Greener Foundations: Innovations Driving Change in Cement Manufacturing

Introduction

Sustainability is more than a goal—it's a powerful commitment to shaping a future where both people and the planet thrive. At its heart, it means meeting our current needs without compromising the ability of future generations to meet theirs. By harmonizing environmental care, social well-being and economic progress, sustainability offers a hopeful path forward - one where innovation, responsibility and compassion drive lasting positive change.

In context to creating a better world for us and our future generation, this article focuses on sustainability related efforts currently being made by the cement industry and those envisaged in the future. Limestone is the main ingredient for producing clinker, that is the key input to produce cement along with other cementitious materials. Limestone is a scarce resource, which over the years will continue to deplete as more and more cement is consumed. During the same moment of time, the process of limestone calcination is one of the key causes of CO_2 emission in the entire production process, which is detrimental to the environment. Increasing climate effect and scarcity of resources are motivating the industry to seek alternative cementitious materials.

Cement is the backbone of modern infrastructure and construction. Being the fundamental component in concrete, the second largest material consumed on the planet after water. It remains in huge demand, especially in developing nations with rapid infrastructure development and urbanization taking place. In 2024 the world production capacity of cement was estimated to be over 7 billion t/yr (tonnes/year) and consumption was about 4 billion t (tonnes). Globally, cement demand is envisaged to increase by 3%-5% over the next 5 to 7 years.

The importance of cement in rapid infrastructure development and construction, particularly in developing countries and considering its detrimental environmental impact, compels the industry to give higher emphasis on attaining sustainable practices in its production process.

Key Sustainability Challenges

Adopting sustainable practices in the hard-to-abate sectors like the cement industry is not easy due to its key challenges which are given below:

1. High carbon emission from clinker production: Clinker is the main ingredient in cement manufacturing. For producing 1 tonne of clinker, limestone required is around 1.5 tonne, which emits roughly 500 kg (0.5 tonne) of CO_2. The chemical process of calcination, where limestone ($CaCO_3$) is heated at around 1400^{O}C temperature to produce clinker, emits CO_2 which is 55-60% of the total CO_2 emission from the cement manufacturing process (assuming Portland Cement CEM-I as per EN 197-1 is produced). Reducing dependency on clinker and/or replacing clinker from the process is a major challenge for the industry.

2. Energy intensive manufacturing process: From limestone extraction to cement transportation to market, the entire process is energy intensive. Energy can be divided into two parts, thermal energy and electrical energy.

    a. Thermal energy (fuel) is used to heat the kiln during clinker production. Commonly used fuel includes coal and pet coke – assuming a judicial mix, CO_2 emission from fuel is roughly 30-35% of the total CO_2 emitted during the cement manufacturing process. Use of alternative fuels (AF) such as biomass, plastics, tyres, RDF (Refuse Derived fuel) from municipal solid waste, pharmaceutical/other hazardous waste materials etc., are beginning to gain higher acceptance in the industry. However, the key challenges in AF gaining a much higher traction include reliable supply chain, technical compatibility with existing kilns and regulatory support.

    b. Electrical energy refers to power/electricity used in the entire process to produce cement. Around 9%-10% of total CO_2 being emitted in the cement production process is from power consumption. To reduce this emission, industry is moving towards renewable energy (RE) such as solar, wind, hydro and hybrid (Grid & CPP and renewable sources). The use of RE is dependent on geological and climatic conditions, storage facilities for nighttime and infrastructure availability.

3. Government support: Government institutes/associations/organizations are starting to support cement companies in their pilot projects by providing collaboration opportunities, incentives, subsidies, etc. However, strong policies are still needed to support cement industry's initiatives such as producing low-carbon cement, adopting alternative fuels and raw materials and advancing R&D in CCUS (Carbon Capture, Utilisation and Storage) technologies. While such policies exist in certain parts of the world, they need to be globalized.

4. Technological vs economic viability: Research institutes and cement companies are working towards developing technologies for reducing CO_2 emission in the industry. However, the key challenge is in making the technology commercially viable and ensuring its widespread adoption across the globe.

Current Industry efforts

Continual efforts of the cement industry towards adapting sustainable practices to reduce CO_2 emission and achieve net zero emissions are mitigating the traditional challenges. The table below compares traditional and modern approaches across key cement industry attributes, highlighting benefits, challenges and providing some real-world efforts.

