

Good practice for Low Carbon and Environmental Friendly Cement

Contents

1. Introduction	3
2. Cement production and the life cycle impact	3
2.1 Raw materials extracted, Preparation, and Grinding (A1)	4
2.2 Clinker Production (Burning Process) (A1)	5
2.3 Cement Grinding and Mixing (A3)	5
2.4 Packaging and Transportation (A2 and A4)	5
2.5 Use Phase & End of Life (A5, B, and C)	5
3. Good Practices in Cement Industry	5
3.1 Alternative Raw Materials	5
(1) Use of supplementary cementitious materials (SCMs)	5
(2) Incorporation of construction and demolition waste	9
3.2 Fuel Substitution and Energy Efficiency	11
(1) Use of renewable energy and waste heat recovery	11
(2) Co-processing of biomass and waste-derived fuels	14
(3) Optimization through AI and advanced sensors	17
3.3 Innovative Production Techniques	20
(1) Development of low-clinker and novel cement types (e.g., LC3)	20
(2) Carbon capture, utilization, and storage (CCUS)	22
3.4 Summary of Good practices	25
4. Overcoming Challenges	26

List of Abbreviations

AI	Artificial Intelligence
BCG	Bio-Circular-Green (Economy Model)
CaCO ₃	Calcium Carbonate
CaL	Calcium Looping
CaO	Calcium Oxide
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CDW / C&D Waste	Construction and Demolition Waste
CO ₂	Carbon Dioxide
CSH	Calcium Silicate Hydrate
EPR / ERPR	Energy Performance Ratio / Emission Reduction per ton of Cement
EPFL	École Polytechnique Fédérale de Lausanne
FA	Fly Ash
GHG	Greenhouse Gas
GGBFS	Ground Granulated Blast Furnace Slag
IDMS	Intelligent Decision Management System
LCA	Life Cycle Assessment
LC3	Limestone Calcined Clay Cement
MEA	Monoethanolamine
NDC	Nationally Determined Contribution
OPC	Ordinary Portland Cement
ORC	Organic Rankine Cycle
PM10 / PM2.5	Particulate Matter ≤10 / ≤2.5 microns
RCA	Recycled Concrete Aggregate
RFECV	Recursive Feature Elimination with Cross-Validation
SCM	Supplementary Cementitious Material
SDC	Swiss Agency for Development and Cooperation
SF	Silica Fume
SFS	Sequential Forward Selection
SRC	Steam Rankine Cycle
UHPC	Ultra High Performance Concrete
VOC	Volatile Organic Compounds
w/b ratio	Water to Binder Ratio
WHR	Waste Heat Recovery

1. Introduction

Cement is a basic building material that is important for the development of national infrastructure because it is a major component of concrete, which is widely used in all types of construction. Compared to other types of building materials, cement plays a very important role in the process of urban and economic development. However, the production process of cement is one of the industries that significantly impacts the environment, especially its high energy consumption and greenhouse gas (GHG) emissions. The cement production release of carbon dioxide (CO₂) in large quantities accounting for approximately 7–8% of global GHG emissions. With cement consumption reaching 30,000 million metric tons per year and increasing in line with the growth of countries around the world, the need to improve the efficiency of the production process is of utmost importance, both in terms of energy efficiency, waste reduction and hazardous waste, and minimizing the impact on the environment as much as possible.

The good practice study for analyzing and comparing the quality of traditional cement with cement that has undergone the improvement of the production process to be more environmentally friendly, focusing on the evaluation of both material properties and the potential to reduce environmental impacts, which will lead to the development of sustainable construction industry in the future.

2. Cement production and the life cycle impact

The life cycle assessment referenced in ISO 14040, whereby Stage A is 'up-front', Stage B is 'in-use', Stage C is 'end-of-life' and Stage D is 'beyond the lifecycle'. Figure 1 describes the lifecycle of CEM I fits into Stages A-C, and the approximate proportion of carbon associated with each.

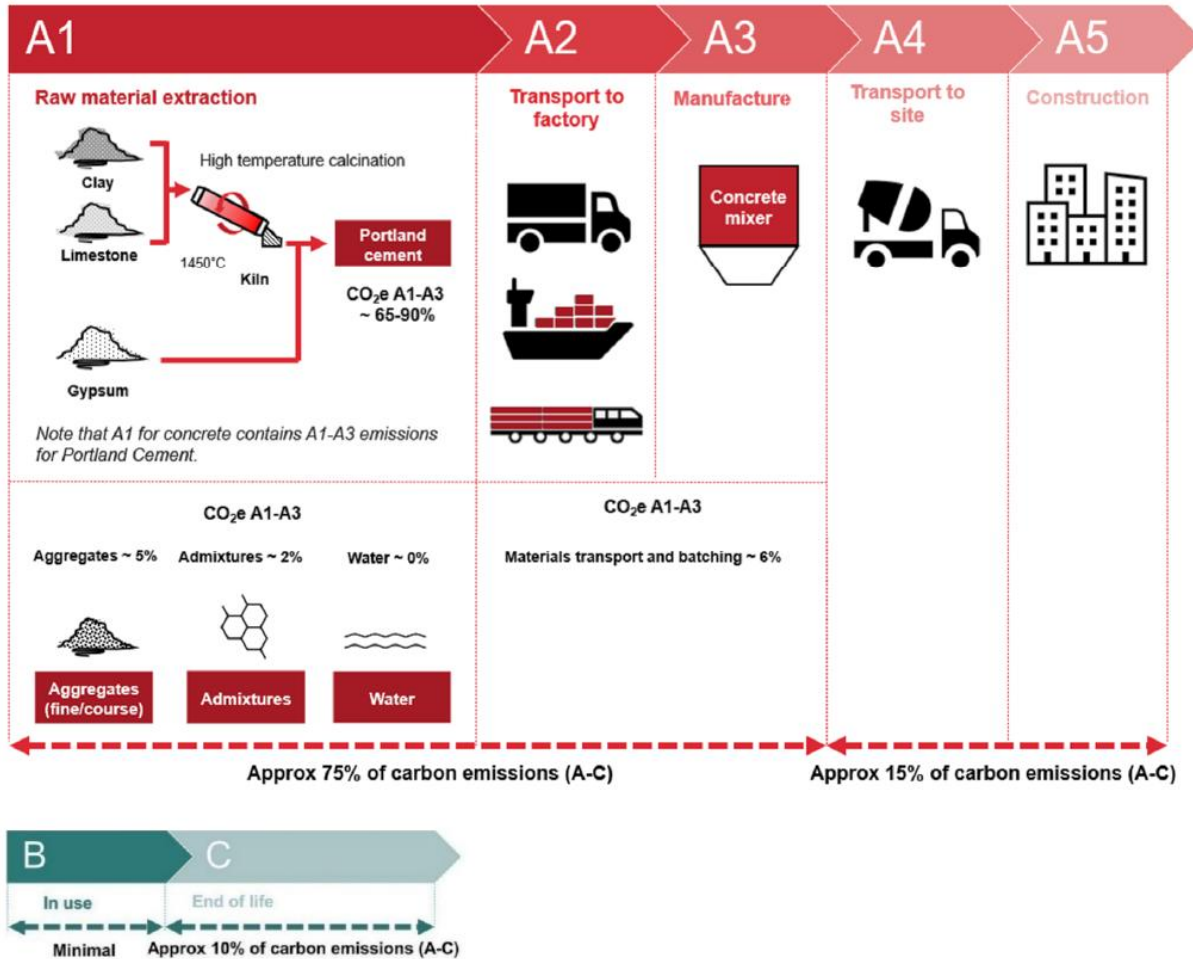


Figure 1. Life cycle stages for Portland cement concrete into corresponding percentages of carbon emissions¹

2.1 Raw materials extracted, Preparation, and Grinding (A1)

Procurement and selection of various types of raw materials, such as limestone, shale, clay, and laterite, especially limestone, which is the main raw material used the most in the production process of cement pellets. These raw materials are ground coarsely and thoroughly and mix them according to the specified proportions. Then prepare to continue the burning process.

Impact:

- Loss of animal habitats
- Land erosion
- Dust generation (PM10 / PM2.5)
- Uses high electrical power, which is a CO₂ emission

¹ Fragkoulis Kanavaris (Arup), Karen Scrivener (EPFL), "The confused world of low-carbon concrete," *Concrete Magazine*, vol. 57, no. 3, pp. 36-39, 2023.

2.2 Clinker Production (Burning Process) (A1)

The ground raw materials are transferred into the incinerator. They must go through the Preheater first, then into the Burning Zone at a temperature of 1450 °C, and then they will be cooled down rapidly.

Impact :

- Releases large amounts of CO₂ (more than 50% of the CO₂ in this industry)
- Releases SO₂, NO_x, CO and VOCs which cause acid rain
- Releases dust

2.3 Cement Grinding and Mixing (A3)

Cement goes into the kiln during the grinding process, gypsum, limestone, fly ash and cement additives are added in appropriate proportions, then it is transferred to the silo to await packing and further transportation.

