PRIED
Policy Research Institute
for Equitable Development

DECARBONIZING CEMENT PRODUCTION

EXPLORING PATHWAYS TO NET-ZERO IN PAKISTAN

APRIL, 2024

DECARBONIZING CEMENT PRODUCTION

EXPLORING PATHWAYS TO NET-ZERO IN PAKISTAN

APRIL 2024

Project Team

Prof. Dr. Muhammad Fahim Khokhar

A Tenured Professor at SCEE(IESE) NUST, Islamabad. He holds a Doctoral degree from Germany and three post-doctorates from Germany and France. Specializing in satellite remote sensing, air quality monitoring, South Asian smog, climate change adaptation and mitigation. He has contributed to European research projects like NOVAAC, GEMS and MACC under 5th and 6th Framework of EC. He is a member of Pakistan's Climate Change Council and leads C-CARGO research group, focusing on atmospheric composition research in Pakistan. He has secured various research grants from IUCN, DoS, ICIMOD and received the SCEE-Best Researcher and innovator award for 2020 and 2021. His work is published in prestigious journals such as Nature, Atmospheric Environment, Environmental Pollution etc.

Dr. Mujtaba Hassan Agha

A Senior Lecturer at Cardiff School of Management (Cardiff Metropolitan University, UK) holds a PhD in Energy Supply Chains from INPT-ENSIACET, France, and is a Certified Supply Chain Professional (CSCP) from ASCM, USA. With a history of successful consultancy projects, he has collaborated with prestigious organizations like the UNODC, World Bank, Pakistan Railways, PTCL, and various SMEs in Pakistan. Previously, he served as Professor and Head of Operations and Supply Chain Department at NUST Business School, Pakistan.

Unib Arshad Lodhi

An Environmental scientist with specialization in Climate change and industrial decarbonization, holds a Master's degree in Environmental Sciences from IESE-NUST. Currently, he serves as a dedicated Research Associate at ES³, leveraging his profound expertise in decarbonization. Unib's impactful research includes a study on decarbonizing the Cement Industry in Pakistan under PRIED. Prior to this, he held a prestigious role as a Senior Environmentalist at Entertech Group of Companies, where he spearheaded impactful projects on both local and international fronts.

Qurrat-ul-Ain

Qurrat-ul-Ain is a dedicated Research Associate at PRIED, specializing in climate change and renewable energy. Holding a post-graduate degree in Environmental Sciences from IESE, NUST, Islamabad. Her extensive experience includes collaborating on projects with the Environmental Protection Department (EPD) Punjab, the World Bank, SDPI and RDPI, reflecting her versatility and expertise in the field of sustainable solutions to environmental issues.

Izaz Rashid

Izaz Rashid is a supply chain professional with Masters in Supply Chain Managment from NBS. He is a dedicated researcher and serving as a Research Associate at ES³. With profound expertise in supply chain management Izaz has conducted a research on decarbonizing with focus on supply chain viability of Cement Industry of Pakistan under PRIED.

Muhammad Mustafa Amjad

An energy and climate change specialist, currently working as the Director Programs for Renewables First, an energy transition and environment think tank based in Pakistan. A Mechanical Engineering graduate from University of Massachusetts, Amherst with a specialization in Renewable Energy and Policy, Mustafa and his organization, has been actively involved and recognized in the transition towards a greener future for Pakistan through extensive research, advocacy and partnership building. He is also currently co-chair at Pakistan Renewable Energy Coalition.

About Us

Environmental Services & Sustainable Solutions (Pvt.) Ltd (ES³) is a consultancy firm based in Islamabad, founded in 2022 as a NUST spinoff. Partnered with the National University of Sciences and Technology, ES³ specializes in high-quality, tailored environmental consultancy services. Our dynamic team of qualified professionals excels in environmental engineering, research, assessment, survey, management, planning, and monitoring. We provide innovative, sustainable, and cost-effective solutions for environmental challenges in domestic, commercial, and industrial sectors.

Policy Research Institute for Equitable Development (PRIED) is a think-tank committed to sustainable and equitable development and a low carbon future. We produce high quality research to partake in and promote a global discourse on transition to renewable sources of energy; institutionalize interaction between all energy sector stakeholders in Pakistan; provide regulatory input, policy critique and research support to the parliament, government departments, aid organizations and international financial institutions; and organize events for networking and information-sharing.

The National University of Sciences and Technology (NUST), established in 1991 in Islamabad, is a premier institution in Pakistan known for its focus on science, technology, and innovation. It offers a wide range of undergraduate, graduate, and doctoral programs across various disciplines. NUST is recognized for its cutting-edge research, strong industry linkages, and commitment to excellence in education, making it a leader in fostering scientific and technological advancement in Pakistan.

Disclaimer

Published by ES³ and PRIED, Islamabad. The opinions expressed are those of the authors and referenced stakeholders and do not constitute an endorsement by ES³ or PRIED.

Attribution

Please cite this work as follows:

Khokhar, M. F., Lodhi, U. A., Agha, M. H., Qurrat-ul-Ain, Rashid, I., & Amjad, M. M. (2024). Decarbonizing the cement production: Exploring pathways to NET-zero in Pakistan. Environmental Services & Sustainable Solutions (ES3), Policy Research Institute for Equitable Development (PRIED), and National University of Sciences and Technology (NUST).

ACKNOWLEDGMENTS

We extend our sincere appreciation to an esteemed constellation of contributors who have illuminated our path with their expertise and collaboration. We extend our heartfelt gratitude to Bestway Cement, Fecto Cement, Askari Cement, Fauji Cement, DG Cement, and Power Cement for their unwavering support and invaluable insights. Additionally, we express our gratitude to Sustainable Development Policy Institute (SDPI) for their pivotal role in fostering dialogue and conducting consultations vital to our study's foundation.

We are deeply thankful to Pakistan Environmental Protection Agency (EPA), Ministry of Climate Change and Environmental Coordination, and the All Pakistan Cement Manufacturers Association (APCMA) for their continuous support and commitment to environmental sustainability. Moreover, we acknowledge the pivotal contributions of individuals and organizations who enriched our discourse and deliberations, including Mr. Irfan Sheikh and Mr. Farrukh Ahmed of Bestway Cement, Mr. Ahsan Anis of Power Cement, and Mr. Samiullah and Engr. Naveed Ashraf Cheema of Fauji Cement.

The Network for Clean Energy Transition (NCET) in Pakistan, spearheaded by SDPI, provided invaluable insights through extensive stakeholder consultations, shaping our study's discourse profoundly. We are indebted to Mr. Muhammad Alamgir Chaudhry of National Productivity Organization (NPO), Dr. Sardar Mohazzam of National Energy Efficiency and Conservation Authority (NEECA), and the diligent efforts of Dr. Kajol, Mr. Deepak Sriram Krishnan, and Mr. Sunil Dahiya from World Resources Institute (WRI) and Centre for Research on Energy and Clean Air (CREA).

Additionally, we extend our gratitude to Pakistan Renewable Energy Coalition, and Renewables First for their invaluable contributions.

Foreward

When we were planning to carry out a research study on the decarbonization of cement industry, we were not really sure if it was a good idea most people in our organization, Policy Research Institute for Equitable Development (PRIED) were on the view that cement industry is hard-to-abate sector of the economy to decarbonize. The reason given were obvious, finally the technology is used in this industry traditionally on high heat energy sources such as natural gas and coal and shifting it to low heat energy sources such as biomass, crop residue is not an economically feasible option. Wind and solar, too, are not deemed feasible because of their intermittent nature. They are not available all the time and at all the places. Secondly, the cement industry does not seen to have any compulsion itself because it's exports do not go to countries and regions which are conscious of carbon emissions and are finalizing it so carbon taxation. Lastly, the cement industry is slow to be owned, mostly if not certainly, by some of Pakistan's largest and also most influential, businesses group as well as the military own businesses entities. So, the argument went, being able to convince these businesses to share infrastructure about their work, let alone decarbonize it, would be impossible.

Some of us however persisted in the face of such argument and called for going ahead with a research study. The most important point raised in this connection was the rather large carbon footprint of the cement industry. Pakistan cannot achieve the commitment it has made under the Paris Agreement to reduce carbon emission if one of the largest industry and largest emitters of carbon does not contribute to this reduction.

They somehow managed to convince others and that is how the work on the study could start.

I am happy to report here that this indeed was a right decision.

Most importantly it show to us that the cement industry is neither secretive about its operation nor its adamant on containing with high carbon emitting fuels provided the availability and viability of other fuels once our research team was able to established its sincerity of purpose and intellectual integrity representative of the industry fully cooperated with them in assessing and analyzing their production process. It was also great to know that same cement plant were already experimenting with alternative fuels and that too without any compulsions from their customers.

These encouraging but admitted small initiatives do not mean that all is well with the cement industry. Far from it, it remains one of the largest consumers of fossil fuels that one deemed to be among the highest sources of carbon in the atmosphere. They also insist to carry on with the old practices as long as strong economic and scientific case is not made for their energy transition.

That is exactly what this study does. I will not go into its details and let it speak for itself. But suffices it to say that it is worth all the money and efforts spent on it and it also illuminates a scientific pathway for decreasing the carbon footprint of the cement industry in Pakistan.

I therefore, sincerely hope that the industry and the government benefits from its findings and recommendations.

Otherwise, it might not be possible for Pakistan to fulfill the Paris Agreement commitment to contribute to limiting global warming to 1.5°C by 2050.

Muhammad Badar Alam
Chief Exective Officer (CEO)
Policy Research Institute for Equitable Development (PRIED)

Contents

List of Figures

List of Tables

Abbreviations & Acronyms

AFs	Alternative Fuels
APCMA	All-Pakistan Cement Manufacturers Association
ASR	Automobile shredder residue
BYF or BCSA	Belite-Ye'elimite-Ferrite Cement
C&IW	Commercial and Industrial Waste
C3AH6	Tricalcium Aluminate Hexahydrate
CA	Monocalcium Aluminate
CAC	Calcium Aluminous Cement
CaO	Calcium Oxide
CBAM	Carbon Border Adjustment Mechanism
CCSC	Carbonate Calcium Silicate Cement
CCUS	Carbon Capture, Utilization, and Storage
CDW	Construction and Demolition Waste
CO2e	Carbon dioxide equivalent
CPEC	China Pakistan Economic Corridor
CS	Calcium Sulfate
CSA	Calcium Sulfoaluminate Cement
C–S–H	Calcium Silicate Hydrate
Al2O3	Aluminum Oxide
CSI	Cement Sustainability Initiative
DS	Degrees Celsius
ECRA	European Cement Research Academy
ETS	Emissions Trading System
EU	European Union's
FED	Federal Excise Duty
GBFS	Granulated Blast Furnace Slag
GDP	Gross domestic product
GHG	Global Greenhouse Gas
GJ	Giga Joule
GoP	Government of Pakistan
IEA	International Energy Agency
IFC	International Finance Corporation
IFC	International Finance Corporation
Kg	Kilogram
Kwh	kilowatt-hour
MACCs	Marginal Abatement Cost Curves