Attributes	Traditional Approach	Modern Approach (Current Efforts)	Benefits	Challenges	Some Examples (Companies / Projects)
Blended Cement	OPC (Ordinary Portland Cement) with 90–95% clinker	Partial clinker replacement with Supplementary Cementitious Materials (SCMs) such as fly ash, slag and clay, thereby producing Pozzolana Portland Cement, Pozzolana Slag Cement and Limestone Calcined Clay Cement (LC3)	Reduction of CO_2 per tonne of cement by 30%-40%, lower production cost	SCM availability	LC3 is already established in Africa, Latin America, India, and Europe - CBI Ghana, Cementos Argos, JK Cement, Holcim, Vicat, etc., are leading the way. UltraTech, CIMAF and Lafarge Malawi are scaling up LC3 production.
Geopolymer Cement	Clinker-based OPC	Fly ash/slag + alkaline activation	Reduces up to 70% CO_2 per tonne of cement	Scaling & market adoption hurdles	CEMEX (Vertua Ultra)
Alternative Fuel (AF)	Coal, Pet Coke	Biomass, RDF, plastic waste, tyres, etc	Reduces reliance on fossil fuels, lowers CO_2 emission and production cost	Requires new handling & feeding system	Holcim, Heidelberg, Ultratech, Dangote, JSW, Adani, JK Cement, etc
Renewable Energy (RE)	Grid & CPP based electricity	Solar, Wind, Hydro and Hybrid (traditional and RE both)	Lowers energy cost, reduces CO_2	High initial investment	Global players
Digitisation & Automation	Manual monitoring	IoT (Internet of Things), smart sensors, predictive tools, etc	System efficiency, real time monitoring, lower downtime	Skilled staff and integration in existing plants	Industry-wide adoption
Waste Heat	Heat wasted	Capture & convert	Lowers power	High capital	Widely deployed

Attributes	Traditional Approach	Modern Approach (Current Efforts)	Benefits	Challenges	Some Examples (Companies / Projects)
Recovery (WHR)		to electricity	cost	cost	
Green Logistics	Diesel trucks	EVs, rail/water transport, use of digital fleet technology	Reduction of CO_2 by 2–3%/ tonne of cement, digital fleet technology is useful for route optimization	Adequate number of EV charging stations in the route	Ultratech, JK Lakshmi, etc are using EVs for clinker transport and cement transshipment
ESG Reporting	Limited transparency	ESG frameworks, reporting CO_2/tonne, AF and RE use	Attracts green funds	Needs robust monitoring	Various players
Circular Economy	Landfill waste disposal	Waste co-processing in kilns	Reduces landfill	Technology upgrade	Various players
Water Management	High water use	Dry-process with ZLD (Zero Liquid Discharge), enabling >90% reuse	Reduces freshwater consumption and water pollution	Expensive ZLD technology	Various players
Carbon Capture and Storage (CCS)	No CO_2 capture	CCS pilots to capture & store CO_2	Large-scale emission cuts	High investment & energy intensive	Heidelberg, Holcim, etc

Innovations Driving Change

The cement industry is moving from traditional resource-heavy practices to smarter and cleaner innovations. From digital tools to carbon capture projects, companies are proving cement can be both durable and sustainable.

The table given below highlights this transformation.

Attributes	Innovations/ Technologies	Some Examples (Company/ Project)	Key Benefits
Low-Carbon Cement	ReAct (ReCarb Technology)	Fortera – ReCarb Plant, Redding (California)	Captures industrial CO_2- forms vaterite; lower kiln temperatures; ISO 9001:2015 certified; 15,000 t/yr capacity
	Red Mud-based Cement	Green360 Technologies (Australia) with PERMAcast JV	Uses aluminium industry waste; reduces clinker by 30%; circular economy solution
	Sublime Cement (Electrochemical process)	Sublime Systems (Somerville, USA) & Commercial Plant (Holyoke, USA)	Near-zero emissions; avoids limestone calcination; room-temperature operation
	Clinker-Free Cement	Hoffmann Green Cement (France – H-UKR), Material Evolution (UK – MevoCem)	Eliminates clinker; alkali-activated; certified under ATEx, ASTM, BSI Flex 350 standards
	Other alternatives (geopolymers, biochar, CO_2-storing concrete)	Holcim, CarbiCrete, Japan & Switzerland R&D	Reduces waste; stores CO_2 in concrete; supports greener construction
Carbon Capture and	Brevik CCS Project (400,000 t CO_2/yr)	Heidelberg Materials (Norcem Plant, Norway)	World's first large-scale CCS in cement; part of Longship initiative