Impact : Fine dust in the air and Continuous energy consumption

2.4 Packaging and Transportation (A2 and A4)

Considering the raw materials transporting to the production site (A2) and after it is finished processing where cement is packed in bags or bulk and transported by trucks, ships or trains (A4).

Impact : There is CO₂ emissions from trucks - Noise and dust pollution during transportation

2.5 Use Phase & End of Life (A5, B, and C)

It is a process of using cement for construction and when you want to renovate any building, you have to demolish the building. Therefore, concrete will become waste.

Impact : Dust from demolition and Concrete waste (if not recycle)

3. Good Practices in Cement Industry

3.1 Alternative Raw Materials

(1) Use of supplementary cementitious materials (SCMs)

The use of supplementary cementitious materials (SCMs) such as fly ash, silica fume and pulverized blast furnace slag is a globally accepted method of reducing carbon emissions from the cement industry. SCMs can replace clinker, the largest CO₂ emitting component in cement production, by approximately 20–50% without affecting the engineering properties of the concrete. In some cases, silica fume, for example, can also improve the durability, strength and chemical resistance. An important advantage is that many SCMs are waste or by-products

from other industries, such as fly ash from coal-fired power plants. Or slag from blast furnaces, thus helping to reduce waste, reduce raw material costs and help solve environmental problems in another way.²

Fly ash (FA)

Effect of Fly Ash (FA) on Compressive Strength of Concrete The use of fly ash to replace cement in concrete has a significant effect on the compressive strength, especially during the initial age of the concrete. Megat Johari et al. found that replacing cement with fly ash in the proportion of **10–30%** resulted in a decrease in the initial strength of the concrete. The more FA used, the lower the initial strength. However, **with increasing age**, the FA concrete continuously increased in compressive strength and after 90 days, the concrete using fly ash had higher strength than the normal OPC concrete, especially the use of 30% FA gave the highest long-term strength. Golewski similarly reported It was found that the concrete **with 20% fly ash had a higher compressive strength than the control concrete after 28 days and the compressive strength of the 30% FA concrete was significantly higher than the OPC concrete at 180–365 days**. This shows the effectiveness of FA in increasing compressive strength in the long term, despite the disadvantage in the early stages of the curing. Siddique et al. studied the use of FA at a high proportion of 50% and found that at 28 days, the FA concrete had a significantly lower compressive strength than the control concrete. However, after that, the compressive strength increased steadily between 91 and 365 days, which is due to the longer pozzolanic reaction of FA than OPC. In another study by Abubaker et al., it was found that concretes with FA at 10%, 25% and 50% showed the same trend, i.e., they had low compressive strength in the initial period but increased with the curing time. It was also found that concretes with high w/b ratio had lower compressive strength.³

² Zhang, Y., Bai, H., Lin, Y., Yang, J., Ma, Y., Wang, D., & Gao, X. (2023). The role of supplementary cementitious materials in reducing CO₂ emissions of concrete: A review. *Environmental Science and Pollution Research*, 30(32), 84170–84189. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10359888/>

³ Haruna, S. I., Ghosh, B., Hasan, M. R. M., Firoz, S. H., Shahin, M. A. I., & Jumaat, M. Z. (2023). A review on the influence of rice husk ash as supplementary cementitious material in concrete. *Buildings*, 13(1), 103. <https://doi.org/10.3390/buildings13010103>

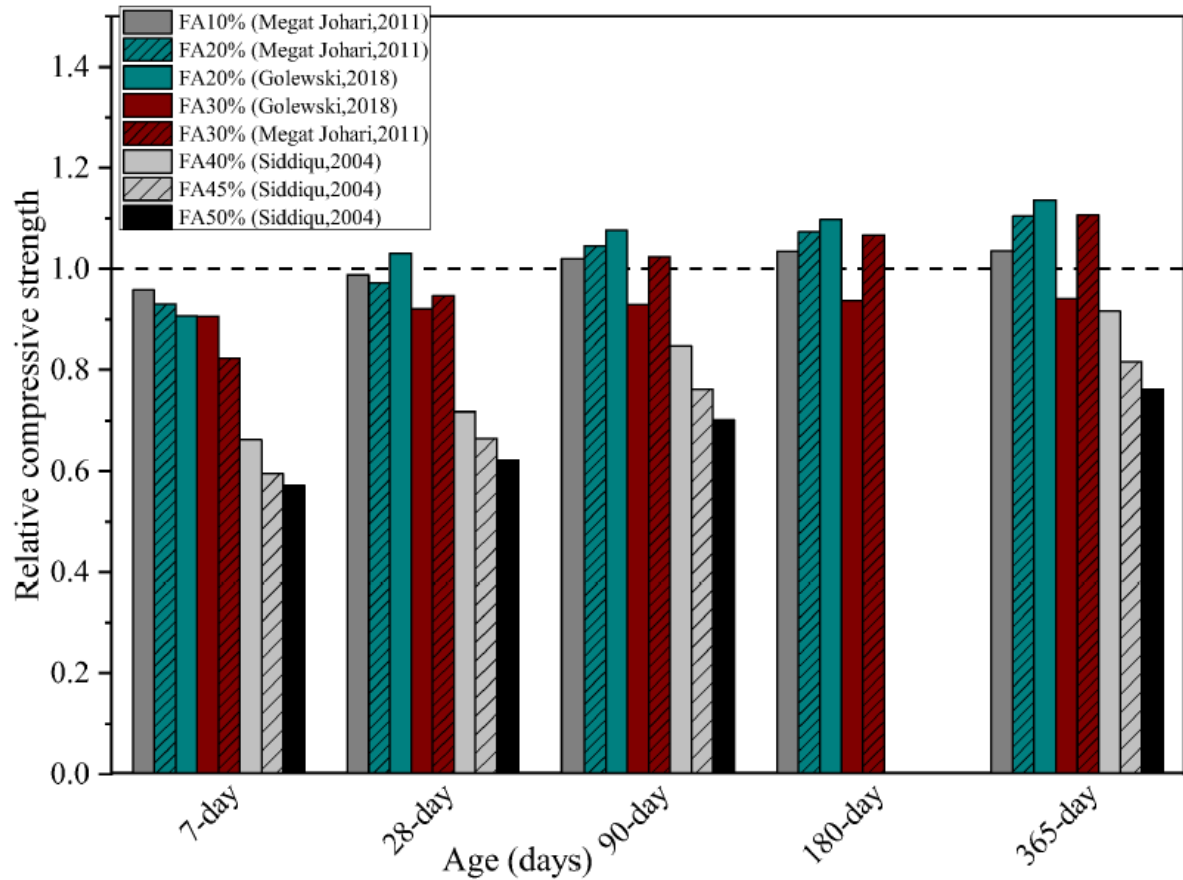


Figure 2. Relative strength of concrete containing fly ash (FA) at different curing ages.

Silica fume (SF)

Due to the limitations of conventional SCMs (e.g. fly ash, silica fume and slag) whose combined production volumes do not meet the global demand, recent research focuses on the development of alternative SCMs, improving the quality of materials through pre-treatment and developing nano-level technologies to enhance the efficiency of cement mortar reactions. A deeper understanding of the effects of SCMs on cement hydration, fresh properties, mechanical strength and long-term durability has driven the application of SCMs further, especially in ultra-high-performance concrete (UHPC).

The research that studied the quality of different types of cements for “the effect of using silica fume as an admixture at room temperature”, which the use of silica fume (SF) as a reinforced cement material (SCM) in concrete plays an important role in improving the quality of building materials. Silica fume, which is a by-product of the silicon melting process, has very fine particles (more than 95% are smaller than 1 micron) that act as a filler that helps fill the spaces between cement

particles, resulting in higher concrete density, reduced internal spaces and reduced water permeability. Or various chemicals are reduced, thus increasing the overall corrosion resistance of concrete. In terms of chemistry, **silica fume reacts pozzolanically with calcium hydroxide⁴ produced from cement hydration. The result is the formation of calcium silicate hydrate (CSH) gel, which is an important component that increases the strength of concrete.** Various research reports that the use of SF in the proportion of **6-15% can increase the compressive strength of concrete by up to 25%, especially in the age range of 28-90 days**, allowing the structure to withstand the force better, suitable for work requiring high-strength concrete. Silica fume also has a beneficial effect on other mechanical properties of concrete, namely tensile strength, which reduces tensile cracking, and increased modulus of elasticity, which enables the structure to withstand shock, vibration and temperature changes better, especially in horizontal structural members such as concrete floors or runways that are subjected to uniform and continuous loads. However, the use of excessive amounts of SF, such as more than 20%, may reduce the long-term strength due to the formation of a chemical reaction product layer that prevents further reactions from proceeding. Therefore, the optimum proportion of SF should be between 5–15%, depending on the water to binder (w/b) ratio and the nature of the construction.⁴