MENAP	Middle East, North Africa, Afghanistan, and Pakistan
MgO	Magnesium Oxide
MMT	Million Metric Tonnes
MOMS	Magnesium Oxides Derived from Magnesium Silicates
MSW	Municipal solid waste
MT	Million Ton
MW	Megawatt
NHA	National Highway Authority
NPV	Net Present Value
OPC	Ordinary Portland Cement
ORC	Organic Rankine Cycle
PSDP	Public Sector Development Program
RDF	Refuse-derived Fuel
ROI	Return on Investment
RTS	Reference Technology Scenario
SCMs	Supplementary Cementitious Materials
SiO_2	Silicon Dioxide
SRF	Solid Recovered Fuel
SSC	Supersulfated Cement
UK	United Kingdom
WBCSD	World Business Council for Sustainable Development
WHR	Waste Heat Recovery

Executive Summary

Cement production is integral to Pakistan's economic growth, contributing substantially to GDP and employment. However, as a carbon-intensive industry representing 7-8% of national emissions, cement also carries a heavy environmental footprint. This report analyses Pakistan's in-depth cement sector dynamics and lays a strategic roadmap for its decarbonization journey. The report examines critical facets shaping the industry, including plant locations, production and dispatch patterns, the predominant use of imported coal as fuel, and the link between infrastructure spending and cement demand. A significant portion of Pakistan's energy consumed is met through coal imports. Detailed calculations reveal the scale of direct and indirect CO_2 emissions from raw material calcination, fuel combustion, and electricity use. Additionally, the report extensively maps out available technologies and alternate fuels that can facilitate a transition to low-carbon cement production in Pakistan. The options explored range from boosting energy efficiency, waste heat recovery, alternate cement and raw materials, and biomass fuels to carbon capture mechanisms. A pivotal analysis involves the development of marginal abatement cost curves to identify cost-effective interventions. Utilizing agricultural residues such as rice husk, wheat straw, corn stover, and rice paddy as alternate fuels emerges as an economically viable option in Pakistan's agricultural context. Substantive emission reductions are feasible at low cost when combined with clinker substitution and energy efficiency measures. The report proposes a multi-pronged strategic framework encompassing policy, technology, capacity building, and financing for decarbonizing the industry. While challenges like entrenched coal dependency and limited investment exist, strategic efforts spanning stakeholder coordination, international collaboration, and flexible policy incentives can enable Pakistan's cement industry to transform green. In conclusion, this report offers an extensive analysis of Pakistan's cement landscape and provides a detailed roadmap for allowing the industry to reduce its carbon footprint substantially. By transitioning to sustainable practices, Pakistan can drive its cement sector to be globally competitive while spearheading climate change mitigation as a responsible global partner.

Chapter 1. Current State of Cement Industry

Cement is indispensable for modern infrastructure but accounts for 7% of global emissions, necessitating urgent decarbonization.

Global cement production has surged over 50% since 2010, with China's explosive growth. But emissions impacts underscore sustainability imperative.

As a top industrial emitter, cement is critical in emissions reduction policies like the EU's carbon border adjustment mechanism, which poses complex dynamics.

Though significant for Pakistan's economy, cement lags in per capita consumption versus regional peers, signaling growth potential.

Cement production capacity expansions were previously aligned with infrastructure investments, but the slowdown presents challenges.

Unlike global norms, Pakistan's plants rely heavily on imported coal, risking exposure to price and forex volatility.

Cement output closely correlates with public infrastructure spending, but recent cuts impacted production.

With cement vital for construction, Pakistan must balance industrial growth and emissions reduction via cleaner technologies.

Urgent adoption of energy efficiency, alternate fuels, and innovative practices can curb emissions amidst economic development.

A nuanced roadmap that considers costs, resources, and growth needs is essential for reducing cement emissions at scale.

Chapter 2. CO_2 Direct and Indirect Emissions

Cement production involves energy-intensive processes that result in high CO_2 emissions, necessitating decarbonization across the supply chain.

Scope 1 emissions from calcination and fuel combustion dominate cement's carbon footprint, increasing 687% from 1990 levels in Pakistan.

Indirect scope two emissions from electricity consumption have also risen markedly, reflecting the energy-intensive nature of cement production.

Though more minor, scope three emissions from transportation/logistics still contribute to cement's overall emissions profile.

Total emissions are projected to continue rising under business as usual, underscoring the urgent need for interventions to curb cement's carbon footprint.

Sustainable practices, including alternative fuels, energy efficiency, clinker substitution, and renewable power procurement, can help the cement industry achieve its net zero emissions goal.

Historical emissions growth provides vital context, while future projections indicate consequences of unrestrained industrial expansion absent decarbonization efforts.

Pakistan's cement industry must act decisively to adopt clean technologies and transform practices to address escalating emissions amidst economic development.

Chapter 3. Available Tech-Solutions and Alternatives

Multiple technologies like alternative fuels, electrification, alternative cement, and CCUS offer pathways to decarbonize cement production.

Switching to waste, biomass, and low-carbon fuels can significantly reduce emissions from cement kilns.

Cement kiln electrification aligned with clean power procurement is promising but requires technical advancements.

Innovative clinker substitutes like calcined clays, limestone, and slag can lower process emissions and clinker factor.

Novel cement chemistries like CSA, calcium sulfoaluminates, and MOMS show potential but necessitate performance validation.

Grinding, chemical activation, and thermal treatment can enhance the reactivity of supplementary materials for cement formulations.

Despite the promise, most technologies remain in a demonstration or early adoption phase, necessitating investments and policy support.

CCUS is vital to mitigate process emissions, but deployment is limited presently due to economic and technical barriers.

Pakistan's cement sector must urgently adopt clean technologies alongside efficiency improvements for substantial emissions reduction.

A nuanced roadmap that factors in economic viability and implementation challenges is critical to technology adoption at scale in a local context.

Pursuing a portfolio of solutions tailored to local resources and conditions can enable cement emissions reductions aligned with a net zero pathway.

Chapter 4. MAC Curves Identifiers

Marginal abatement cost curves (MACCs) graphically illustrate the relationship between the cost of reducing emissions and the number of emissions reduced by ranking different technological control options from least to most expensive per ton of CO_2 reduced.

Negative marginal abatement costs signify cost savings and emission reduction for the control option, whereas favorable costs indicate emissions reduction, incurring a net expense.

Among production technologies, significant CO_2 emission reductions with negative marginal abatement costs can be achieved by converting to Precalciner kilns and using alternate raw materials. Blended cements reduce emissions substantially but with a nominal favorable marginal cost.

For alternate fuels, rice paddy, rice husk, and wheat straw mixed with various coals offer the most significant CO_2 emission reduction potential with negative marginal costs. Abatement potential should be balanced with practical implementation challenges for a feasible clean technology roadmap.

Chapter 5. Case Study: Sustainable Solution for Cement Production in Pakistan

The reliance of Pakistan on imported coal for cement production stems from the lower quality of local coal.

To diminish this dependence, utilizing alternate fuels, a blend of locally available biomass and imported coal, in kilns presents a viable solution.

Given the sizeable agricultural output, cost-saving and emission reduction potential residues like rice husk, corn Stover, wheat straw, and rice paddies offer viable biofuel options. The utilization of these residues aligns with circular economy principles.

Rabi (wheat) and Kharif (rice, corn) crops can provide a year-round supply of alternate fuel, with Punjab and Sindh's agriculture base proving sufficient to meet the biomass requirements of cement plants.

Rice paddy is an excellent option as the current practice of open burning in fields causes environmental pollution, which can be tackled by controlled burning in cement kilns.

Locally produced Agro waste presents a promising opportunity for import substitution, cost savings, supply security, and emissions reduction.

Chapter: 6. Way Forward

Industry government collaboration through structured dialogues can enable more tailored and effective emissions reduction policies.

Bridging the industry-academia gap by strengthening partnerships can enhance innovation and ensure research addresses industry needs.

Widespread installation of indigenously developed CO_2 capture technologies like NUST's CO_2 Arrestors can tackle emissions directly.

Subsidies and low interest rates can encourage investments in green technologies and can ease the transition to renewables for industries.

Prioritizing high-reduction, low-cost solutions identified through MACCs ensures cost-effective emissions reduction.

Installing and upgrading waste heat recovery systems offers substantial energy efficiency gains and emission cuts.

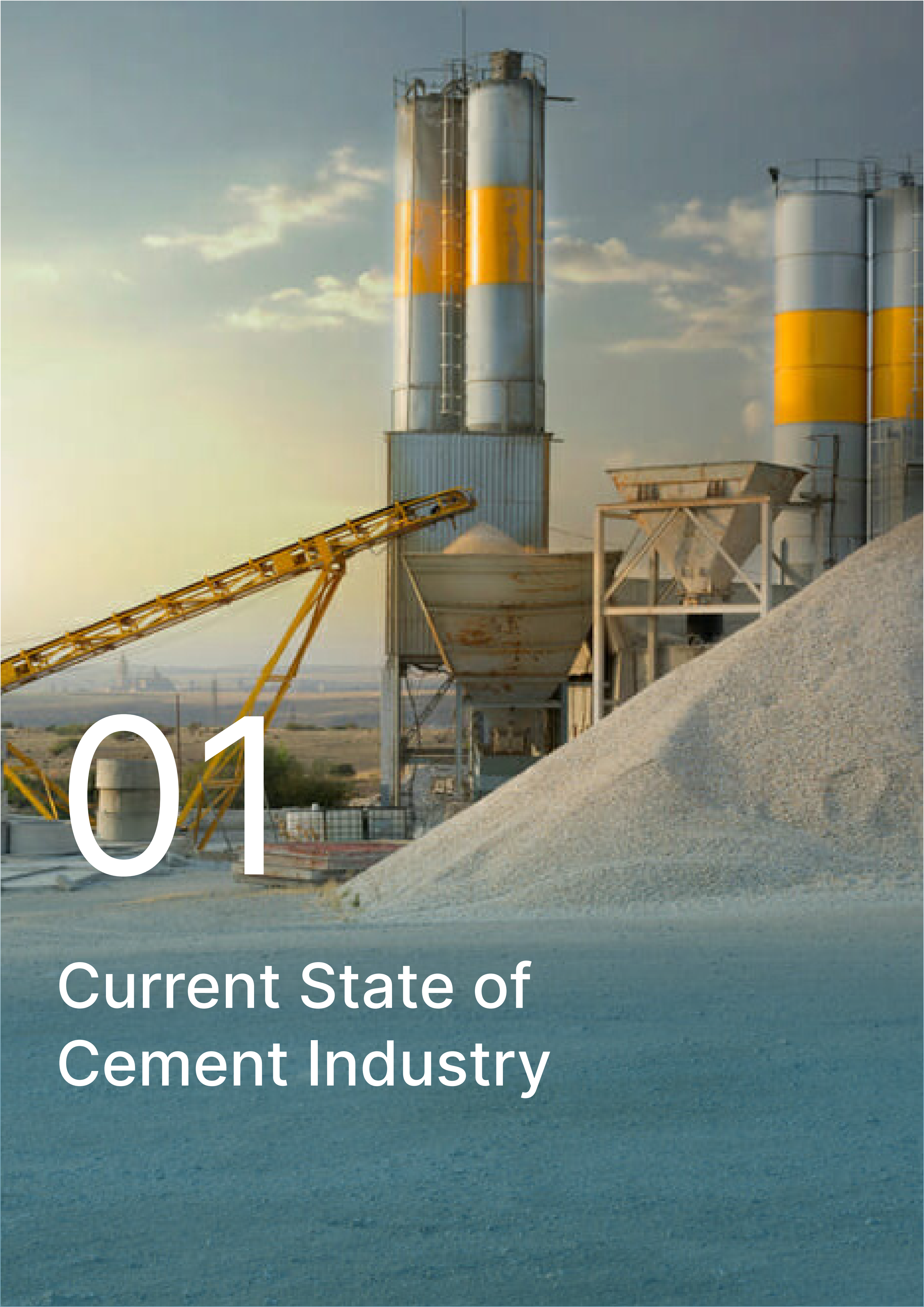
Transitioning towards alternate fuels (biowaste) can significantly reduce reliance on fossil fuels and associated emissions.