Attributes	Innovations/ Technologies	Some Examples (Company/ Project)	Key Benefits
storage	OLYMPUS Project	Holcim (Milaki Plant, Greece)	Near-zero cement (2 Mt/yr cement production by 2029); supported by EU Innovation Fund
	Peak Cluster	UK consortium (cement & lime plants)	Captures & pipes CO_2 to Irish Sea storage; backed by UK's National Wealth Fund
	Seabound Onboard CCS	Seabound + Heidelberg Materials + partners	From cement carriers CO_2 emissions are captured by carbon capture technology that converts the CO_2 into limestone onboard the carrier
Carbon Capture and Utilisation	Hydrothermal CO_2 processing	U.S. & UK innovators	Converts CO_2 into insulation materials
	Injecting captured CO_2 into concrete	CarbonCure Technologies and Solidia technologies	Lower carbon footprint, maintains strength, cost-effective, permanent CO_2 storage
	Cement-free concrete blocks	CarbiCrete	Absorbs CO_2 during curing process; carbon-negative building materials
Technological Advancements	Carbon-negative cement	RockFuel	Closed-loop kiln; converts CO_2 into solid carbon & oxygen
	Electric arc calciner	SaltX + Holcim + Fuelre4m	Electrifies clinker production; avoids fossil fuels
Digitalisation & Automation	AI for mix design & optimization	Converge (UK), Carbon Re, Meta (AI tool)	Optimizes input materials; lowers emissions; faster curing
Green Hydrogen	Hydrogen integration in kilns	Cementos Molins (Spain), TKIL (India), Holcim, CEMEX, OMV (Austria)	Replaces fossil fuel; supports net-zero targets
AF & Circular Economy	Plastic-to-fuel for kilns	Shree Cement + Rajasthan PCB; Holcim (Plastics2Olefins)	Waste-to-fuel; reduces CO_2 & plastic pollution
RE and BSS (Battery Storage System)	Thermal storage, hybrid solar-wind, green loans	SiBox (Australia), Adani, Ultratech, Taiwan Cement, NTPC, SAEL, HyperStrong & Repono (EU) BSS - Cummins India	Decarbonizes industrial heat; renewable integration
Green Logistics & Supply Chain	EV fleets, green methanol ships	Indian cement players (EVs), Climeon (Canada)	Reduces logistics related CO_2 emissions

<u>Government Support</u>

Globally, various governments are formulating strategies and providing initiatives aimed at achieving their country's net zero target in the cement industry. Some key schemes and initiatives supporting this transition are highlighted in below:

Countries	COP28 Net Zero Goal	Key Government Schemes/ Initiatives
India	Net zero by 2070	DST's (Department of Science and Technology) National Mission on Transformative Mobility & Battery Storage (funding CCU pilots)
		Perform, Achieve and Trade (PAT) Scheme for energy efficiency in cement plants
		Support for LC3 low carbon cement tech at IIT Delhi
		Green Hydrogen Policy promoting green hydrogen in heavy industries

