelberg Materials plant in Hannover (LEILAC, 2020).

4. CO_2 Utilization and Storage (CCUS)

4.1. CO_2 Utilization Options

4.1.1. Concrete Curing with CO_2 (e.g., Carbon Cure, Solidia)

- **The CO_2 captured** is injected into fresh concrete during mixing or curing.
- The CO_2 reacts with **calcium compounds** (mostly calcium hydroxide) to form **calcium carbonate ($CaCO_3$)**:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

This process enhances concrete strength and durability while permanently storing CO_2 in solid form, enhances permanent CO2 sequestration and concrete performance.

Large-scale Example

- CarbonCure Technologies (Canada): Injects CO_2 into ready-mix concrete, used in commercial projects across North America.
- Solidia Technologies (USA): Uses a special low-lime cement that cures with CO_2 instead of water, very effective in reducing total CO_2 footprint by up to 70%

4.1.2. Mineral Carbonation

- CO_2 is reacted with alkaline solid materials, such as cement kiln dust, steel slag, or olivine, to form stable carbonates (e.g., $MgCO_3$, $CaCO_3$).
- This mimics natural weathering but accelerates it industrially.

Example Reaction

$$MgO + CO_2 \rightarrow MgCO_3 \text{ or} CaO + CO_2 \rightarrow CaCO$$

Applications

- Forms aggregates or filler materials used in construction
- Can be applied to cement by-products, reducing landfill waste and sequestering CO_2.

Benefits

- Potential reuse of industrial waste materials
- Could reduce demand for virgin limestone and aggregates
- Long-term, stable CO_2 storage

4.1.3. Enhanced Oil Recovery (EOR)

- Captured CO_2 is injected into depleted oil fields to increasing pressure and improve oil flow by reducing viscosity.
- Acting as a form of geological sequestration and part of the CO_2 remains trapped underground.

Application

- Long used in the **United States (Permian Basin)**.
- Some cement plants near oilfields can **sell captured CO_2** to oil companies.

Uses

- Provides a commercial pathway for captured CO_2.
- Offsets capture and transport costs.

Controversy

- Only partially stores CO_2 some is returned to surface with oil
- Viable only where oil reservoirs and pipelines exist nearby

Table 4 CO2 Utilization Summary

Utilization form	**Main Product/Use**	**CO_2 Storage Type**	**Suitability for Cement Plants**
Mineral Carbonation	Aggregates, filler	Permanent (stable carbonates)	Medium – with solid waste integration
Concrete Curing (CarbonCure)	Concrete strengthener	Permanent (mineralized)	High – easy integration into concrete
Enhanced Oil Recovery (EOR)	Oil field stimulation	Partial underground storage	Low – needs oil fields and infrastructure
Chemical Synthesis	Methanol, Urea (fertilizer)	Temporary or recycled use	Low – requires nearby chemical plants

Critics argue it prolongs fossil fuel use

4.2. CO_2 Storage Methods in the Cement Industry

CO_2 captured particularly from cement plants calcination process is most often stored using either mineral-based or geological pathways to ensure permanent sequestration. The method of storage must be in compliance with the environmental policies and safety regulations to ensure long-term climate benefits and avoid leakage. Two methods of storage discussed here are: geological storage, that is; depleted Oil and Gas Reservoirs and secondly the deep saline aquifers, the first one refers to the underground rock formations that once was filled with hydrocarbon and now empty and depleted, very good in capacity to trap or hold fluids (i.e) gases for millions of years. Also, facilities like the pipelines and oil wells can be used to inject the captured CO2. Sleipner (Norway) and Quest (Canada) (Reservoir, 2025)are real life examples in full operation. The only challenges are varying regulatory and social acceptance by regions, tendency of old well leakages, and distance from cement plants. Secondly, the deep saline aquifers are all about injecting the CO2 captured into the porous rock formations that are saturated with non-potable and salty water greater than 80m below surface. where once CO2 is injected can be trapped by structural, soluble and mineral trapping and eventually forming carbonates or another mineral, example Mg_2SiO_4 (olivine) + $CO_2 \rightarrow MgCO_3 + SiO_2$. The advantage of this method is that it is the largest storage capacity of 10,000Gt of CO2, wide spread than oil and gas reservoir, and it offers a long-term storage mechanisms. Though, it is expensive to explore, more complex to monitor and high uncertainty with geology compare to oil/gas fields. The EU CCS Directive, IPCC Guidelines, or ISO 27916 are some of the frameworks, regulations or policies put in place to ensure that stored CO_2 remains securely contained for decades to centuries, and to meet environmental and legal compliance (IPCC, 2005).