Enhanced carbon taxation with incentives for cleaner practices can discourage high emissions.

Tailored green financing and investment schemes, especially for SMEs, can facilitate sustainable transition.

Mandating national emissions standards with compliance timelines promotes environmental responsibility.

Public-private partnerships allow the pooling of expertise and resources for sustainability initiatives.



01

Current State of Cement Industry

Introduction

Human-induced global warming surpassed the 1ºC mark in 2017 compared to pre-industrialization levels and continues to escalate at a rate between 0.1 and 0.3 ºC per decade[1]. Numerous nations are committing to achieving net-zero emissions by 2050 or earlier, aiming to curtail the escalation of global temperatures to 1.5 ºC above pre-industrial levels. Failing to address climate change will result in global temperature surges exceeding 3-4 ºC by 2100. This scenario would lead to recurrent droughts, floods, and storms, impacting small and large businesses and incurring substantial annual costs on the global economy [2]. Concrete, often described as a synthetic rock, primarily comprises sand, gravel, water, and cement, serving as the foundational material for construction and playing a pivotal role in the rapidly industrializing and urbanizing world. Its versatile application spans various domains, including power systems, water and wastewater infrastructure, buildings ranging from single-story dwellings to towering high-rise structures, and transportation infrastructure. Cement, a vital constituent in concrete and mortar, forms the backbone of these widely used construction materials within the built environment[3]. More than 150 countries all over the world produce cement. However, cement production is energy-intensive and accounts for approximately 7% of global carbon dioxide emissions, significantly contributing to climate change. Scientists and governments have called for increasingly stringent greenhouse gas (GHG) emissions targets as climate change's consequences become more apparent. Thus, decarbonizing the cement sector supply chain is crucial to achieving global climate goals [2].

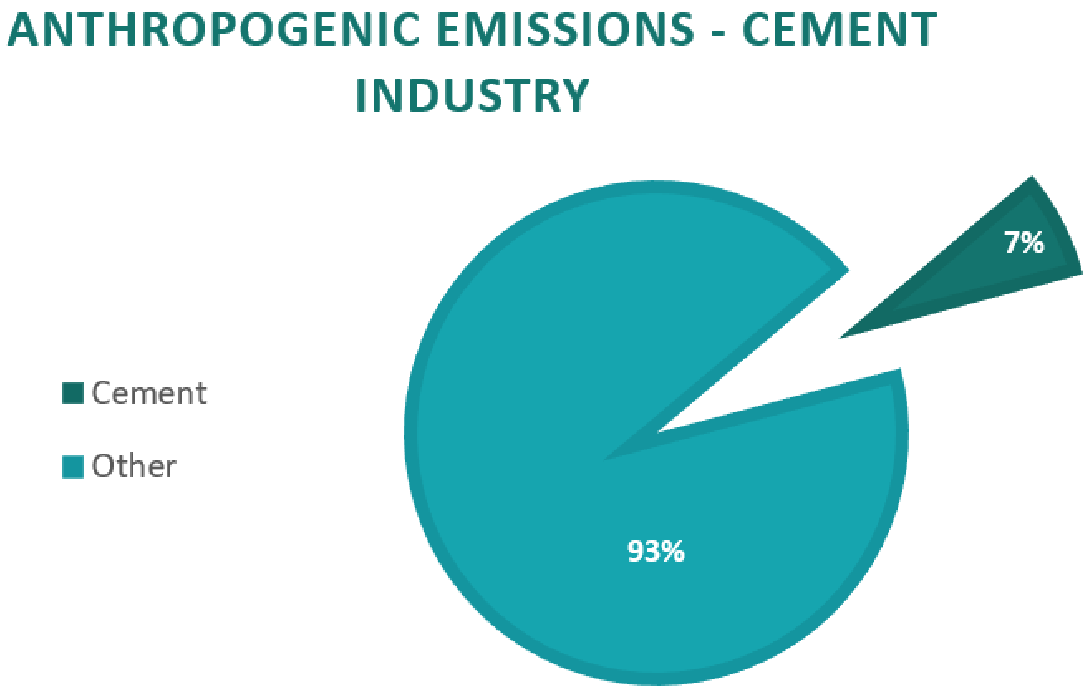


Figure 1: Global anthropogenic emissions from the cement industry.

Global Cement Industry

Cement Industry and Its Impact

The primary sectors contributing to carbon emissions encompass industry, power generation, buildings, and transportation, exerting a substantial influence on carbon emissions affecting our environment [4]. The power generation sector is the most prominent contributor to carbon emissions, with the industrial sector being the second major contributor [5]. Specific industries within the industrial sector, such as cement, steel, and chemicals, play significant roles in generating carbon emissions [4]. Cement and concrete, fundamental building materials, constitute modern society's infrastructure. Their widespread use in construction can be attributed to their abundant availability, ease of use, resilience, and versatility, making them the preferred choice for builders worldwide. Moreover, nowadays, there is a two-faceted demand for infrastructure development [6] to rehabilitate deteriorating infrastructure and [7] to construct new infrastructure in response to evolving urbanization trends. This dual dynamic mirrors the ever-evolving landscape of global urban development [6]. There has been a noticeable surge in the production of common infrastructure materials to meet the increased demands, with cement being a prominent example. This rise has kept pace with population growth and outstripped the production of all other infrastructure materials [5], [7], [8], [9].

Cement production has risen remarkably, from 1.5 billion tonnes in 1998 to 4.5 billion tonnes in 2023. A defining feature of recent cement production history is the explosive growth experienced in China. In 1999, China accounted for 36% of the world's cement production, but this share had skyrocketed by 2019 to an impressive 55%, equating to a staggering 2.3 billion tonnes of global cement production. See Figure 2. In contrast, the European Union's (EU) share of global cement production has declined, from 10% in 1999 to a reduced 5% in 2019. It is noteworthy that the impact of the COVID crisis and the geopolitical tensions on Europe's eastern borders over the past two years, while still in the early stages of comprehensive assessment, is anticipated to have negligible effects on global cement production. Global cement production is expected to resume its growth trajectory based on the figures observed in 2019 [10].

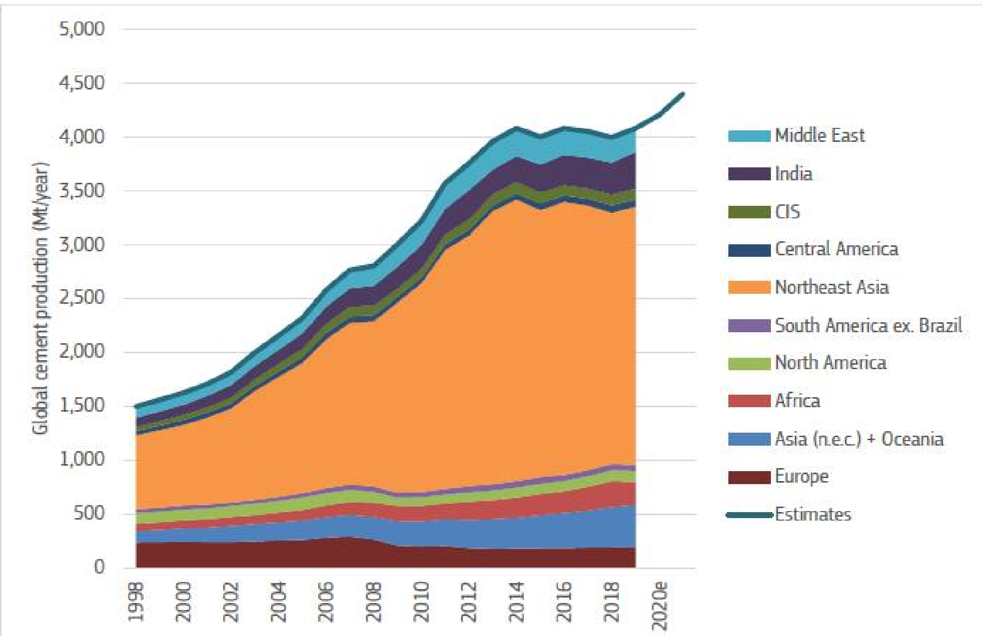


Figure 2: Global cement production for the period of 1998 – 2020 [103]

The significance of cement in shaping modern industrialized society cannot be overstated. It is one of the cornerstone materials for construction and development, with its production scale measured in billions of tonnes. However, it's imperative to acknowledge that these materials come with an environmental cost. In 2019, it was estimated that CO_2 emissions throughout their entire life cycle, encompassing production, transportation, usage, and eventual demolition, accounted for approximately 10% of global energy-related CO_2 emissions. These energy-related emissions encapsulate fuel combustion, power consumption, and carbonate decomposition, highlighting the pressing need for sustainable innovations in the construction industry to mitigate their environmental impact [11].

Approximately one-quarter of global greenhouse gas (GHG) emissions can be directly attributed to the production of materials [12]. The cement industry holds a critical position in the global carbon emissions landscape, and a substantial portion of these emissions is attributed to the top 10 cement-producing countries [13]. China, the leading global cement producer and consumer, has observed a remarkable upsurge in cement production and the ensuing emissions. Between 1990 and 2015, there was a significant rise in CO_2, SO_2, and NOx emissions from China's cement industry. Intriguingly, CO, PM2.5, and PM10 emissions declined[14]. Cement accounts for approximately 10% of the overall volume of global concrete production. This underscores the considerable environmental impact of cement production within the broader context of greenhouse gas emissions [15].

Global Policy Context

In the global context of climate policy, the European Union (EU) has introduced a comprehensive framework to achieve climate neutrality. This policy impacts various sectors, including energy-intensive industries such as cement production. The EU's efforts align with global ambitions to combat climate change and include targets for significant emissions reductions, a legislative framework to support sustainable practices, strategies to accelerate the green transition of industries, and research and development initiatives to promote low-carbon technologies. Furthermore, the EU's commitment to the EU Emissions Trading System (ETS) underscores its dedication to carbon pricing and emissions reduction in line with broader international discussions on carbon pricing. The policies enacted by the EU contribute to the global effort to mitigate climate change and transition to a more sustainable and environmentally responsible global economy.

The EU's Carbon Border Adjustment Mechanism (CBAM)

A Carbon Tariff, or a Carbon Border Adjustment Mechanism (CBAM), is a financial measure levied on imports based on their carbon emissions during production. Its primary aim is to discourage carbon emissions and level the playing field between countries with strict climate regulations and those without, thus promoting global decarbonization efforts. Carbon tariffs deter carbon emissions by imposing a duty on carbon-intensive imports, influencing production and exports. These tariffs are seen as a tool to ensure fair trade and competitiveness between countries with stringent climate policies and those with lax or no such regulations.[15], [16], [17] Carbon tariffs might be proposed or advocated by industrialized countries towards imports from developing countries, triggering international debates on their fairness and implications [18] The EU's proposed CBAM would initially apply to specific sectors, including cement, iron and steel, aluminum, fertilizers, and electricity. CBAM was introduced with a probationary period starting October 1, 2023 requiring importers to collect and report emissions data for these products. The enforcement phase begins in 2026, with full coverage and higher costs expected by 2034. This could generate over US$80 billion annually for the EU[19].