Countries	COP28 Net Zero Goal	Key Government Schemes/ Initiatives
United States	Net zero by 2050	DOE (Department of Energy) Industrial Decarbonisation Programs funding CCS and low carbon cement pilot projects
		Infrastructure Investment and Jobs Act supporting clean energy and hydrogen hubs
		Investment Tax Credit (ITC) and Clean Energy Incentives
United Kingdom	Net zero by 2050 (68% cut by 2030)	Innovate UK Net Zero Innovation Portfolio funding low carbon cement projects
		Industrial Energy Transformation Fund (IETF) for energy efficiency
		Hydrogen Strategy encouraging green hydrogen in industry
Norway	Net zero by 2050 (55% cut by 2030)	Longship CCS Project government funded CCS demonstration
		Norwegian Hydrogen Strategy for green hydrogen in heavy industries
		Incentives for renewable energy adoption
Thailand	Carbon neutrality by 2050; net zero by 2065	Energy Efficiency Improvement and Cleaner Production (EEP) Programme
		Partial funding for low carbon cement and concrete pilot projects
		National Green Hydrogen Roadmap (under development)
Ireland	Net zero by 2050	Enterprise Ireland Climate Action Fund for sustainable cement material pilots
		Climate Action Plan incentives for electrification and renewable energy
		Early-stage support for green hydrogen pilot projects
Canada	Net zero by 2050	Clean Fuel Standard promoting low carbon fuel use
		Net Zero Accelerator Fund grants for CCUS and hydrogen pilot projects
		Support for clean electricity grid and energy integration
France / EU	Climate neutrality by 2050; 55% cut by 2030	EU Innovation Fund co-funding low carbon cement and CCS projects
		Fit for 55 Package – objective to reduce GHG emission by at least 55% by 2030. Package includes carbon pricing, clean energy & hydrogen scaling incentives, promote cleaner transportation, etc
		French EcoCem ACT subsidy for low carbon cement scaling

In addition to the above efforts, governments in various countries are working to develop clear standards and framework for low-carbon and non-clinker cementitious material. These endeavours are likely to provide regulatory clarity & compliance, enhance industry efforts and support the broader adoption of sustainable alternatives.

<u>Road Ahead (particularly for developing countries)</u>

Some major technological improvements in the cement sector require high CAPEX (capital expenditure), hence, developments should be carried out in well-thought-out phases. A phase-by-phase execution ensures a smooth fit of new technologies, like waste heat recovery plants, alternative fuel co-processing, or carbon capture units, without unnecessarily hampering regular plant operations. This facilitates improved financial planning, skill acquisition and risk handling in each stage of implementation. Also, it gives cement businesses the ability to evaluate the expected plant performance and environmental gains prior to making significant investment. This is particularly vital when adopting innovative sustainability technologies such as Carbon Capture, Utilization and Storage (CCUS) or going to green hydrogen and renewables.

Developed nations including the United States, United Kingdom and Germany are technologically advanced with high GDP growth underpinned by them and better placed to enable such capital-driven shifts. Their governments tend to offer financial support/incentives, carbon credit schemes and policy assistance to drive green innovation in the cement industry. Besides, well-developed financial systems and ESG-linked investment streams also make cement manufacturers in these countries more adept in embracing sustainable operations on a large scale. Meanwhile, developing nations are gradually marching towards the integration of such technologies with support of their respective governments.

The following phased roadmap is designed for existing plants that can upgrade or modify their operations through technological upgradation. For new cement plants, companies could combine phase 1 and 2 (enumerated below) to minimize subsequent additional CAPEX. Plants built with modern technology may initially find an increase in their CAPEX outlay, but this approach ensures that all upcoming new cement plants are future ready to meet the challenges of going-green. Incorporating modern technologies and digitization during plant construction phase minimizes the need for later upgradation and reduces future capital expenses.

Phase 1: Quick Wins Through Technological Upgradation

In the short term, cement plants could focus on retrofitting existing facilities with proven technologies that enhance efficiency, cut production cost and reduce CO_2 emissions. These are low-hanging fruits aimed at reducing OPEX (operational expenditure) and emissions at the same time.

1) Use of **electric vehicles** (trucks, etc) to transport limestone from mines to cement plants, if a conveyor belt is not installed.
2) Replacing ball mills with **vertical raw mills (VRMs)** or **Roller Press** for both raw material and clinker grinding.
3) Upgrade to **6-stage preheater** to reduce the burden on the kiln.
4) Improve **kiln control systems and automation** to reduce energy fluctuations and downtime. Also, use advanced combustion systems for better fuel efficiency.
5) Upgrade to IE3/IE4 motors, variable frequency drives (VFDs) and optimized fans to improve energy efficiency.
6) Process biomass, plastic waste and RDF to use as **alternative fuel**.
7) Integrate **WHRs** into the plant to reduce electricity cost.
8) Source **solar/wind/hydro power** to reduce dependency on fossil fuel to meet energy requirement.
9) Produce **low-carbon cement** to the extend possible, depending upon availability of local SCMs and shifting market demand/construction practices.