⁴ Haruna, S. I., Ghosh, B., Hasan, M. R. M., Firoz, S. H., Shahin, M. A. I., & Jumaat, M. Z. (2023). A review on the influence of rice husk ash as supplementary cementitious material in concrete. *Buildings*, 13(1), 103. <https://doi.org/10.3390/buildings13010103>

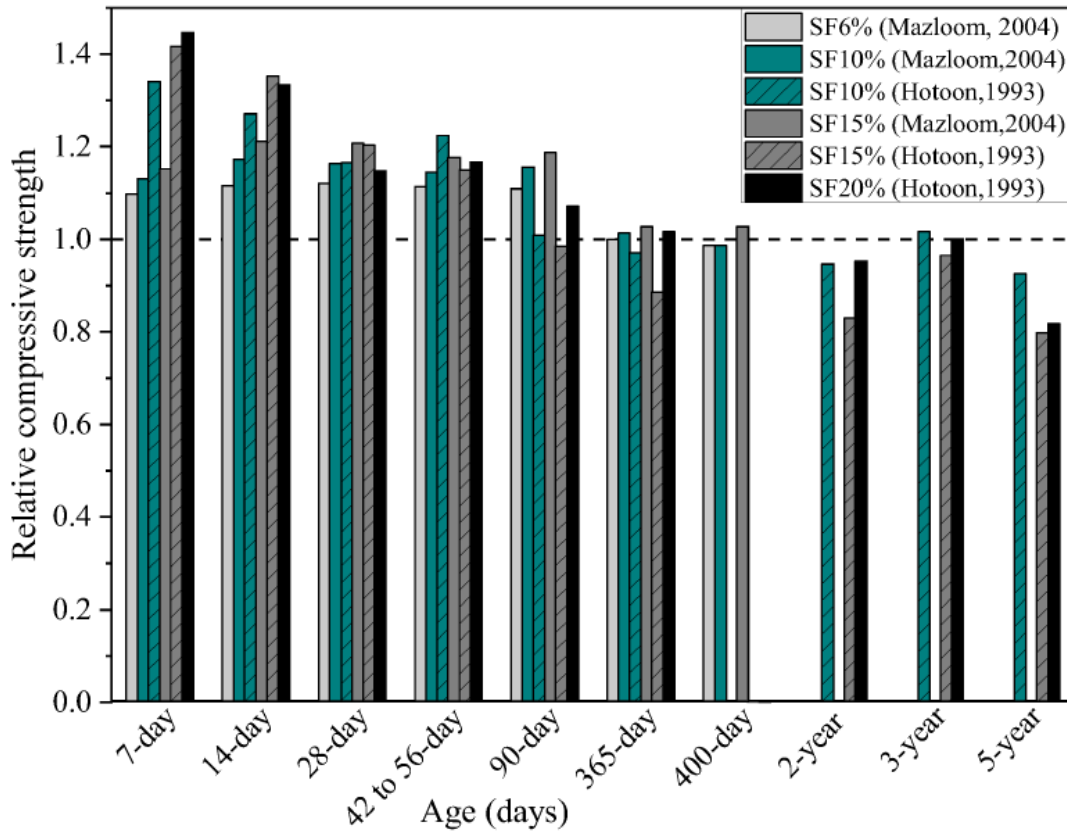


Figure 3. Relative compressive strength of concrete containing silica fume (SF) at different curing ages.

(2) Incorporation of construction and demolition waste

Construction and demolition waste (CDW) can be incorporated into cement production as a partial replacement for raw materials, offering a sustainable solution for waste management and reducing reliance on natural resources. This involves processing C&D waste to produce recycled aggregates, which can then be used in cement manufacturing. CDW especially hydrated cement from demolition—is transformed from waste into a resource. When processed and reused, it substitutes for mined limestone, clay, or schist in raw meal, or partially replaces clinker in blended cement, improving resource efficiency and conserving natural inputs.

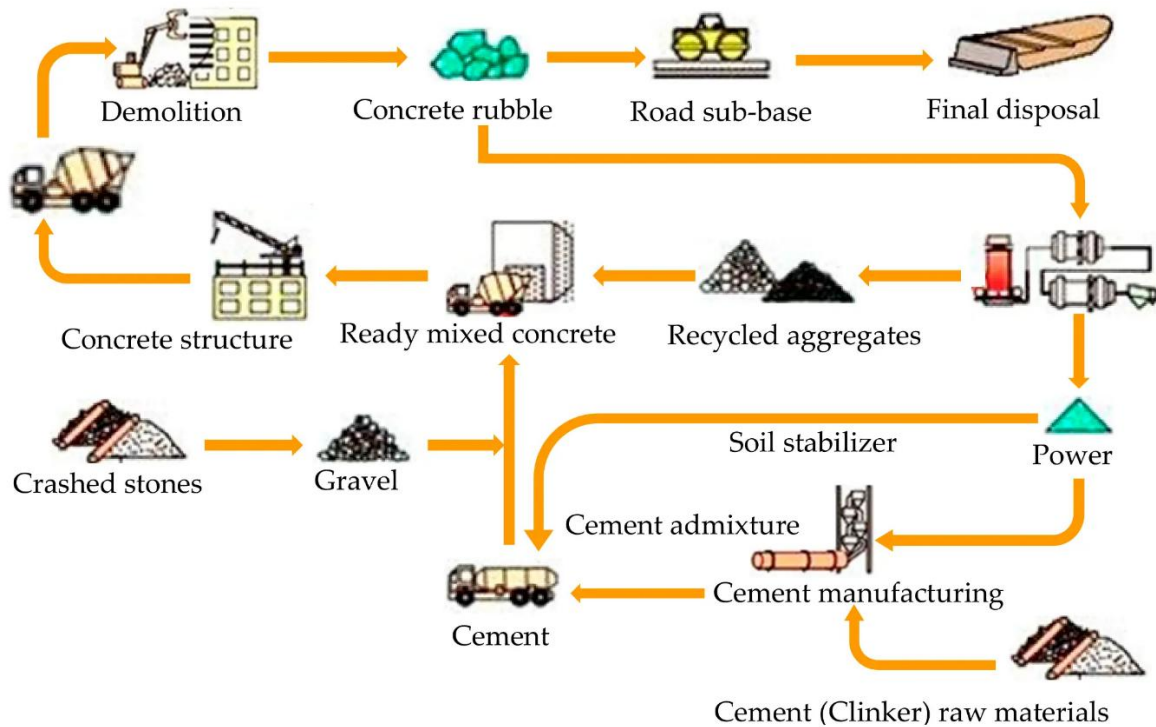


Figure 4. Substituting CDW in Cement production

Mechanical Performance and Material Suitability

Moderate substitution of construction and demolition waste (CDW) at around 30% can maintain clinker-like mineralogical properties, while higher levels up to 55% may alter the clinker composition. However, blended cement products using **20–40% CDW** still achieve long-term strength comparable to conventional pozzolanic cements. Additionally, fine CDW powders **smaller than 0.15 mm**, especially **after calcination, can serve effectively** as supplementary cementitious materials (SCMs) or fillers in cement mixtures.⁵

Environmental and CO₂ Emission Benefits

Using CDW as a partial replacement in both raw meal for clinker and in blending with Portland cement enables significant reductions in CO₂ emissions. One case study replaced **30–55% of raw mix** with hydrated cement waste: a 30% substitution cut decarbonation emissions by approximately **one-third**, while higher substitutions produced secondary cementitious materials suitable as supplementary cement that also reduce emissions.

⁵ An investigation on the recycling of hydrated cement from concrete demolition waste, April 2015, [Cement and Concrete Composites](https://doi.org/10.1016/j.cemconcomp.2015.04.010), DOI:10.1016/j.cemconcomp.2015.04.010

Lifecycle assessments estimate that **recycled cement** can reduce emissions by **~0.68 t CO₂ per tonne**, and **recycled aggregates** can additionally contribute to comparable CO₂ savings relative to virgin materials—leading to net reductions of roughly **0.5 t CO₂ per tonne of recycled concrete**.⁶

CO₂ Sequestration via Carbonation

Beyond emission reductions during production, recycled cement-containing aggregates captured CO₂ during their service life and forced carbonation experiments. Recycled concrete aggregates (RCAs) stored approximately **52 to 491 kg CO₂ per tonne of cement paste**; mixed recycled aggregates captured **123-225 kg CO₂ per tonne of paste**. That equates to about **0.6–4.1% sequestration per tonne of aggregate**, offering a secondary carbon sink benefit.⁷

Summary of Core Benefits

In conclusion, substituting CDW in Portland cement production yields a compelling combination of climate mitigation, circular resource use, and retained engineering performance. The practice aligns well with sustainable material strategies, offering both emission savings and a novel path toward carbon-aware cement design.

Core benefits include substantial CO₂ emission reductions (around 30–68% per tonne of material) through partial clinker and raw material replacement, while maintaining comparable strength and durability to conventional cement. The process promotes waste valorization by converting demolition waste into valuable feedstock, reducing landfill use, and enabling additional carbon sequestration through natural and accelerated carbonation in recycled aggregates. It also conserves resources by lowering reliance on virgin minerals and reducing the need for energy-intensive raw material production.