The CBAM will operate similarly to the EU's current Emissions Trading System (ETS), utilizing certificates. Importers will need the authorization to import carbon-intensive goods covered by the CBAM and trade CBAM certificates to account for emissions, with allowances priced according to weekly auctions of EU ETS credits. Importers will only pay the tariff if there isn't already a carbon price in the country of origin; otherwise, they'll be charged the price difference[19]. While aiming to extend decarbonization efforts beyond Europe and ensure fair trade, the CBAM has sparked controversies regarding the need for more differentiation based on the country of origin. Critics argue that underdeveloped nations might not be prepared for the exact requirements of traders from leading markets, necessitating a careful analysis during the probationary period to understand and address the implications[19].

The EU has been at the forefront of the CBAM introduction under its Green Deal, aiming to tackle climate change, emissions, pollution, and biodiversity loss. This step signifies a substantial move towards global climate regulation, setting a precedent that other regions might follow [19]. These aspects highlight the multifaceted nature of carbon tariffs, encompassing economic, environmental, and geopolitical dimensions. Through mechanisms like the CBAM, regions aim to balance economic competitiveness with the urgent need for global carbon emissions reduction, albeit amidst international debates and operational challenges[19].

CBAM challenges and opportunities for Pakistan

Carbon pricing mechanisms, such as carbon taxes or emissions trading schemes, present challenges and opportunities for Pakistan to address climate change impacts while fostering sustainable economic development. Pakistan has witnessed a steady rise in greenhouse gas (GHG) emissions in recent decades. Since 1990, the country's GHG emissions have surged over 160% - a figure below the 175% average increase among Middle East, North Africa, Afghanistan, and Pakistan (MENAP) nations but substantially exceeds the global average of 50%. This stark contrast underscores the imperative for Pakistan to adopt effective carbon mitigation strategies to curb its escalating emission levels. The preliminary analysis emphasizes the dual potential of carbon pricing in Pakistan, highlighting its revenue generation capacity and emissions reduction. Robust carbon tax implementation could yield an annual contribution to the nation's GDP ranging from 1.2% to 2.7%, concurrently delivering environmental advantages. Insights from the World Bank suggest that adopting such a carbon pricing strategy can curtail Pakistan's emissions substantially, projecting a reduction of up to one-third by the year 2050. Initial estimations propose that a $25 per ton carbon tax could generate over 1% of Pakistan's GDP annually, earmarked for financing the country's transition towards a greener economy. Nevertheless, the success of this approach necessitates complementary measures, including targeted assistance for groups disproportionately affected. More precise revenue projections are imperative to refine policy formulation and gather broader support.

Introducing a carbon tax or trading scheme could play a pivotal role in realizing this ambitious emissions reduction goal. Beyond serving as a deterrent or revenue source, carbon pricing can also catalyze private-sector businesses to adopt more sustainable practices. By attaching a defined cost to carbon emissions, carbon pricing may motivate companies to opt for renewable energy, improve energy efficiency [20], and invest in low-carbon technologies that reduce their overall emissions footprint. While carbon pricing holds clear advantages, Pakistan's journey towards successful policy implementation faces some looming challenges. Past efforts in 2013 and 2017 to introduce carbon pricing mechanisms met bureaucratic resistance, hinting at potential hurdles ahead.

Moreover, Pakistan's economic landscape presents unique complexities surrounding carbon pricing. The economy's heavy reliance on imported fossil fuels, the power sector's substantial carbon emissions, and the nationally owned oil, gas, and transport sectors all demand additional considerations. A nuanced approach is required to analyze global best practices while considering those grounded in Pakistan's distinct socioeconomic realities. Broad-based carbon taxes could prove more effective than narrow sectoral interventions. Establishing robust monitoring, reporting, and verification systems will be essential to gauge any impact of carbon pricing policies accurately. Additionally, forging partnerships with international entities can provide Pakistan with critical financial and knowledge-based resources to support successful carbon pricing implementation. Pakistan faces potential pressure from significant trading partners like the EU and UK to introduce carbon pricing, as they consider border carbon adjustments on imports from countries without explicit carbon prices. However, Pakistan needs more consensus on the competitiveness and leakage risks of unilaterally implementing carbon pricing. While carbon border fees could incentivize Pakistan to adopt carbon taxes, they may also risk retaliation due to the absence of careful policy design and dialogue.

In addition to domestic carbon taxes and trading schemes, Pakistan has opportunities to engage internationally through carbon market collaboration. In January 2025, China is set to launch the world's most extensive national carbon emissions trading program. Carbon markets spur investment into emissions-reducing projects and facilitate capital flows from developed to developing nations. However, many countries have struggled to realize their full potential, often hindered by technical, fiduciary, and implementation barriers. With significant potential for low-carbon development and climate change adaptation, Pakistan could derive substantial economic and environmental benefits through cooperating with China's carbon market. This collaboration could assist Pakistan in meeting its GHG emission targets, developing into a seller of carbon credits, generating state revenue, and creating positive co-benefits like improved public health and job creation [21]. Voluntary emissions reduction programs like the Gold Standard offer Pakistan alternative routes to access private climate finance through certified carbon credits. Moreover, with carbon markets and pricing set to gain increased prominence under the Paris Agreement, Pakistan could develop innovative policies that address climate change while supporting equitable and sustainable growth. While carbon pricing presents complex challenges, Pakistan can derive considerable social, economic, and environmental gains through well-designed policies and partnerships. As Pakistan endeavors to fulfill its climate commitments, valuable insights from domestic experiences and regional collaborations can guide the development of effective global carbon pricing strategies. While the consideration of carbon pricing remains active, Pakistan focuses more on immediate climate solutions and alternative policies, with a moratorium on implementing a nationwide carbon tax [22]. Notably, initiatives such as the 10 Billion Tree Tsunami Program, launched in 2019, aim to enhance carbon sequestration through large-scale reforestation efforts significantly. Concurrently, Pakistan has taken measures to shift away from coal-based energy, implementing a ban on new coal power plants and imports. The goal is to transition 60% of the country's energy production to renewable sources by 2030. Additionally, addressing urban air pollution, Pakistan has announced plans to transition 30% of vehicles to electric cars and buses by the same year [23].

Given that the energy and agricultural sectors contribute substantially to emissions, Pakistan is strategically prioritizing nature-based solutions, renewable energy initiatives, and the promotion of electric mobility. These policies align with the country's emissions reduction goals while concurrently exploring the viability of a national carbon tax. This multifaceted approach reflects Pakistan's commitment to advancing sustainable practices and mitigating climate change on regional and global scales [21].

Cement Industry in Pakistan

Cement Plant Dynamics in Pakistan

Pakistan boasts a robust cement industry, benefiting from ample domestic access to raw materials. The nation stands among the world's top ten cement exporters and ranks 14th largest cement producer globally. Nonetheless, the per capita cement consumption, currently at 215 kg, lags that of many regional counterparts and falls short of the global average of 550 kg [24].

The cement industry in Pakistan constitutes 5.3% of the nation's Gross Domestic Product and represents a 7.5% contribution to the primary sector of large-scale manufacturing [25]. Pakistan's cement sector comprises 16 companies with 26 manufacturing facilities with a collective annual production capacity of 83.1 million tons [26]. The industry is demarcated into northern (Punjab, KPK, AJK, and Gilgit Baltistan) and southern zones (Sindh and Baluchistan), as shown in Figure 3.

Both the North and South regions exhibit distinctive demand-supply patterns. In the Southern market, industry participants can explore export opportunities in Nigeria, Tanzania, Mozambique, Iraq, Ethiopia, and the Democratic Republic of Congo, expanding their revenue streams. Conversely, the northern zone accounts for approximately 80% of production capacity and sales. The reliance on exports is relatively lower, and local demand is robust in the North Zone. Export prospects for entities in the North Zone are primarily limited to Afghanistan and India.

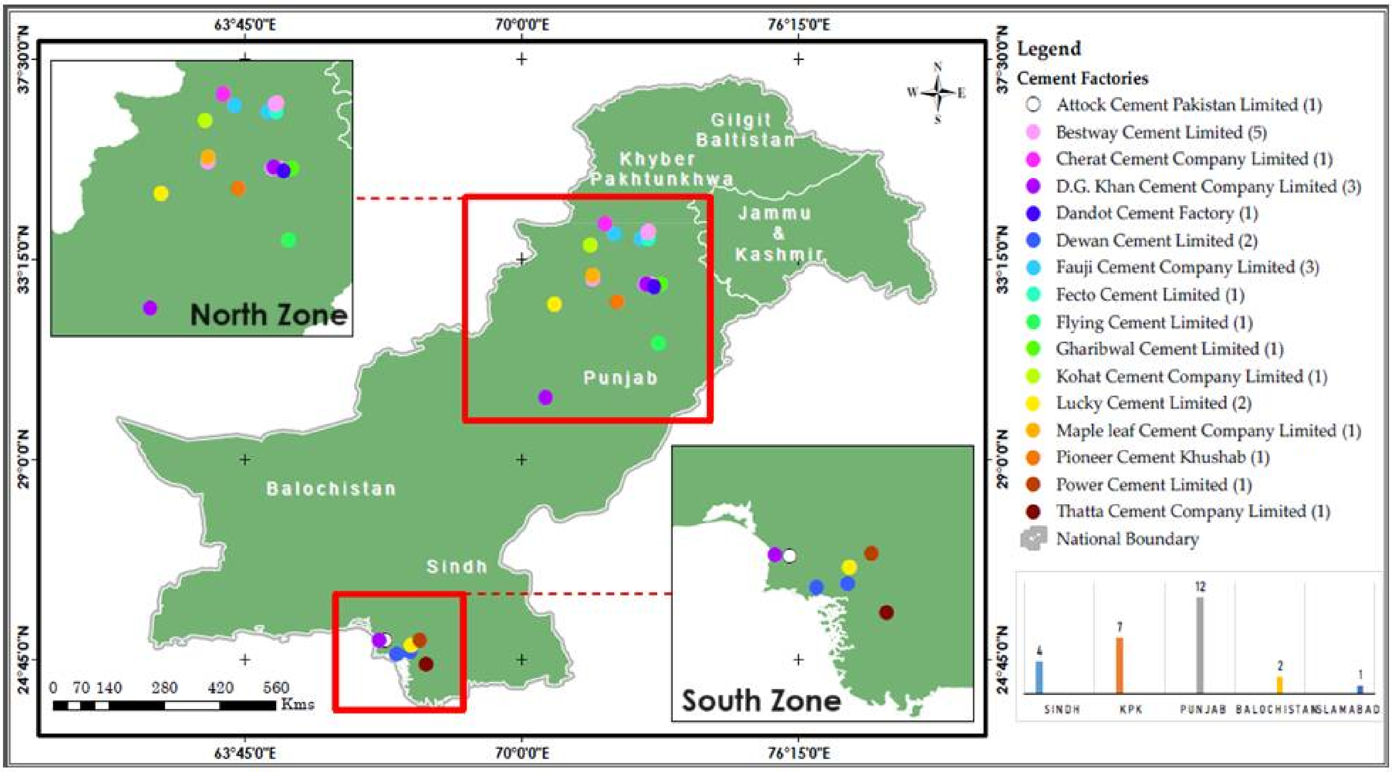


Figure 3: Location of cement production plants of various companies in Pakistan for both North and South Zones.