The combined implementation of the technologies & measures in cement plants can typically reduce CO_2 emission by approximately 15% to 30%. The exact percentage will depend on plant condition and the scale of implementation.

Phase 2: Digitalization & System Efficiency

1) Artificial Intelligence: Integrate **AI tools** that analyses real time data to optimize raw mix design, fuel usage and kiln performance.
2) IoT sensors: Install **IoT sensors** in raw mill, kiln, cooler, AF system, etc. They continuously monitor key emission parameters across the plant, allowing early detection of inefficiencies and enabling timely corrective actions that reduce downtime and improves process efficiency.
3) **Digital twins**: A digital twin in a cement plant is a virtual model of the complete production system created with real-time data, IoT sensors and advanced analytics. It enables operators to monitor operations, identify inefficiencies and test various scenarios without interrupting actual production. This technology improves decision-making, reduces downtime and enhances safety, making it essential for operational excellence and sustainable performance.

4) **Blockchain and Supply Chain Digitization**: It provides secure, transparent and real-time tracking of input and output materials, enhancing traceability, reducing inefficient practices and improving efficiency throughout the supply chain.
5) Sustainability monitoring and controlling: **Carbon accounting tools** help track and quantify greenhouse gas emissions across all operations from raw material sourcing to product dispatch & delivery, enabling data-driven decision-making for emission reduction.

These technologies collectively enhance combustion control, reduce energy waste, promote higher AF usage and lowers clinker factor - leading to significantly cutting a cement plant's carbon footprint. Monitoring and controlling CO_2 emission enables cement plants for third-party certifications like Environmental Product Declarations (EPDs), Green Labels and Carbon-Neutral certifications which enable transparency, stakeholder trust and market access - offering both environmental responsibility and a competitive advantage in the low-carbon economy.

Phase 3: Deep Decarbonization Pathways

1) **Electric Kilns**: Instead of calcining limestone using fossil fuel, cement plants will start using electric arc calciner. In case electricity is also generated by renewable energy sources, the calcination process can become emission-free. For e.g. Holcim invested in SaltX Technology and became a strategic shareholder to develop the world's first all-electric cement plant using renewable energy.

2) **Green Hydrogen**: Hydrogen produced from renewables is a clean fuel, emitting only water vapour; thereby can be used as fuel for energy-intensive clinker production. Although it requires high initial capital investment and faces infrastructure challenges - integrating green hydrogen supports deep decarbonization, aligns with net-zero targets and marks a significant technological advancement toward a low-carbon cement industry.

3) **Carbon Capture and Utilisation (CCU)**: This technology is used to capture CO_2 and transform it into fuel, additives and/or concrete. Examples include CarbonCure (Canada) and Solidia (USA). Though this technology is capital intensive, CCU adds value by reducing CO_2 emission in industries like the cement sector.

4) **Carbon Capture and Storage (CCS)**: CCS captures and securely stores CO_2 in aquifers or geological formations. Leading cement companies like Heidelberg Materials are already implementing full-scale CCS projects, such as the one in Brevik (Norway), while others are conducting pilot trials globally. Despite its high potential, CCS adoption currently faces CAPEX & OPEX challenges, apart from requiring extensive infrastructure.

Some of above technologies are still in their nascent stage and are yet to be commercialized – which will depend on their economic and financing viability - however, in the long run, they are likely to play a crucial role for the industry in achieving its net-zero goal.

Ongoing CCS/CCUS pilot projects in major countries are illustrated in the map.

Conclusion

The journey to a sustainable cement industry is both challenging and inspiring. Cement is at the heart of our infrastructure, yet its environmental impact must be minimised. As this article explores, the good news is that change is already underway. From using alternative fuels and renewable energy to adopting smart technologies and low-carbon materials, the industry is actively rethinking how cement is made - this transition won't happen overnight. It requires collaboration, investment and a willingness to try new approaches even when the path isn't fully clear. We need to scale up promising technologies, retrofit existing plants and create policies that support long-term sustainability.

At the end of the day, it's about building not just structures, but a future we can all be proud of, where growth and responsibility go hand-in-hand. As we stay committed, the cement industry can likely become a cornerstone of the low-carbon world we all aspire to live in.

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