3.2 Fuel Substitution and Energy Efficiency

(1) Use of renewable energy and waste heat recovery

The integration of **waste heat recovery (WHR)** systems in cement production is a proven and effective strategy for reducing greenhouse gas emissions. Cement plants release a large amount of thermal energy—**approximately 35–40% of total input—through clinker cooler discharge and kiln or preheater flue gas**. This waste heat can be captured and converted into electricity using technologies such as the **Organic Rankine Cycle (ORC) or Steam Rankine Cycle (SRC)**. The electricity

⁶ An investigation on the recycling of hydrated cement from concrete demolition waste, April 2015, [Cement and Concrete Composites](https://doi.org/10.1016/j.cemconcomp.2015.04.010), DOI:10.1016/j.cemconcomp.2015.04.010

⁷ Pathway to Carbon Neutrality in the Cement Industry: CO₂ Uptake by Recycled Aggregates from Construction and Demolition Waste, *Appl. Sci.* **2024**, *14*(12), 5224; <https://doi.org/10.3390/app14125224>

generated through WHR systems displaces grid electricity, which results in significant reductions in indirect CO₂ emissions.^{8,9}

Thailand has made notable progress in adopting WHR, with about 263 MW of installed capacity across cement plants, producing roughly 1.66 terawatt-hours of electricity annually. This contributes to an estimated reduction of 793,600 tons of CO₂-equivalent per year, accounting for approximately 7.2% of the country's Nationally Determined Contribution (NDC) mitigation target. In terms of efficiency, studies comparing different working fluids in ORC systems have found that R245fa offers a good balance of thermal efficiency (~21.4%) and environmental safety, while toluene provides slightly higher efficiency (~24.6%) but presents greater toxicity and flammability risks. On average, large kilns equipped with ORC systems can generate 30–45 kWh of electricity per ton of clinker produced, contributing to further emission reductions depending on grid intensity.¹⁰

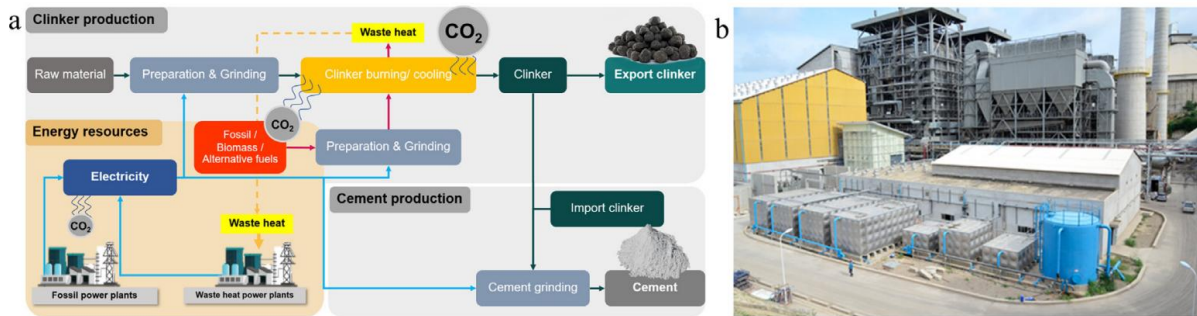


Figure 5. (a) Clinker and cement production process and GHG emission sources; (b) Waste heat power plant in Thai cement factory¹¹

In addition to environmental benefits, **WHR** also offers economic advantages. It has been shown to **reduce the cost of clinker production by around 3.8%**, from USD 58.20 to USD 55.98 per ton, and lower the levelized production cost by approximately 7.5%. Payback periods for WHR systems vary by project scale and technology type, ranging from about 3 to 9 years. One example demonstrated a WHR

⁸ Ige, O.E., Von Kallon, D.V. & Desai, D. Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Techn Environ Policy* **26**, 579–597 (2024). <https://doi.org/10.1007/s10098-023-02683-0>

⁹ Turakulov, Z.; Kamolov, A.; Norkobilov, A.; Variny, M.; Fallanza, M. Enhancing Sustainability and Energy Savings in Cement Production via Waste Heat Recovery. *Eng. Proc.* **2024**, *67*, 11. <https://doi.org/10.3390/engproc2024067011>

¹⁰ [Greenhouse gas mitigation potential from waste heat recovery for power generation in cement industry: The case of Thailand - ScienceDirect](https://www.sciencedirect.com/science/article/pii/S2352484723000000)

¹¹ TPI Polene Power Public Company Limited. Thailand (2021) Electric energy product <http://www.tpipolene.com.th/index.php/en/enproduct/energy-utilities-business/electric-energy>.

system producing 27.5 GWh of electricity per year and saving approximately 17,000 tons of CO₂, with a payback period of roughly 9 years.^{6 12}

On the renewable energy front, electrification of high-temperature processes using renewable sources is emerging as a critical pathway for decarbonization. Technologies like **solar-based radiant heaters (e.g., Coolbrook’s RDH™)**¹³ offer a fossil-free alternative to traditional fuel-based kilns. **These systems can reduce process-related CO₂ emissions by up to 30%.** Additionally, integrating concentrated solar power (CSP) for calcination, along with WHR, enhances energy efficiency and provides cleaner CO₂ streams for capture and storage.¹⁴

In summary, the combination of **waste heat recovery** and **renewable energy integration** presents a powerful solution for decarbonizing the cement industry. WHR alone can **reduce indirect emissions by 30–63%** at the plant level and significantly cut production costs. At the national scale, as in Thailand, WHR contributes meaningfully to climate targets. When complemented with renewable heat sources and alternative fuels, the cement sector can achieve deep emission cuts while maintaining or even improving economic performance.

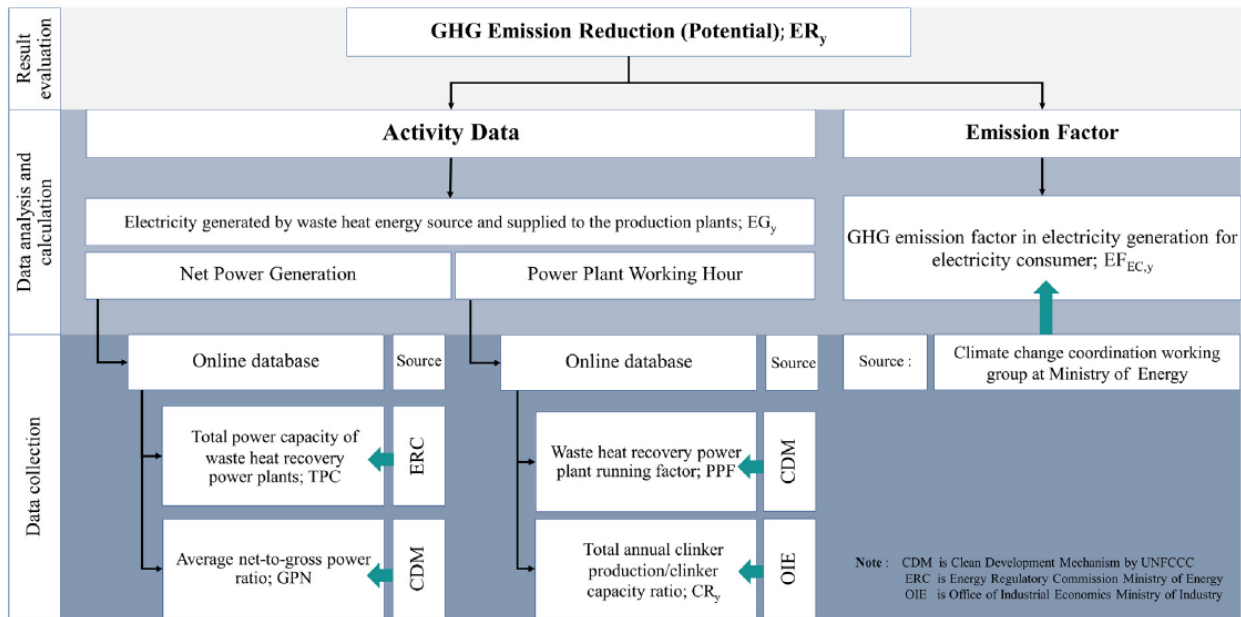


Figure 6. Data collection and research procedure.