Table 1 below provides information regarding different cement companies, including their provinces and cities of operation. The cement industry in Pakistan is oligopolistic, with the top four corporations controlling over 56% of the market share. The remaining businesses hold only 44% of the market share, as shown in Figure 4.

Table 1: Annual Production Capacity of the Cement Sector

SR. #	NAME OF INDUSTRY	PROVINCE	ANNUAL PRODUCTION CAPACITY (TONES)
1	Attock Cement Pakistan Limited - Hub Chowki, Lasbela	Baluchistan	3,027,150
2	Bestway Cement Limited - Hattar	KPK	3,654,000
3	Bestway Cement Limited - Chakwal	Punjab	3,600,000
4	Bestway Cement Limited - Farooqia	KPK	2,976,750
5	Bestway PakCem Limited - Kalar Kahar	Punjab	2,299,500
6	Bestway Cement Limited - Pai Khel	Punjab	2,268,000
7	Cherat Cement Company Limited-Nowshera	KPK	4,536,000
8	Dangote Cement Limited - Jehlum	Punjab	504,000
9	Dewan Hattar Cement Limited - Hattar	KPK	1,134,000
10	Dewan Cement Limited - Dhabeji	Sindh	1,953,000
11	D.G.Khan Cement Limited - D.G.Khan	Punjab	2,110,500
12	D.G.Khan Cement Limited - Chakwal	Punjab	2,110,500
13	D.G.Khan Cement Limited - Hub	Baluchistan	2,835,000
14	Fauji Cement Limited - Wah	Punjab	1,102,500
15	Fauji Cement Limited - Nizampur	KPK	3,748,500
16	Fauji Cement Company Limited - Fateh Jang	Punjab	3,503,640
17	Fecto Cement Limited - Sangjani	Punjab	945,000
18	Flying Cement Limited - Lilla	Punjab	1,197,000
19	GharibWal Cement Limited - Jehlum	Punjab	2,110,500
20	Kohat Cement Company Limited - Kohat	KPK	5,017,500
21	Lucky Cement Limited - Pezu	KPK	9,645,000

22	Lucky Cement Limited, - Indus Highway, Karachi	Sindh	5,309,625
23	Maple Leaf Cement Factory Limited - Daudkhel	Punjab	8,190,000
24	Pioneer Cement Limited - Khushab	Punjab	5,454,225
25	Power Cement Limited - Nooriabad, Dadu	Sindh	3,370,500
26	Thatta Cement Limited - Thatta	Sindh	577,080
Total		83,179,469	

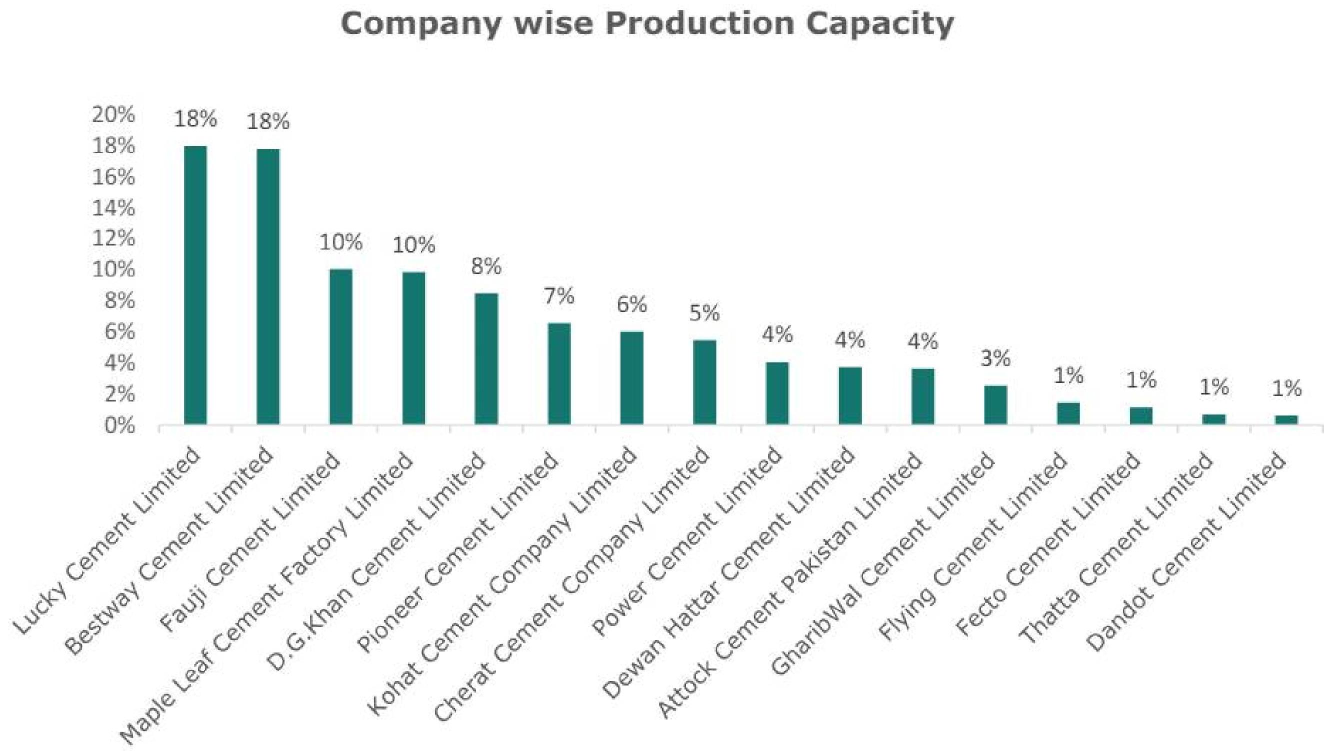


Figure 4: Company-wise production capacity of cement plants in Pakistan

Fuels Used in the Cement Industry

Many cement manufacturers rely on imported coal for their energy needs, making them vulnerable to fluctuations in international coal prices and exchange rate variations. Cement manufacturers in the South region benefit from lower transportation costs due to proximity to ports, reducing the cost of imported coal from Indonesia and Australia. In contrast, businesses in the Northern Region have access to export markets in Afghanistan and India, albeit at higher transportation costs [24]. Countries worldwide increasingly adopt waste products and alternative materials to replace fossil fuels in cement manufacturing. Industrialized nations have over two decades of successful experience in this field. Countries such as the Netherlands and Switzerland have achieved notable substitution rates of 83% and 48%, respectively, making them global leaders in this practice. In the United States, it's common for cement plants to derive a significant portion of their energy needs, ranging from 20% to 70%, from alternative fuels. According to the development of alternative fuels in the U.S. cement industry - cement lime gypsum, the share of alternative and waste fuel usage in the US cement industry increased from minor amounts to 16% of all fuel used in the cement industry in 2016. The same report states that coal and coke, once the dominant share of fuels, have dropped from 74% to just over 57%, while natural gas has increased from just over 7% to nearly 16% based on BTUs consumed. Waste fuel use increased slightly from 5.5% to 6.8%, but alternative fuel use more than quadrupled. The use of other alternatives has also increased significantly. In 1996, other alternative fuels were just under 5% of the total alternative and waste fuel use heat consumption, but by 2016, that single category had increased by nearly a factor of 5. However, in Pakistan, Cement plants have yet to embrace alternate fuels and still rely primarily on a mixture of foreign and local coal for cement production.

In a strategic move to bolster the cement and construction industry, the Pakistani government has rolled out a series of subsidies and incentives, marking a significant push toward infrastructure development. The 2021-22 federal budget saw an unprecedented allocation for the Public Sector Development Program (PSDP), earmarking PKR 2,135 billion for development projects, a move expected to boost cement demand substantially. Additionally, the National Highway Authority (NHA) allocated PKR 114 billion to enhance highways and roads, indirectly promoting increased cement consumption.

A notable aspect of this governmental support is the emphasis on housing. The Naya Pakistan Housing Authority received PKR 30 billion and a PKR 3 billion mark-up subsidy to invigorate the construction sector, a direct boon for cement manufacturers. Furthermore, allocating funds for essential dam and hydropower projects like Dasu, Diamir-Bhasha, Mohmand, and Neelum Jhelum is anticipated to escalate cement demand as these projects progress significantly. In addition to direct funding, the government has introduced tax incentives and waivers under the Prime Minister's Package for the Construction Sector. These fiscal measures are designed to stimulate private sector investment in construction, thereby enhancing cement demand. However, despite these initiatives, industry stakeholders, including the All-Pakistan Cement Manufacturers Association (APCMA), continue to lobby for additional measures such as the abolition of the Federal Excise Duty (FED) and a reduction in other taxes to control costs further and stimulate growth. Despite varying opinions on the effectiveness of these measures, the consensus leans towards a positive impact on Pakistan's cement sector.

These concerted efforts by the Pakistan government underscore a commitment to supporting the cement and construction industry and laying the groundwork for sustained economic growth through infrastructure development. Cement plants often receive payments to accept alternative fuels, and sometimes, these fuels are acquired for free or at a considerably lower cost than coal's energy equivalent. Consequently, the lower fuel costs can offset the expenses of installing new equipment for handling alternative fuels. Energy typically accounts for 30-40% of the operating costs in cement manufacturing. Therefore, any opportunity to save on these costs can provide a competitive advantage over cement plants using traditional fuels.

Cement Production and Dispatch Trend Analysis

Figure 5 provides a year-wise breakdown of production capacity and actual production (based on the amount of cement dispatched) by cement plants in Pakistan from 1990 to 2023. It illustrates that the production capacity has grown from 8.89 MMT (Million Metric Tons) in 1990 to 73 MMT in 2023. However, production has been at a lower capacity during these years due to limited market demand. For example, the output in 1990 was 7.29 MMT, which increased to 57.43 MMT in 2021 but decreased to 44.58 MMT in 2023 due to a decrease in demand. During the 1990s up to the year 2000, production experienced a modest 36% increase. However, cement production has surged by 348% during the last decade. This remarkable growth can be attributed to substantial investments in the infrastructure sector, with the nation channeling resources into significant projects like highways, dams, and energy infrastructure. For a detailed year-wise breakdown of annual production, please refer to Chapter 12. The cement Industry in Pakistan started exporting cement with a meager 0.11 MMT in 2002, but the cement export increased to 14.28 MMT in 2021. However, with the onset of COVID-19 and poor trade relations with India, the cement export was reduced to 4.56 MMT in 2023. During the same period, the local cement demand in Pakistan decreased from 43.15 MMT in 2021 to 40.01 MMT in 2023 (refer to Figure 5).

In terms of Capacity Utilization, the ratio of total dispatches to the production capacity (Capacity Utilization= (Total Dispatches)/ (Production Capacity)), the maximum utilization was achieved in 1993, amounting to 92.7%. The current utilization in 2023 is 61%, showing a significant slowdown.