5. Process Integration and Energy Penalty

Carbon capture processes (post-, oxy-fuel, or calcium looping) are energy-intensive and require modifications to the cement process, especially at the preheater, calciner, and kiln stages. Some of the integration challenges are: thermal profile needs to be maintained in the clinker, fuel and electricity consumption increase, and space constraints in existing plants.

5.1. Energy Penalty

- CO_2 capture systems usually increase total energy demand by **30-60%**, depending on the capture method: for the **Post-combustion (amine-based);** High thermal energy for solvent required for regeneration of approximately 3-4 GJ/ton CO_2), **Oxy-fuel:** Additional energy to produce pure oxygen, **Calcium Looping:** Energy needed for dual reactors and sorbent regeneration.

5.1.1. Heat Recovery Options

To offset the additional energy penalty from carbon capture, there is need to integrate heat recovery systems. These include: Waste Heat Recovery (WHR) from: Clinker cooler vents and Preheater exhaust gases. While the recovered heat is used for: Solvent regeneration in post-combustion capture, Power generation via Organic Rankine Cycle (ORC) or steam turbines, and for drying alternative fuels or raw materials. The benefits are; improves overall efficiency of plant, can be retrofitted with minimum cost and reduce fuel consumption.

5.1.2. Combined Use with Alternative Fuels (Biomass, RDF)

Introducing low-carbon or carbon-neutral fuel like the Biomass (e.g., rice husk, palm kernel shell (PKS), wood chips) and Refuse-Derived Fuel (RDF) from municipal solid waste to replace the traditional fossil fuel like coal or petcoke. The advantages include reduction of net CO2 footprint, makes cement plant more sustainable and flexible. And the challenges include: fuel handling modification and kiln stability arising from combustion variability

5.2. Integration with CCUS

- RDF reduces landfill waste and supports circular economy goals
- Biomass is considered carbon-neutral; when paired with CO_2 capture, it can deliver negative emissions (BECCS – Bioenergy with CCS) (CEMBURAEU The European Cement Association, 2021).

5.2.1. Digital Monitoring, AI/ML for Process Optimization

This is used to optimize CO_2 capture systems in real-time using digital tools to monitor and control plant operations. Example digital twin to simulate cement kiln behavior under new CCUS configuration, and application of AI/ML algorithms for predictive maintenance of CO2 capture units, controlling kiln dynamic temperature and optimization of amine usage in oxygen supply. Advantages are system stability, energy efficiency, enabling real-time CO2 monitoring and compliance and gradual operational cost reduction (Reports, 2024).

5.2.2. Retrofit vs Greenfield Plant Considerations

Challenges of retrofitting existing kilns are

- Lack of space for heat recovery systems and capturing units
- Higher integration cost due to custom redesign
- Disruption to operations during installation

Strategies

- Modular CCUS units
- Hybrid capture solutions
- Strategic phasing of retrofit during maintenance cycles

Greenfield (New Plants)

Pros

- Capture-ready design (space, pipelines, integration)
- Optimized layout for heat and gas flow
- Can include carbon-neutral clinker substitutes and electrified kilns

Future-Ready Technologies

- LEILAC-based calciners
- Renewable energy supply (solar/biomass)
- Integration with local carbon storage/utilization infrastructure

5.3. Techno-Economic Analysis

- Cost of capture per tonne of CO_2 ($40–$120 depending on tech)
- CAPEX and OPEX considerations
- Levelized cost of cement with CCS
- Carbon credits, subsidies, and regulatory impacts

Challenges and Limitations

- High energy consumption and cost
- Material degradation and sorbent stability
- Integration with existing process lines
- CO_2 transport and storage infrastructure
- Policy uncertainty and market readiness

5.4. Policy, Regulatory, and Market Drivers

- EU ETS, U.S. Inflation Reduction Act (IRA)
- Carbon pricing and border adjustment taxes
- Green cement certification (e.g., EPDs, LCAs)
- Corporate Net Zero pledges

Future Outlook and Research Directions

- Development of low-cost sorbents and membranes
- Modular, scalable capture systems
- Hybrid systems (capture + utilization)
- Lifecycle analysis of integrated CCUS systems
- AI/ML for process control and predictive maintenance
- Collaboration across industry, academia, and policy