¹² [Innovative Waste Heat Recovery in Cement Production Reducing CO₂ Emissions and Energy Consumption | International Journal of Research and Review in Applied Science, Humanities, and Technology](#)

¹³ [Green Technology Book. Solutions for climate change mitigation.](#)

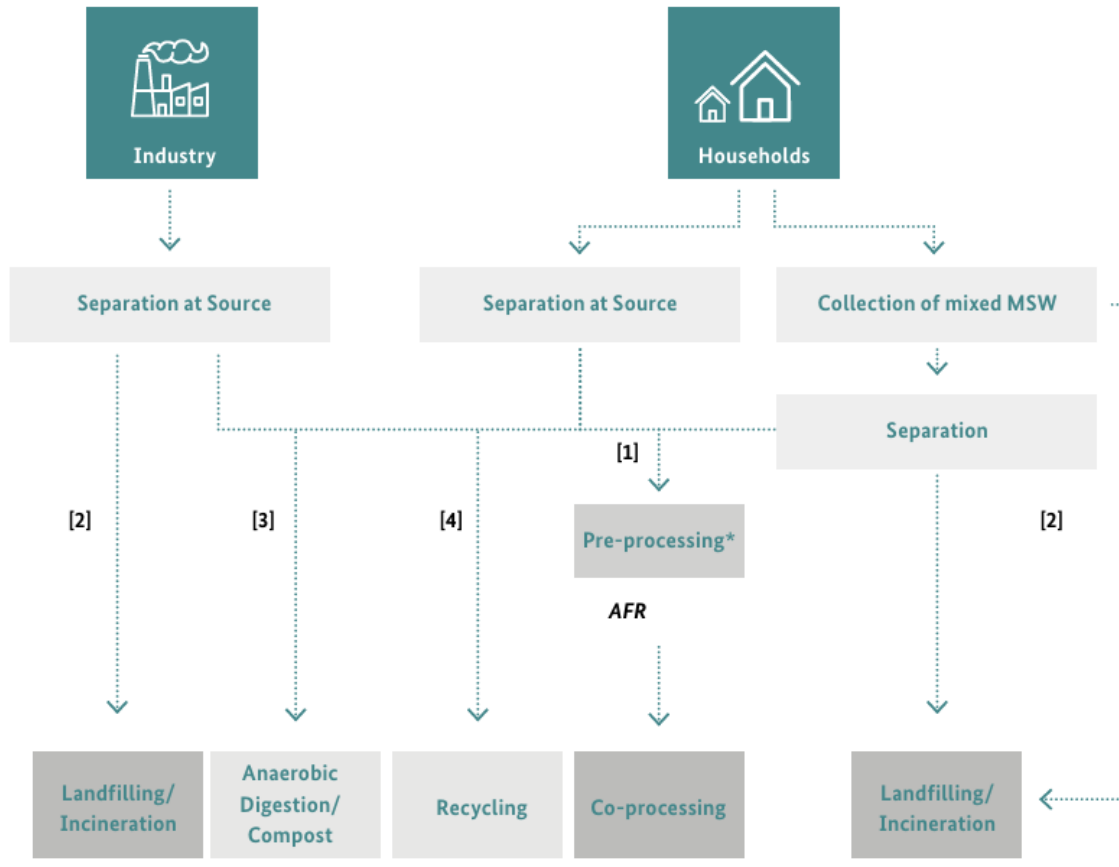
¹⁴ [Reducing carbon emissions in cement production through solarization of the calcination process and thermochemical energy storage - ScienceDirect](#)

(2) Co-processing of biomass and waste-derived fuels

Another key approach involves **co-processing of biomass and waste-derived** fuels, which, while not part of WHR, significantly reduces the carbon intensity of cement production. Many European cement plants already derive over 40–60% of their thermal energy from such renewable alternatives, effectively displacing fossil fuels and further cutting GHG emissions.

Co-processing in cement production involves using waste-derived fuels and materials as a substitute for traditional fossil fuels and raw materials. This process, also known as **alternative fuels and raw materials (AFR)**, **utilizes the heat from waste combustion to power cement kilns and incorporates the mineral content of waste into the final cement product.** This approach offers a sustainable solution for waste management, promoting energy and material recovery while reducing reliance on primary resources and minimizing landfill waste.¹⁸

¹⁸ https://www.giz.de/en/downloads/giz-2020_en_guidelines-pre-coprocessing.pdf



* selected industry wastes such as waste oils and solvents do not require pre-processing

Legend:

- [1] Non-recyclable waste
- [2] Non-recyclable and non-applicable for co-processing
- [3] Biomass
- [4] Recyclables

Conditions:

- [1] - High calorific value
- Raw material substitutions
- Secure thermal treatment of hazardous waste

Figure7. Integration of pre- and co-processing in the management of waste from industry and households.

Types of waste co-processed by INSEE Ecocycle in most cases is subjected to pre-processing procedures, requiring engineering expertise to ensure the waste is suitable for co-processing.

 Municipal Solid Waste	 Industrial Hazardous Waste	 Industrial Non-Hazardous Waste	 Agricultural Waste & Residual	 Alternative Raw Materials
<p>Waste Type</p> <ul style="list-style-type: none"> Sorted municipal waste Dried municipal waste 	<ul style="list-style-type: none"> Oil sludge Chemicals Refinery catalyst Iron dust Fly ash/bottom ash Drilling Mud Resin Spray can Coolant 	<ul style="list-style-type: none"> Write-offs products Paper Packaging materials Rubber Foil Foam Leather Textile 	<ul style="list-style-type: none"> Husks (Rice, Soya, etc) Wood Seeds Bagasse 	<ul style="list-style-type: none"> Iron, aluminum Silica, clay, gypsum Fly ash, slag Construction & demolition waste (soil, bricks, glass)
<p>Typical Generators</p> <ul style="list-style-type: none"> Municipalities Waste management companies 	<ul style="list-style-type: none"> Factory/Manufacturers Power plant Refinery 	<ul style="list-style-type: none"> Factory/Manufacturers 	<ul style="list-style-type: none"> Farmers, plantations, millers Brokers, traders 	<ul style="list-style-type: none"> Local and multinational companies Property developer, Construction companies

Source: <https://www.siamcitycement.com/thailand/inseeecocycle/en/about/our-processes>

The **benefits of co-processing waste and biomass fuels in cement production**, as described in the 2020 GIZ Guidelines and associated sources. Co-processing of waste and biomass fuels in cement production offers multiple benefits. It significantly reduces greenhouse gas emissions by replacing coal with carbon-neutral biomass and diverts waste from landfills, minimizing methane release and environmental harm. This approach supports a circular economy by substituting both fuel and raw materials, turning waste into energy and mineral input while conserving natural resources. Economically, it is more cost-effective than building new waste-to-energy plants, lowers production costs, and boosts local value chains. Operationally, high-temperature kilns ensure complete waste destruction, safely immobilize contaminants, and maintain product quality. Co-processing also aligns with international waste management standards and improves public health outcomes through reduced pollution and regulated waste handling.

(3) Optimization through AI and advanced sensors

Cement Production Optimization AI empowers businesses with pragmatic solutions to optimize cement production processes through advanced AI techniques. This solution leverages algorithms and machine learning to optimize production, predict demand, manage inventory, identify inefficiencies, and enhance cement quality. By leveraging this AI, businesses can increase efficiency, reduce costs, ensure optimal inventory levels, address inefficiencies, and meet industry standards, ultimately gaining a competitive edge and driving innovation in the cement industry.

The process begins with **data acquisition**—advanced sensors (mill and kiln units) continuously collect process variables. The **user interface** allows the plant engineer to select a forecasting target (e.g., energy use, emissions, product quality), choose relevant features (either manually or via algorithms like RFECV/SFS), and define whether to use a custom-tuned model or let the system auto-select the optimal AI model and its hyperparameters.

Once the model is specified, training proceeds on historical data. **The system evaluates performance (NRMSE)** and either activates the best player or stores configurations for later. Upon deployment, the AI subsystem feeds its output into an **IDMS optimizer**, where the user establishes an objective function—like minimizing fuel consumption or CO₂ emissions. They choose which variables can be manipulated, set target ranges, and initialize the Differential Evolution optimizer (e.g., population size, iterations).

Finally, the system generates **real-time operational recommendations**—adjustments to manipulated variables designed to hit objectives while respecting constraints. These recommendations are shown on the dashboard for plant operators to review and implement.²⁰

²⁰ Data-Driven AI Models within a User-Defined Optimization Objective Function in Cement Production, *Sensors* **2024**, *24*(4), 1225; <https://doi.org/10.3390/s24041225>