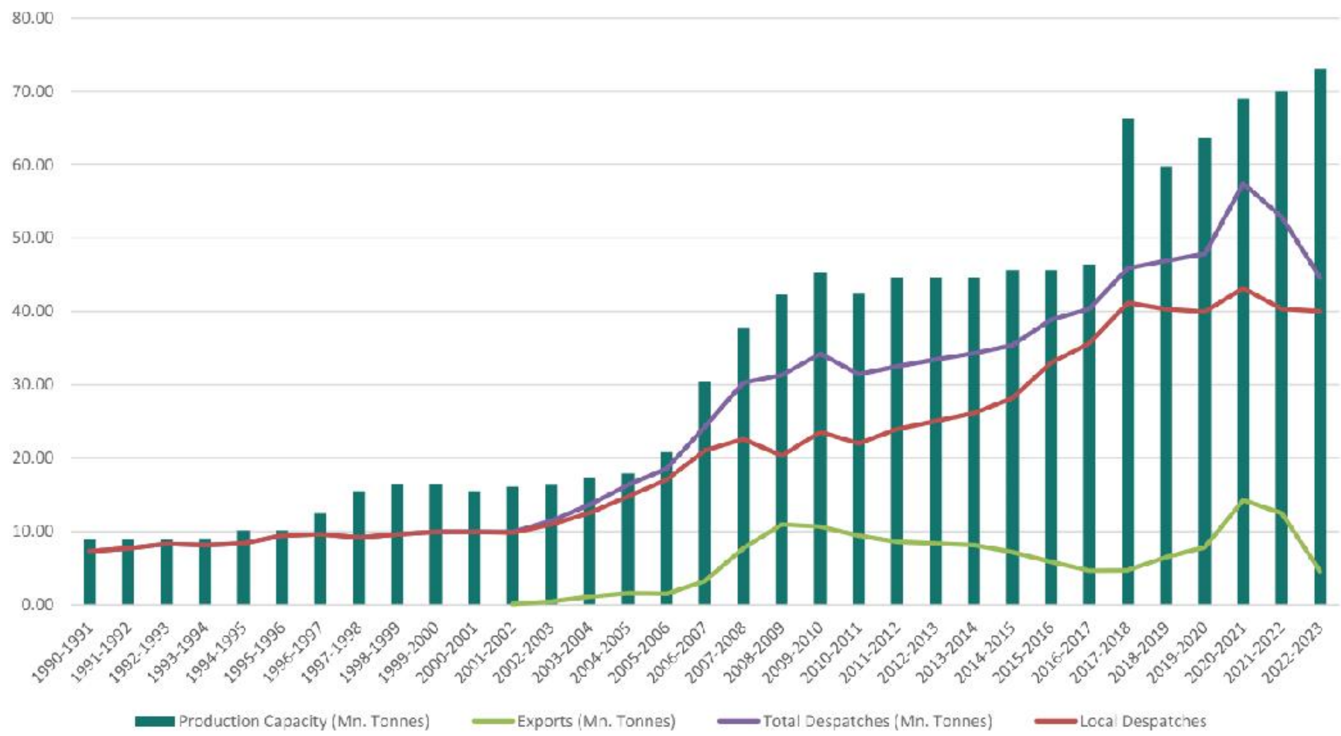


Figure 5: Year wise cement production capacity and dispatch comparison

Public spending and cement production

According to the State Bank of Pakistan, over 50% of the industry's players have undertaken capacity expansions in the last three decades. The increase in production capacity can be observed in three waves of expansion from 1195 to 2021 (Figure 6). In the first wave, the production capacity increased from 10 to 19 MMT (1995- 2005). In the second wave, the production capacity was enhanced to 47 MMT (2005-2010), and in the third wave, the production capacity increased from 48 to 72.8 MMT (2015-2021).

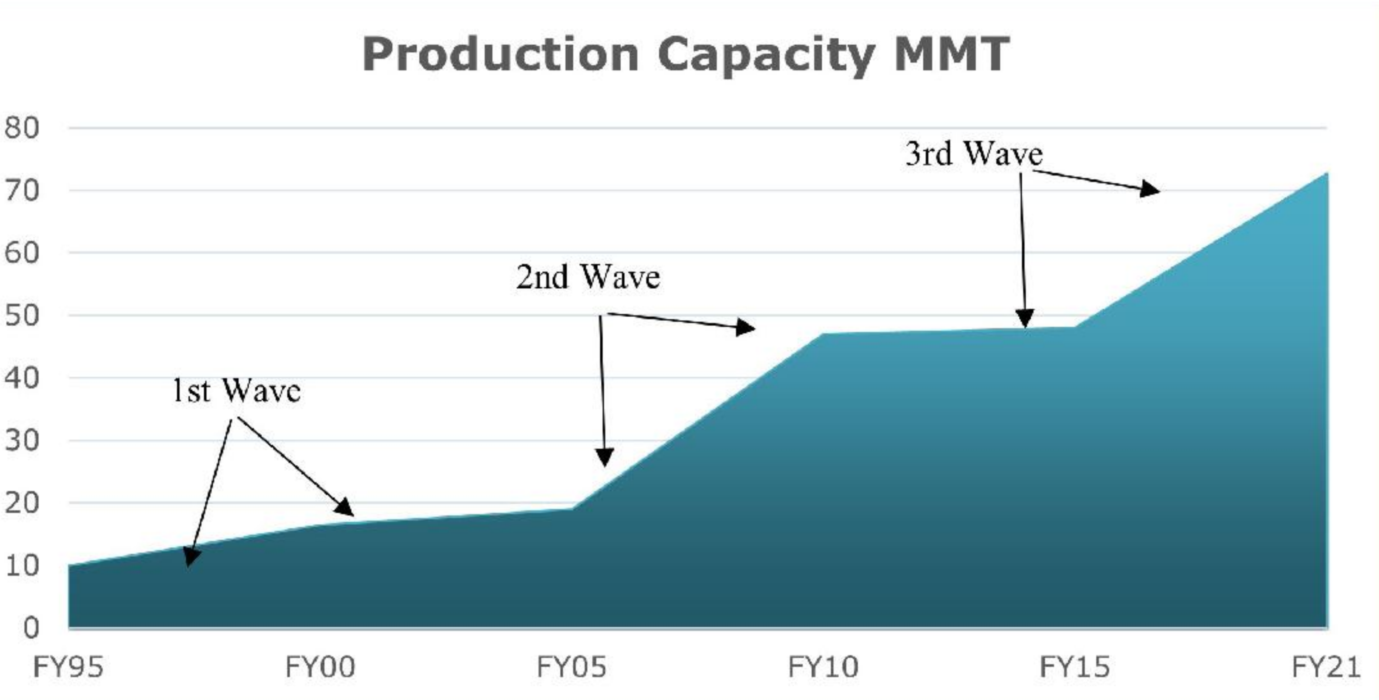


Figure 6: Change in cement production capacity during the last three decades

Notably, the construction sector gained momentum through the extensive expansion of infrastructure initiatives under the PSDP (Public Sector Development Programme), CPEC (China Pakistan Economic Corridor), and heightened interest in private housing developments. The growing demand and favorable profit margins (from 2015 to 2021) motivated cement manufacturers to escalate their production capacities. PDSP is a government initiative in Pakistan aimed at facilitating the financing and implementation of diverse economic development programs. Among these are the development of infrastructure, education, health, energy, transportation, and other crucial areas of national development. In the context of the cement industry, the subsectors of Power, Water, Transport & Communication, and Physical Planning and Housing are the most significant because they involve large construction projects, such as dams, roads, and water and power infrastructure, which increase the demand for cement production and consumption.

Figure 7 provides a year-wise spending analysis of PSDP (Power, Water, Transport & Communication, and Physical Planning and Housing) and annual cement production. From 2005 to 2008, infrastructure expenditures increased from PKR 86.66 billion to PKR 193.4 billion, increasing yearly output from 16.36 million tons to 30.3 million tonnes. In addition, from FY 2011 to FY 2020, the total expenditure on infrastructure increased from PKR 111.7 billion to PKR 390 billion, resulting in an increase in annual cement production from 32.52 million to 57.43

million tonnes.[25] PSDP spending has significantly decreased in the past few years because of the widening fiscal deficit. As a result 2023, cement production declined to 44 million tonnes as PSDP spending dropped to PKR 300 billion.

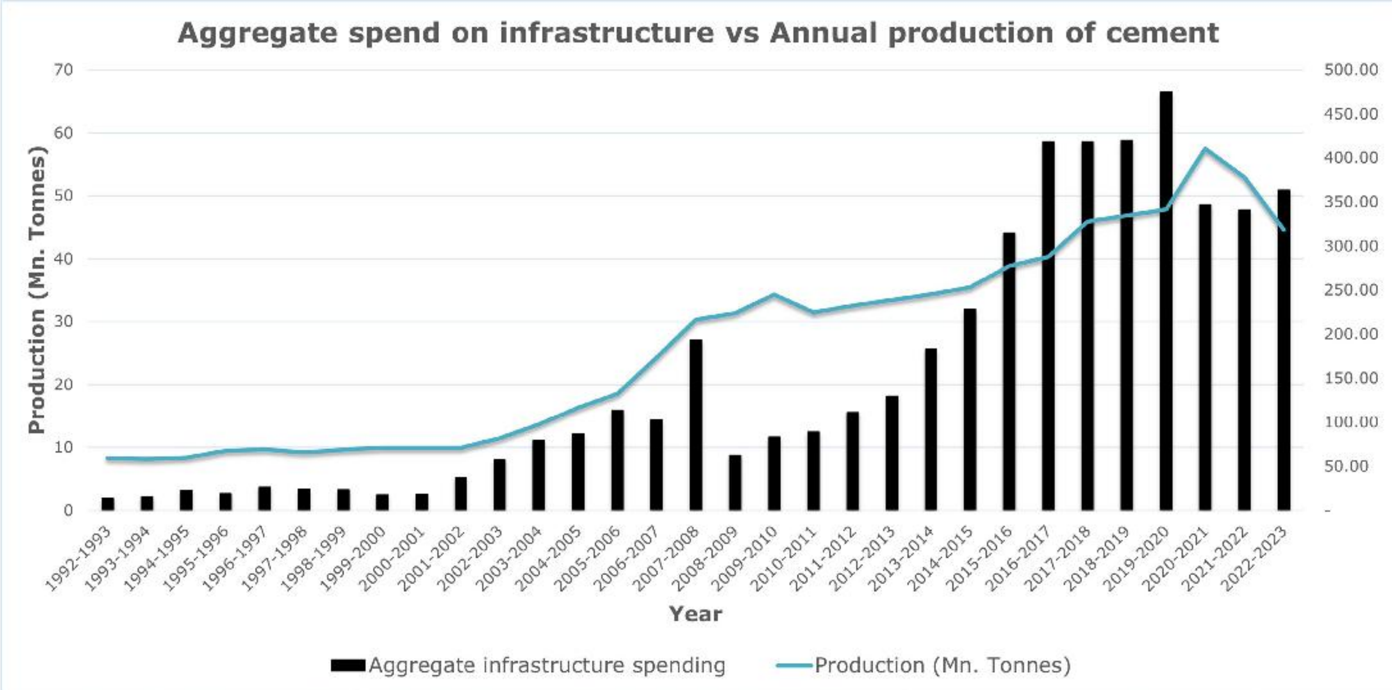


Figure 7: PSDP spending on infrastructure vs annual cement production.