6. Summary of CCUS Technologies in Cement Plants

In summary, the following is a detailed breakdown points regarding Carbon Capture in Cement Plants, the best-fit strategies, the way forward and summarizing the technologies:

Table 5 Comparison of Available Technologies

Technology	CO_2 Capture Unit	Maturity	Pros	Cons
Post-combustion (Amine-based)	Flue gas (after kiln)	Commercial	Retrofit-ready, flexible	High energy for solvent regeneration
Calcium Looping (CaL)	Calcination and flue gas	Still Pilot/demo scheme	Synergy with kiln CaO cycle	Dual-reactor complexity, sorbent decay
Oxy-fuel combustion	Combustion process	Pilot/demo	High-purity CO_2, simplified separation	High O_2 production cost, kiln retrofit
Pre-combustion	Fuel gasification	Not applicable in cement	High capture rates	Not compatible with current kiln operations
Direct Separation (LEILAC)	Only Calcination step	Demo stage	Pure CO_2, modular, minimal interference	Capital intensive and Still scaling,

6.1. Most Promising Capture Methods (e.g., Oxy-fuel + CaL, Direct Separation)

To harness their effectiveness, and hybrid solutions that combine technologies adaptable with cement chemistry, these three are the most promising.

6.1.1. Oxy-fuel + Calcium Looping:

- Has High CO_2 concentration from combustion
- Enabled additional CO_2 captured via cyclic CaL reactions
- Enhanced shared infrastructure and heat management potential

6.1.2. Direct Separation (LEILAC):

- Capture pure CO_2 from calcination without flue gas mixing
- There is minimal disruption to kiln operations
- Modular design favour both retrofit and greenfield

6.2. Integration Advantage

- These technologies are material-compatible, suited for long-term decarbonization and scalable.
- Enables good combination with biomass, seamless digital control systems, and CO_2 utilization pathways.

6.2.1. Need for Holistic Integration (Techno-Economic, Policy, Social)

Technical

- Heat integration, Raw material feedstock and kiln stability are optimized
- For process monitoring and optimization we deploy Digital twins and AI tools

Economic

The following incentives are necessary:

- Subsidies and Carbon pricing
- capture-ready designs Tax incentives
- creation of Market for CO_2 utilization products

Social and Policy

- Public awareness and acceptance of CO_2 storage and pipelines infrastructure
- Skill development for CCUS workforce and local job creation,
- Clear regulatory policy on liability, monitoring, and permanence

Cement Industry Coalitions

- CEMBUREAU**,** GCCA, and Mission Innovation are some of the global initiatives that are promoting integrated decarbonization strategies

6.2.2. Urgent Scale-Up for Meeting 2030–2050 Climate Goals

The need for Urgency Matters:

- Because Cement accounts for approximately 8% of global CO_2 emissions.
- Deep decarbonization of cement is nearly impossible without CCUS, due to process emissions.

Climate Targets

- By 2030 there should be up to 10 - 20 large-scale CCUS-integrated cement plants in commercial quantity.
- By 2050 the Net-zero emissions across the global cement sector should have been met via:
    - Mass adoption of carbon capture
    - Clinker substitutes, Green hydrogen, and electrification
    - CO_2 storage and utilization in Large-scale

Required Actions

- There should be accelerated R&D and policy alignment
- Massive and proactive investment in pipeline infrastructure and storage centers
- Global collaboration for technology transfer, especially to developing economies

7. Conclusion

CO_2 capture technologies for the cement sector are diverse, each has unique advantages and challenges. They all aimed to address the two primary CO_2 sources in cement plants: **process emissions** from limestone calcination **and combustion emissions** at the kiln. Carbon capture is not just a guess effort, but a deliberate one that is **critically necessary** for decarbonizing the cement industry. LEILAC method is found to be the breakthrough process, producing pure CO_2 without flue-gas contamination. With well-organized and coordinated actions across technology, policy makers, and industry, CCUS will enable a **climate-resilient, economically viable cement sector** by 2050. Highlighted in this review is the need for all-inclusive integration, economic policy, and digital innovations with AI-driven monitoring and the use of alternative fuels like biomass. Urgent scale-up of CCUS technologies is essential to achieving the 2030-2050 climate targets. infrastructure Investment, Cross-sector collaboration, and supportive regulations are vital for transitioning to a low-carbon and climate-resilient cement industry.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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