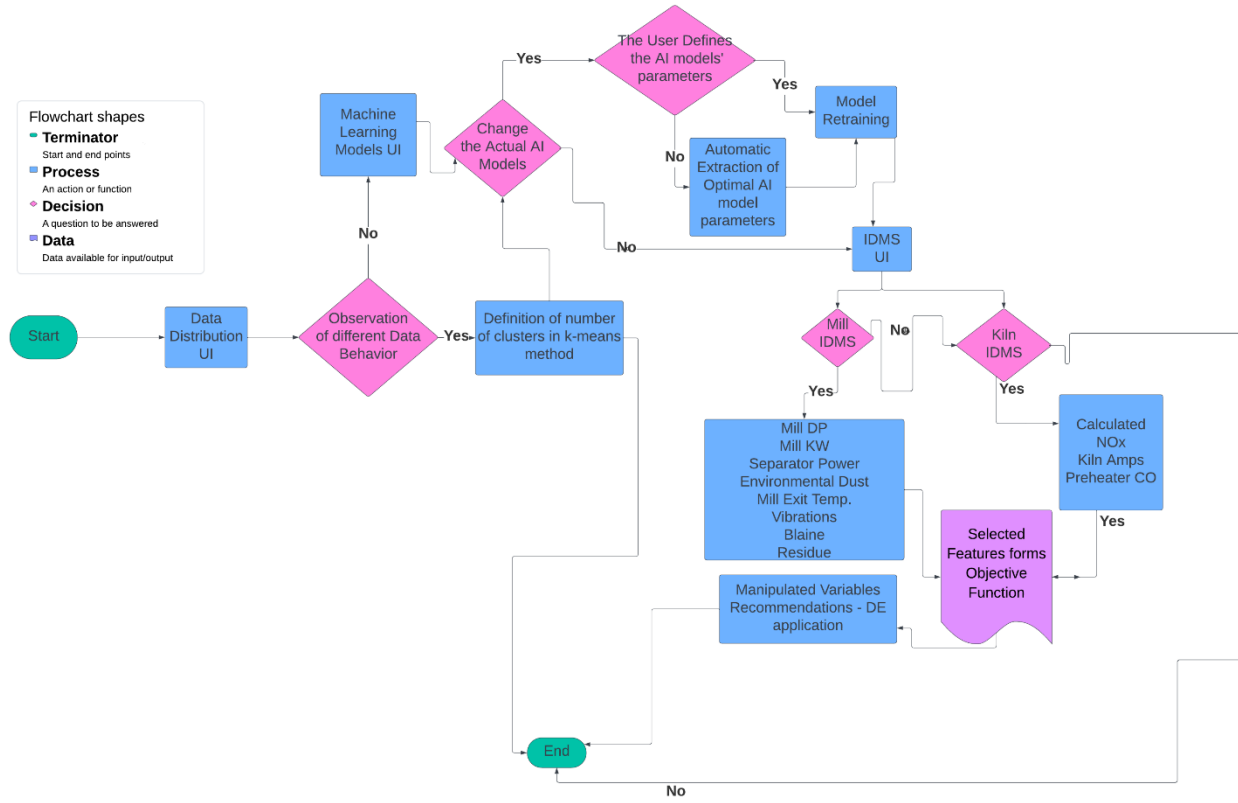


Figure 8. The flowchart of the platform.

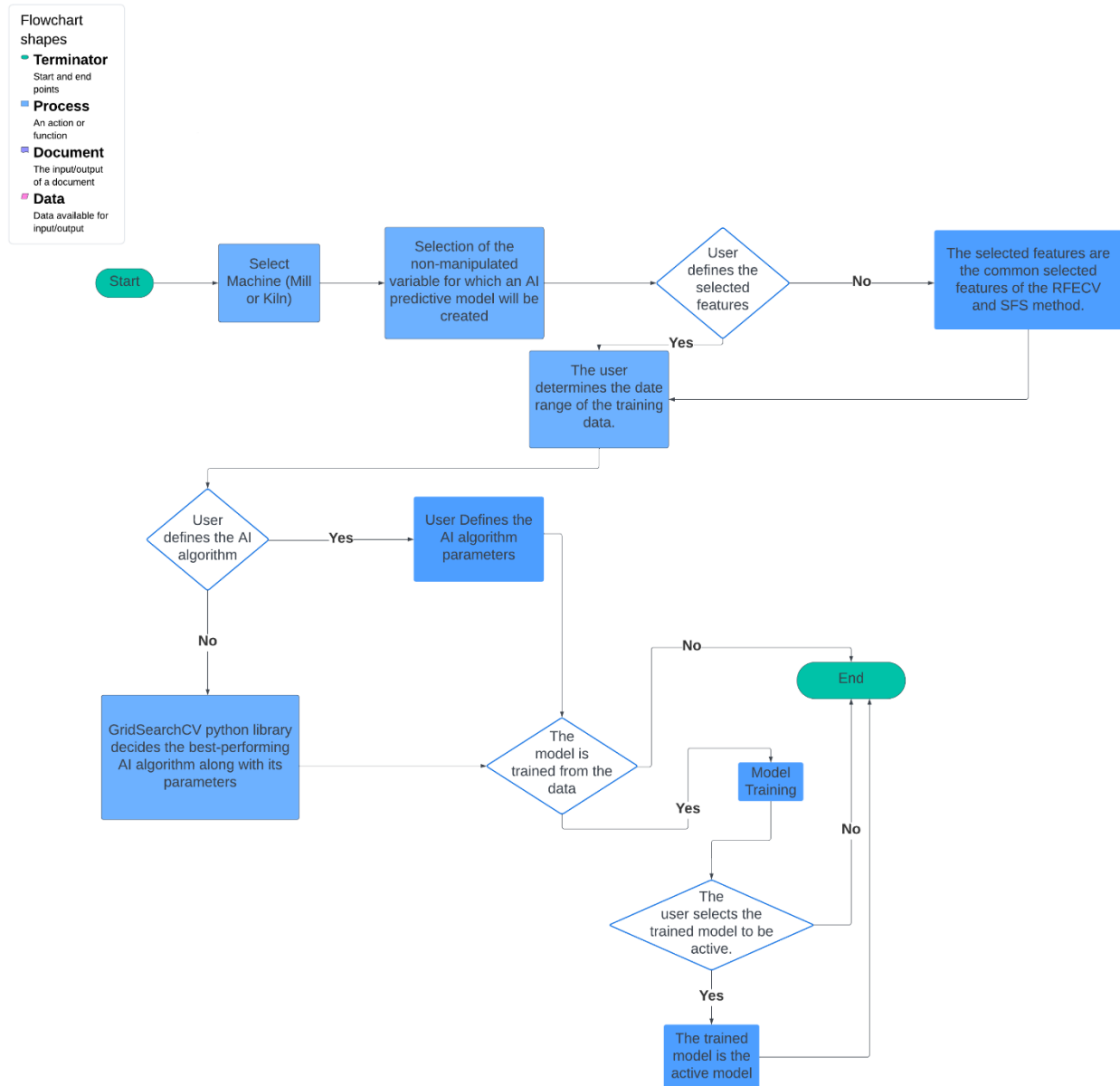


Figure 9. The flowchart of the AI subsystem.

In essence, this flowchart describes a sensor-to-savings pipeline: from raw data to optimized operational settings, enabling cement plants to reduce energy use, emissions, and costs through smart AI-driven control.

★ Key Improvements for a Cement Producer

AI-based optimization systems in cement production enhance decision-making by allowing engineers to set targets such as energy use, emissions, or cost, and receive real-time recommendations. The system streamlines deployment through smart feature selection and adaptive modeling, while a continuous optimization loop adjusts variables for improved

efficiency. Its user-friendly interface enables operators to easily implement strategies, reducing trial-and-error and enhancing reliability.

3.3 Innovative Production Techniques

(1) Development of low-clinker and novel cement types (e.g., LC3)

Limestone Calcined Clay Cement (LC3) is a substitute for conventional cement. LC3 is the brainchild of the École Polytechnique Fédérale de Lausanne (EPFL) and the Swiss Agency for Development and Cooperation (SDC) and has been developed as a low-carbon alternative to conventional Portuguese cement. A typical LC3-50 cement mix consists of 30 percent burnt clay, 15 percent limestone, 5 percent gypsum and 50 percent clinker. Together, they reduce carbon emissions by approximately 40 percent compared to conventional Portuguese cement.²¹

CO₂ reduction using LC3

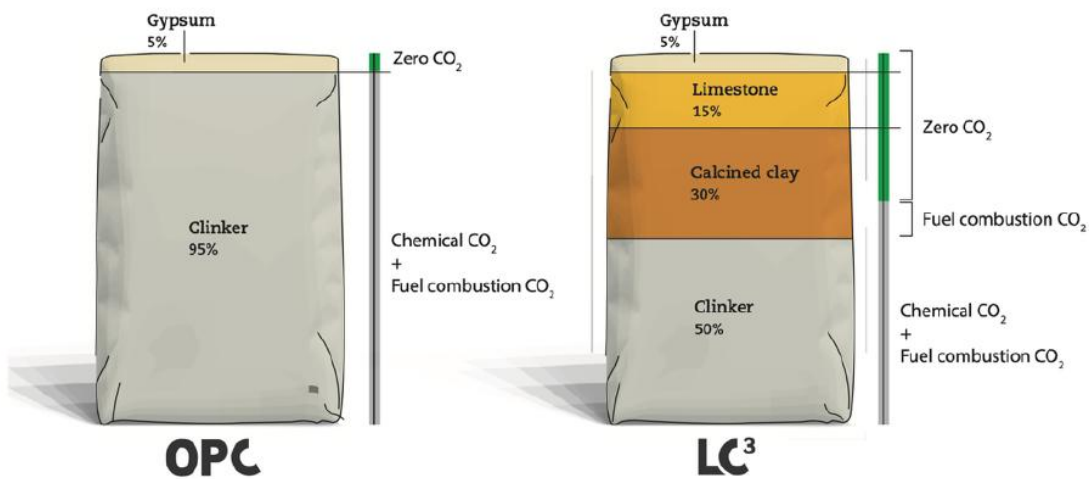


Figure 10. Comparison of raw material proportions in cement production between OPC (conventional) and LC3 (alternative) types.