Figure 8 shows the relationship between Infrastructure spending by PSDP (independent variable) and Cement production as the dependent variable: an R2 value of 0.79 shows a high correlation between cement production and PSDP infrastructure expenditures (details in Annex-C).

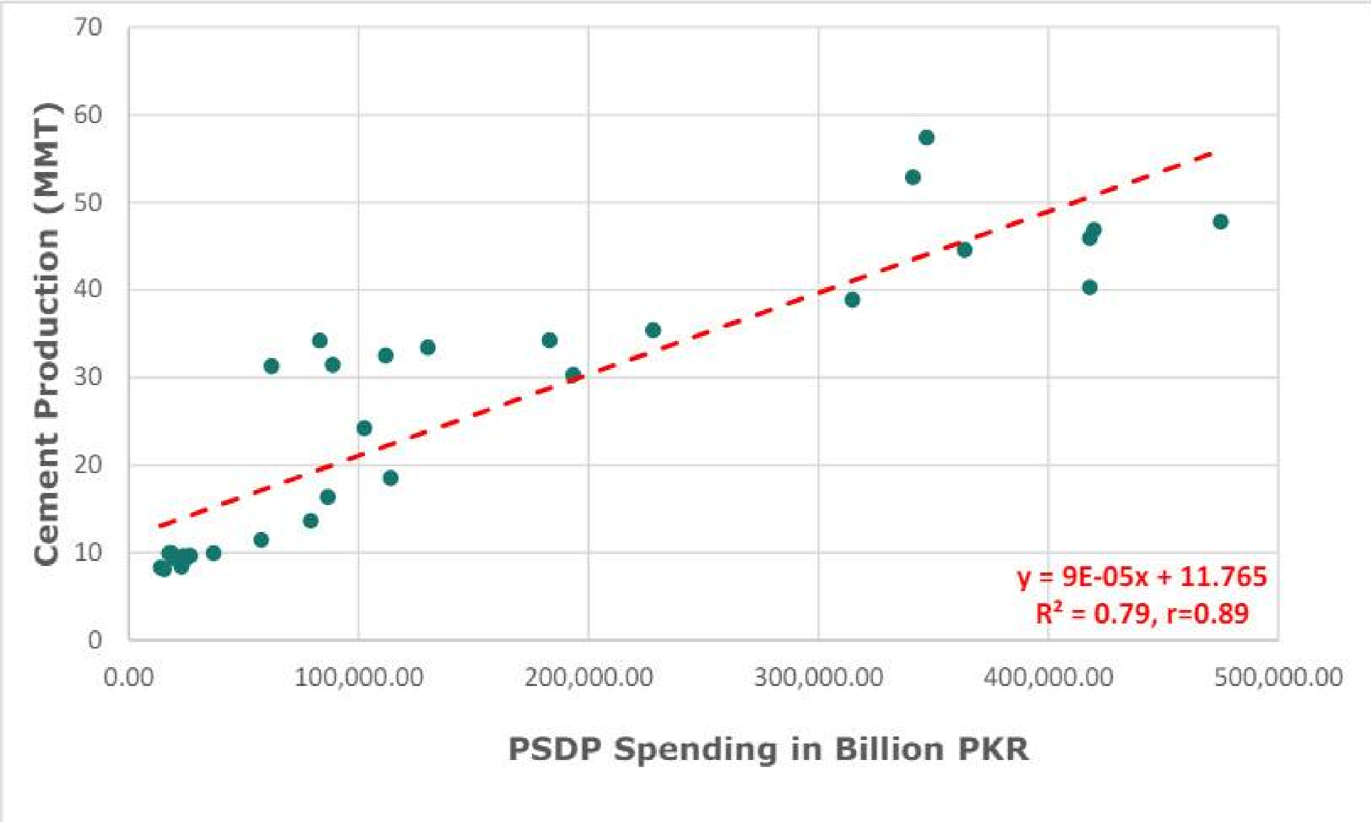


Figure 8: Cement Production (MMT) vs PSDP spending (PKR Billion)

02

CO_2 Direct and Indirect Emissions

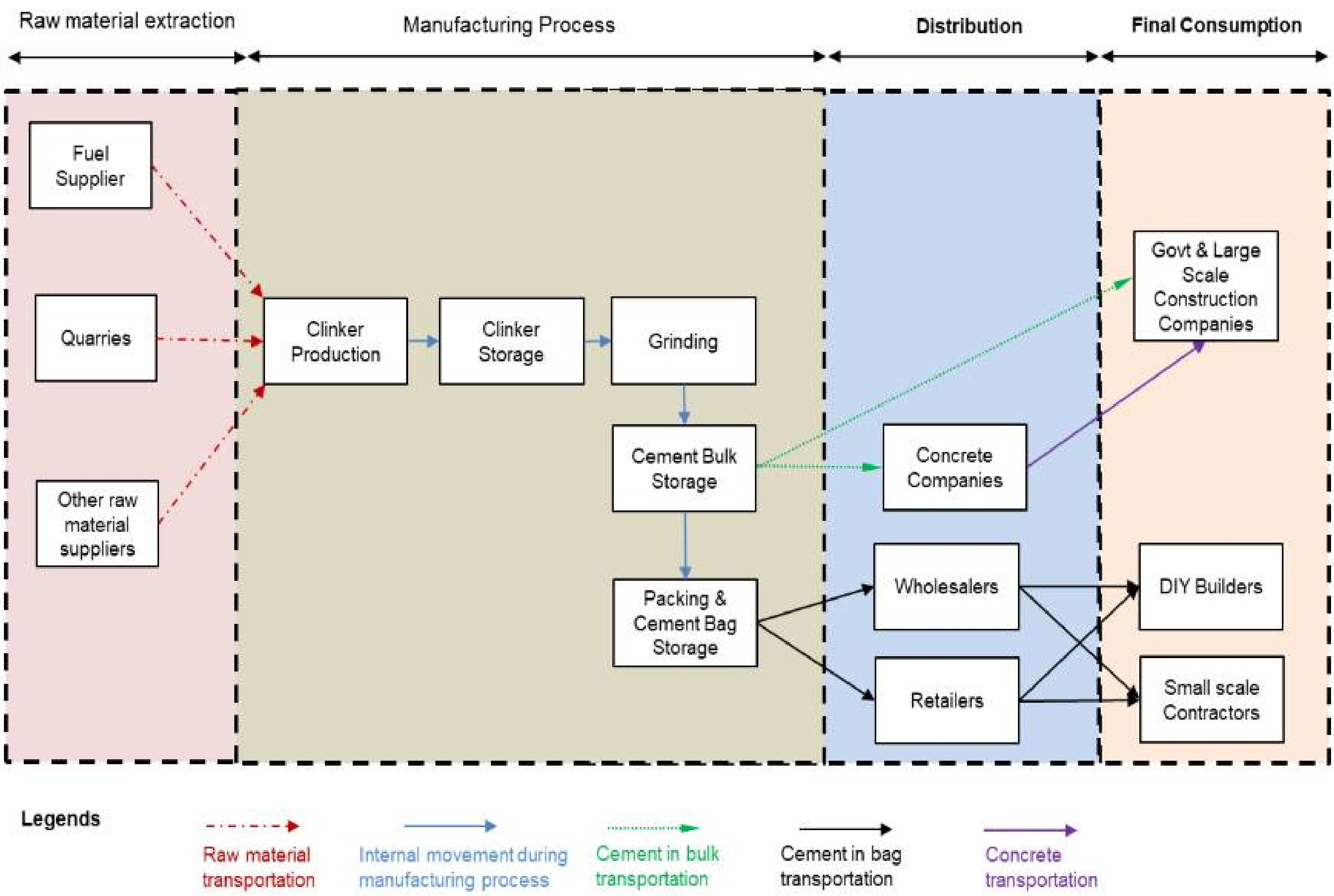


Figure 9: End-to-end supply chain of cement production.

Globally, the concrete industry uses about 1.6 billion tons of Portland cement to produce 12 billion tons yearly. It accounts for 7-8 percent of the country's greenhouse emissions. In the future, to achieve green growth, the industry will have to adapt to climate change challenges and rework business models to ensure environmental stewardship and robust growth [23].

Decarbonizing the cement sector supply chain requires a multi-pronged approach that involves reducing emissions throughout production, from raw materials extraction to product delivery. The end-to-end supply chain of the cement industry is shown in Figure 9. It can be divided into four stages:

Raw material extraction: The materials required for cement production, such as limestone and clay, are mined from quarries or open-pit mines. Furthermore, depending on location, cost, and availability, fuel for cement industry kilns can vary between coal, petroleum coke, natural gas, and waste-derived fuels.

Manufacturing Process: The mined raw materials are crushed and ground into a fine powder. The powder is mixed with other materials, such as iron ore and gypsum, to create a homogenous mixture. The mixture is then preheated in a preheater tower to remove any moisture. The preheated mixture is fed into a kiln, which is a large rotating furnace. The mixture is heated to high temperatures, causing chemical reactions that transform it into a clinker. The hot clinker is then cooled and stored. The cooled clinker is ground into a fine powder and mixed with gypsum and other additives to produce cement.

Distribution: The cement is packaged in bags or bulk containers and shipped to customers. The packaged cement in bags is distributed to retailers, construction companies, and other customers through a network of transportation providers, including trucks, trains, and ships. It is important to note that transportation means/machinery/infrastructure differs for bulk cement transport and cement in bags.

Customer Use: Finally, customers use cement in various construction projects, such as building homes, bridges, and roads. Bulk cement is dominant in developed countries, and large-scale government projects and large construction companies generally generate demand for it. Bagged cement is dominant in emerging markets and is caused by Do-It-Yourself customers and small contractors.

There are opportunities to reduce CO_2 emissions in all cement manufacturing and distribution stages. This study aims to study how to decarbonize the cement industry in Pakistan.

CO_2 Emissions from Cement Production

The cement production steps and various stages are depicted in Figure 10. Emissions from the cement industry predominantly stem from two key sources: the calcination of limestone to produce clinker, which is the primary component of Portland cement, and the energy-intensive processes used for clinker production and cement milling. Mitigating these emissions in the cement and concrete sector involves several strategies, such as:

- **Deploying Concretes with Better Performance:** One approach to reducing emissions uses enhanced performance characteristics. This means that less concrete is needed in construction, which, in turn, can help lower overall emissions.
- **Using Concrete with Alternative Compositions:** Another strategy is to employ concrete with alternative compositions. This can involve reducing the cement content in concrete, as the quantity used in various applications may vary (ranging between 260 kg/m3 and 400 kg/m3, according to [24]. Click or tap here to enter text. This variation in cement content can reduce emissions.
- **Reducing Clinker Content in Cement:** The clinker content in cement can be reduced, leading to decreased clinker production. Clinker is a significant contributor to emissions, so reducing its use in cement can substantially impact overall emissions.