Clay is produced at lower temperatures and does not emit CO₂ to the atmosphere. Limestone is used without burning, resulting in a CO₂ emission of fresh limestone clay cement that is 30% lower than that of conventional Portland cement.

²¹ Wikipedia contributors. (n.d.). *Limestone calcined clay cement*. Wikipedia. https://en.wikipedia.org/wiki/Limestone_Calcined_Clay_Cement

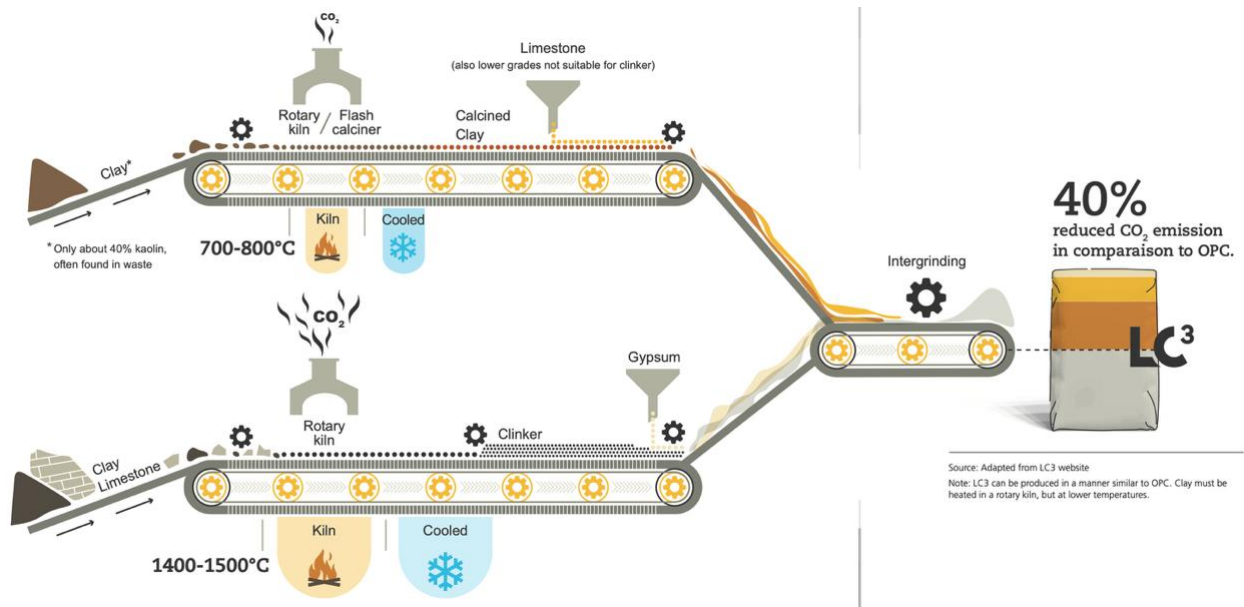


Figure 11. LC3 cement production process diagram

Also, **LC3 is 25% cheaper to produce due to the reduced energy-intensive clinker content** with widely available and energy-efficient materials. The investment cost is also low as existing technologies can be used for LC3 production. Moreover, the economic attractiveness of this product can be increased by the government through incentives such as tax breaks to accelerate LC3 production.

Currently, the use of LC3 (Limestone Calcined Clay Cement) is gaining global attention as an alternative material that can effectively reduce greenhouse gas emissions. LC3 is unique in that it uses only half the amount of clinker than conventional cement and replaces it with a larger proportion of calcined clay and limestone, both of which are readily available and have a much lower carbon footprint than clinker. In the LC3 production process, **the clay is fired at a temperature of only about 750–850°C**, which is much lower than the clinker firing that uses temperatures exceeding 1400°C, thus **reducing fuel consumption and CO₂ emissions by 30–40% compared to conventional cement**.

In terms of cost, LC3 has many advantages. In addition to the cheap and domestic raw materials, the existing production lines in cement factories can be modified to support LC3 production without having to invest in building a new factory. The energy cost of burning clay is also significantly lower, making LC3 a worthwhile choice in both economic and environmental terms.

(2) Carbon capture, utilization, and storage (CCUS)

Cement production emits CO₂ from two main sources: (1) the combustion of fuels such as coal or alternative energy sources to create high temperatures in the kiln, and (2) the chemical reactions that convert limestone (CaCO₃) into lime (CaO), which releases CO₂ directly from the limestone molecular structure. Therefore, even with the shift to clean energy, CO₂ from chemical processes will still be generated. The use of CCS technology has become essential if the industry is to truly reduce CO₂ emissions.

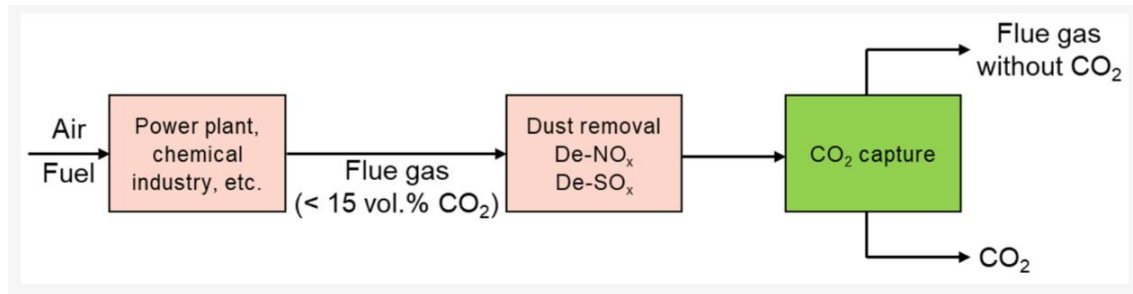


Figure 12. Simplified scheme for the post-combustion route for carbon capture²²

In the cement industry, there are two main types of carbon capture technologies: carbon capture and storage (CCS) and carbon capture, utilization and sequestration (CCUS).

1. Carbon capture and storage (CCS): Focuses on capturing carbon dioxide (CO₂) from sources such as cement plants. After capture, the CO₂ is transported and stored underground in deep rock formations or in other safe storage sites. The main goal is to reduce CO₂ emissions into the atmosphere.

2. Carbon capture, utilization and sequestration (CCUS): Similar to CCS, it captures CO₂ from the source. However, CCUS also includes the utilization of the captured CO₂ in various fields, such as the production of synthetic fuels, cement production, or other industrial processes. If it cannot be utilized, it will be stored like CCS.

The examples of technology used as CCUS

- **Amine scrubbing**, a commercially proven post-combustion capture technology. The principle is to use a solution containing an “amine” (e.g. MEA: monoethanolamine), which can react chemically with carbon dioxide. When the exhaust gas from the combustion engine, which contains high concentrations of CO₂, flows through an absorber containing the amine, the CO₂ is captured in the liquid. This liquid is then sent to a stripper (or regenerator) which uses heat at

²² Madejski, P.; Chmiel, K.; Subramanian, N.; Kuś, T. Methods and Techniques for CO₂ Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies* **2022**, *15*, 887.

about 100–120°C to separate the CO₂ from the amine, resulting in pure CO₂ gas, and the amine can be reused in a recirculating system.²³

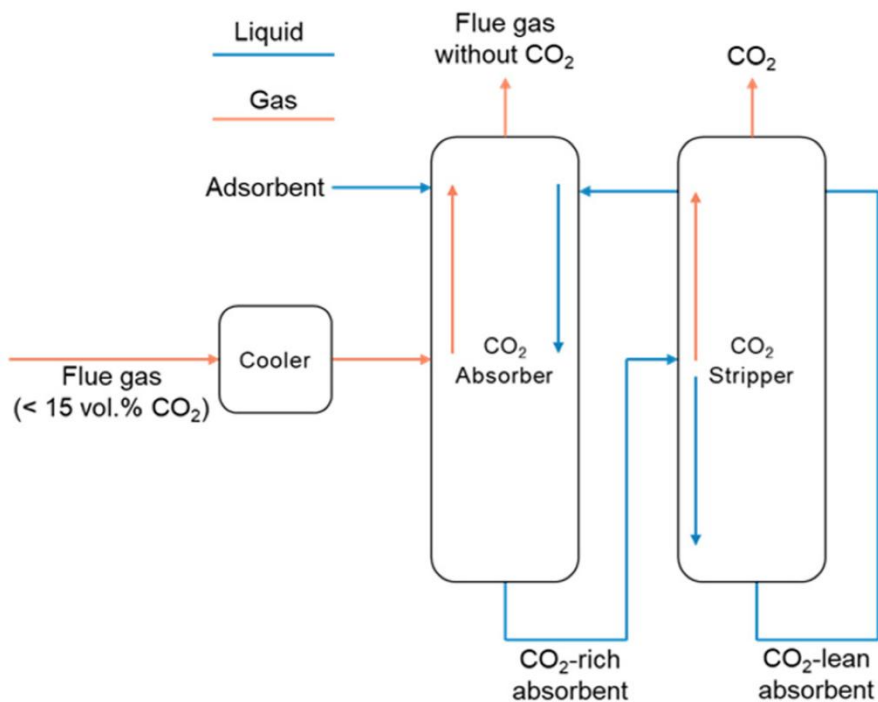


Figure 13. Simplified flowsheet of CO₂ absorption via fluid absorbents²⁴

- **Calcium looping (CaL) technology** – also known as the regenerative carbon cycle (RCC), captures CO₂ from flue gases in cement plants and other industrial facilities using a calcium oxide (CaO) sorbent. The process involves two key reactions: carbonation, where CaO reacts with CO₂ to form calcium carbonate (CaCO₃), and calcination, where CaCO₃ is heated to 850°C–950°C to release pure CO₂ and regenerate CaO for reuse. The captured CO₂ is then either stored or utilized. Heat for calcination can be supplied directly through oxyfuel combustion, which requires significant oxygen input, or indirectly, which avoids oxygen use but is generally less efficient.

The main technical challenges of CaL are the high energy demand for oxygen production in direct heating and the gradual degradation of the CaO sorbent, which

²³ A Compact Review of Current Technologies for Carbon Capture as Well as Storing and Utilizing the Captured CO₂ by Tim M. Thiedemann and Michael Wark, *Processes* 2025, 13(1), 283; <https://doi.org/10.3390/pr13010283>

²⁴ Osman, A.I.; Hefny, M.; Abdel Maksoud, M.I.A.; Elgarahy, A.M.; Rooney, D.W. Recent Advances in Carbon Capture Storage and Utilisation Technologies: A Review. *Environ. Chem. Lett.* **2021**, 19, 797–849.

requires regular replacement. Disposing of spent sorbent increases costs, but it can be repurposed in cement production or flue gas desulfurization to avoid landfilling.²⁵

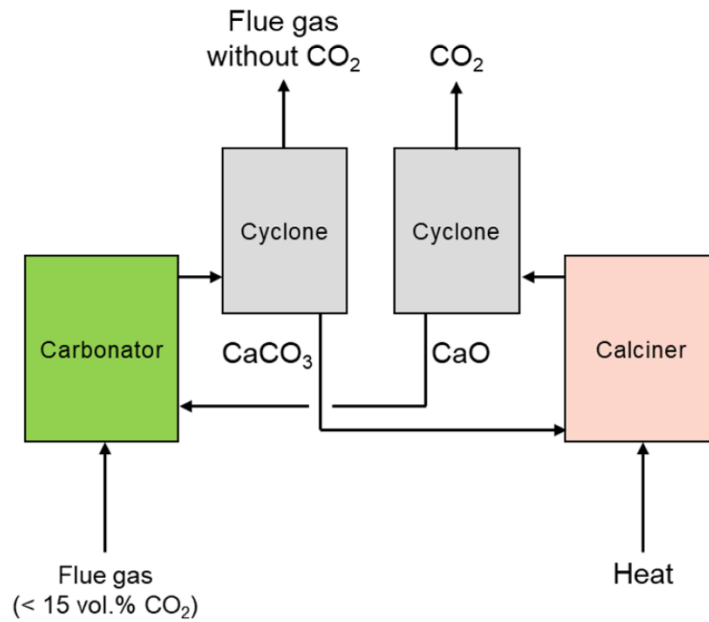


Figure 14. Simplified flowsheet of CO₂ capture via calcium looping²⁶

²⁵ Calcium looping: <https://gccassociation.org/cement-and-concrete-innovation/carbon-capture-and-utilisation/calcium-looping/>

²⁶ Liu, H.; Lu, H.; Hu, H. CO₂ Capture and Mineral Storage: State of the Art and Future Challenges. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113908. <https://www.sciencedirect.com/science/article/abs/pii/S1364032123007669>

3.4 Summary of Good practices

Technology / Approach	CO ₂ Reduction Potential	Investment Cost	Readiness Level	Environmental Impact	Suitability for Thailand
SCMs (FA, SF, GGBFS)	● High (approx. 20–50%)	● Low	● High	Waste reduction, resource reuse	● Very High
Construction and Demolition Waste (CDW)	● → ● Medium to High	● → ● Low to Medium	● Medium	Reduces landfill, carbon sink	● High
Waste Heat Recovery (WHR)	● High (30–60%)	● High	● High (already applied)	Cuts CO ₂ and electricity use	● Very High
Co-processing of Biomass/Waste Fuels	● High (>40%)	● Medium	● High	Circular economy, waste to energy	● Very High
LC3 (Low-Carbon Cement)	● High (~40%)	● → ● Low to Medium	● Medium (requires line adaptation)	Less energy use	● Very High
Carbon Capture and Storage (CCS/CCUS)	● Very High (up to 90%)	● Very High	● Low	Direct CO ₂ elimination	● Medium
AI and Advanced Sensors	● Medium	● Medium	● High	Operational efficiency, reduced loss	● Very High

4. Overcoming Challenges

While many of the benefits using recycled materials and innovative in cement production are clear, there are challenges that need to be addressed:

- **The SCMs** cost of most is lower than that of cement granules, making their use of SCMs a significant reduction in overall production costs. Only silica fume, which is more expensive, is popularly used in specialized applications that require special properties, such as high-strength concrete. In the context of Thailand, SCMs are very suitable because the country has fly ash from Mae Moh power plants and some plants that still use coal, as well as cooperation with the steel industry to supply GGBFS (Grind Slag). In addition, most cement plants in Thailand can use SCMs without having to invest in new structures, allowing immediate operation without having to wait for complex technologies such as CCS, according to the report's authors. Although the amount of some SCMs may decrease in the future (e.g. fly ash), SCMs are currently the most promising approach to decarbonize the cement industry, due to their low cost, immediate availability, and global acceptance by the industry. If the government further supports them in terms of standards, certification, and implementation in government construction projects, it will help drive effective decarbonization at the national level.
- In the Thai context, using **construction and demolition waste (CDW)** in cement production faces key challenges such as the lack of systematic waste separation and contamination with unsuitable materials, which affects quality and consistency. Infrastructure for processing CDW—such as crushing, sorting, and calcination facilities—is still limited, especially outside major urban areas. Moreover, existing cement standards and procurement policies in Thailand do not yet fully support or incentivize the use of CDW-derived materials. Without clear regulations, quality certification systems, and market awareness, the adoption of CDW in cement production remains slow despite its environmental potential.
- **Waste heat recovery utilization for power generation** is considered to improve energy efficiency by using thermal energy in clinker production as which partially replaced the on-grid electricity for cement production. The GHG mitigation and energy reduction have been estimated their performance tracking in this study. In Thailand , there are 12 waste heat power plants with a total 263.5 MW installed capacity in the Thai cement industry currently that is the potential of 1,663,674.21 MWh electricity production annually and GHG mitigation potential at 793,572.60 tons CO₂eq per year in 2019. Therefore, EPR and ERPR of the cement industry are 37.81 kWh/ton cement and 18.04 kgCO₂eq/ton cement, respectively. This GHG mitigation figure accounts for 7.21% of GHG mitigation targets for the NDC roadmap.

- **The use of LC3** is very appropriate in the context of Thailand because Thailand has a lot of suitable quality clay sources, especially in the East and the North. In addition, there are cement factories in many regions with infrastructure that can be immediately modified to produce LC3. Importantly, Thailand has a goal to reduce carbon emissions in the industrial sector, but does not yet have infrastructure ready for CCS technology. Therefore, the use of LC3 is a method of reducing carbon that can be done immediately and has a lower cost than using advanced technology. Promoting the use of LC3 is also consistent with the BCG (Bio-Circular-Green Economy) economic policy and can be integrated with government construction projects, such as increasing LC3 scores in the procurement system or promoting through standards. Green Building
- **Carbon capture and storage system (CCS)** shall be considering instalation for Thai cement production because Thailand has large industries which are sources of large amounts of carbon dioxide emissions. However, with budget constraints and relatively high operating costs, it is appropriate for the government to play a role in supporting the budget in order to push for the project to be carried out in a tangible way and promote long-term environmental sustainability.

For Thailand, despite the potential to use CCS in some industries, such as large cement and petrochemical plants, it still lacks many necessary components, such as systematic exploration of underground CO₂ storage sources, pipeline systems, legal support, and domestic carbon prices that are still too low compared to the operating costs of CCS. In addition, there is no agency directly overseeing CCS, making operations at the large-scale project level highly complex. However, if there is long-term planning, such as promoting pilot projects in large industrial areas, issuing laws to support underground CO₂ storage, and exploring storage sources together with the Gulf of Thailand or expired gas sources, CCS may become another important tool in the country's Net Zero policy. It must be combined with clinker reduction, the use of alternative materials in cement, and the improvement of energy efficiency in the production process, not relying solely on CCS.