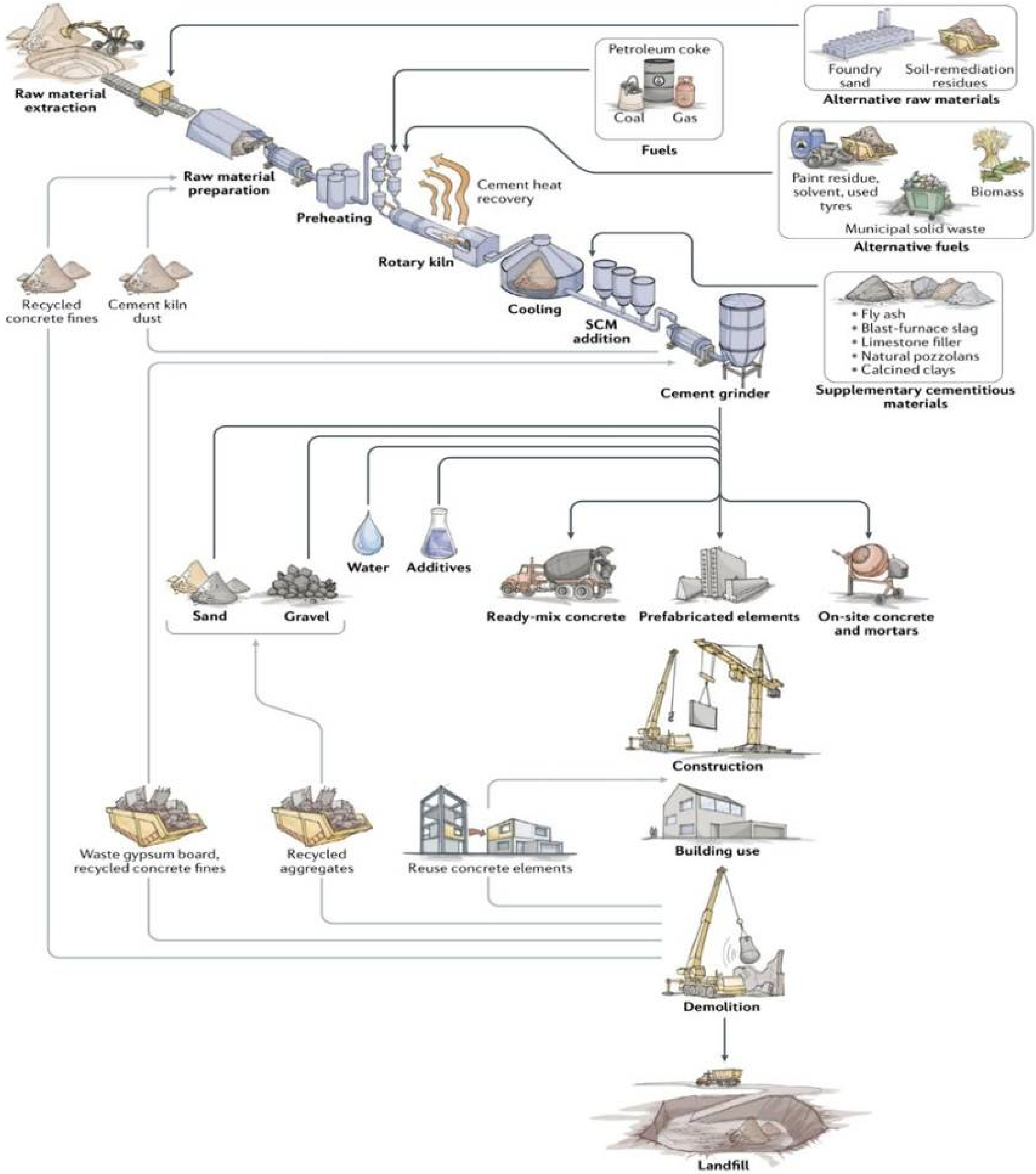


Figure 10: Schematic flow of the cement industry process and various stages [50].

Various stakeholders operate independently from extraction to demolition. However, alternative fuel and raw material choices can curb environmental impact during clinker production. Integrating supplementary cementitious materials (SCMs) and recycling construction waste at different value chain stages offers further environmental benefits.

Ipcc Scopes For Ghg Emissions Estimations

Calculating a company's greenhouse gas (GHG) emissions is the basis for a corporate climate action strategy. Understanding the different types of emissions, classified into scopes 1, 2, and 3, is a crucial step towards achieving the net zero carbon target.

Scope 1- Direct Emissions

It refers to emissions from sources that an organization owns or controls directly. The two primary mechanisms that release carbon dioxide as a byproduct are calcium carbonate's calcination into calcium oxide and fuel combustion during the thermal processes integral to clinker production. The degree of emissions intensity exhibits considerable variation contingent upon the precise production process employed and the nature of the fuel utilized. For instance, facilities employing biomass as their energy source tend to exhibit notably lower CO_2 emissions, starkly contrasting the considerably higher emissions often associated with wet processes reliant on shale oil as the primary fuel.

Calcination is a pivotal phase in cement production and is essential for clinker formation. The process involves the conversion of calcium carbonate ($CaCO_3$) into calcium oxide (CaO), releasing carbon dioxide (CO_2) as a by-product. The chemical reactions involved are fundamental:

$$CaCO_3 + \text{heat} \rightarrow CaO + CO_2$$

Additionally, the decomposition of magnesium carbonate (MgCO3) also contributes to CO2 emissions, although to a lesser extent:

$$MgCO_3 + \text{heat} \rightarrow MgO + CO_2$$

Understanding the CO_2 emissions associated with calcination is vital in the context of Pakistan's industrial decarbonization goals. Measurement of these emissions can be challenging due to the diversity of operational scenarios across cement plants. Alternative approaches, such as estimating emissions based on the amount of limestone used in production, play a crucial role in understanding and managing emissions from the calcination process.

In 1990, Pakistan's cement industry emitted 3.6 million tons of CO_2 from calcination. A disquieting trend emerges as we stand at the midpoint between that historical benchmark and today. Current emissions from calcination have surged to approximately 28.6 million tons, marking a 687% (within the baseline period of 1990 – 2020) increase since 1990. This dramatic uptick is a stark reminder of the industry's substantial carbon footprint and underscores the pressing urgency to confront and mitigate these emissions.

On the other hand, fuel combustion is another significant contributor to Scope 1 emissions in Pakistan's cement industry. Bituminous coal is a primary energy source, with approximately 150 kilograms required to produce one metric ton of cement. The combustion process generates heat in cement production but releases CO_2 directly into the atmosphere. Traditional fossil fuels, including coal, petroleum coke, fuel oil, and natural gas, are utilized, each contributing to direct CO_2 emissions through the kiln stack.

The industry should rely on alternative fuels (AFs) derived from waste materials and biomass/biowaste to address these emissions. This transition includes using mixed fuels containing both fossil and biogenic carbon, contributing to efforts to reduce emissions.

In 1990, the Pakistan cement industry contributed around 2.7 million tons of CO_2 emissions from fuel combustion. Today, the cement industry's emissions from fuel combustion have surged to approximately 21 million tons (687% within the baseline period of 1990 – 2020). This stark contrast highlights a significant increase, necessitating a heightened focus on emissions management and adopting more sustainable practices.

Understanding and managing Scope 1 emissions are pivotal for Pakistan's cement industry, as they align with broader industrial decarbonization goals. The industry's commitment to reducing emissions from calcination and fuel combustion processes is essential, mainly as it balances the need for economic growth with environmental responsibility. Addressing these emissions directly from owned or controlled sources is a significant step toward sustainable and environmentally conscious cement production in Pakistan.

Scope 2 – Indirect Emissions From Energy Uses

The cement industry in Pakistan faces substantial Scope 2 emissions primarily attributed to electricity consumption. As of June 2022, Pakistan's total installed power generation capacity was 43,775 MW, comprised of 26,683 MW from thermal sources, predominantly oil, gas, and coal, and 10,635 MW from hydroelectric sources. This highlights the importance of thermal power in Pakistan's energy mix. Using international reference data, a combined margin emissions factor of 0.61537 kg CO_2 per kWh is applied, although adapting this to Pakistan's unique energy landscape is imperative. Calculating Scope 2 emissions becomes vital for the cement sector, aligned with the GHG Protocol Corporate Standard, enabling emissions reduction initiatives, low-carbon energy procurement, and overall sustainability performance tracking. Methodologically consistent with best practices, this carbon footprint assessment seeks to move the Pakistani cement industry towards decarbonization, given the substantial electricity intensity of 130 kWh per ton of cement produced.

In 1990, the Pakistan cement industry was responsible for approximately 0.58 million tons of CO_2 emissions from electricity. Presently, the industry's emissions from power generation alone have climbed to around 4.59 million tons, illustrating a marked increase (687 % within the baseline period of 1990 - 2020) and underscoring the urgent need for the industry to address its carbon footprint and transition towards more sustainable practices, consistent with global environmental goals.

Scope 3 – Indirect Supply Chain Emissions

Scope 3 refers to indirect greenhouse gas emissions due to business activity not directly owned or controlled by a particular organization. In the context of the cement industry of Pakistan, the CO_2 emissions from downstream activities, i.e., cement being transported from cement plants to distribution centers via trucks, are considered (scope three emissions estimation). For Scope 3 emissions calculations, a survey involving approximately 30 truck drivers was conducted to determine critical parameters. The survey revealed that 30 tons of 3-axle trucks are used chiefly for cement logistics, overloading by 10 tons, with an average mileage of 2.9 km/liter for allowable loads and overloaded trucks mileage of 1.9 km/liter. After cement production, it is typically transported by trucks to various distribution centers for local consumption (residential and commercial) and exported through Port Qasim.

To estimate CO_2 emissions from cement logistics, we made certain assumptions based on this information. On average, when exporting from the north zone (Punjab and KPK), a truck covers 1000 kilometers distance on one side (we used travel distance from factory to port only as the practice is on the way back; identical trucks/vehicles are being used for logistic of other goods). Meanwhile, when exporting from the south zone (Sindh), the average distance traveled by truck is 100 kilometers. To meet local demand, the average travel distance for a truck is 250 kilometers. As per data from the fiscal year 2019-2020, reported by [22], the total cement production was 47.82 million tons, with local dispatches of cement amounting to 39.97 million tons, whereas exports dispatches of 7.85 million tons, of which 1.97 million tons of cement were exported from the north zone, and 5.88 million tons were exported from the south zones. Based on research published in the Pakistan Journal of Meteorology (Khan & Siddiqui, 2017), the CO_2 emissions factor per liter of diesel is equal to 2700 grams approximately. Furthermore, the CO_2 emissions per kilometer for compliant and overloaded trucks are 931 grams and 1,421.1 grams of CO_2, respectively.

Table 2: Scope 3 emissions parameters

Local & Export dispatches of Cement (million tons)				
Million Tons	2019-2020			
	Exports from the North Zone	Exports from the South Zone	Local Dispatches	Total Production
	1.97	5.88	39.97	47.82
Avg. KM Traveled	1000	100	250	

Using data given in Table 2, the following CO_2 emissions are calculated using a 3-axle truck highlighted in Table 3 below.

Table 3: CO_2 emissions comparisons of local dispatches vs exports

Dispatches	Truck Capacity (Allowed Load)	Truck Capacity (Overload)	No trips allowed	No trips Overload	Allowed capcity CO_2 emissions (tons)	Allowed capcity CO_2 emissions (tons)
Local	29.5	39.5	1,354,915.00	1,011,899.00	315,366.60	359,490.40
Export north	29.5	39.5	66,793.00	49,883.00	62,186.30	70,886.40
South export	29.5	39.5	199,210.00	148,777.00	18,547.00	21,142.00

The graph presents a detailed examination of the Pakistani cement industry's emission patterns over six decades, starting from 1990 and extending to forecasted values till 2050. Derived from cement dispatch metrics and computed using IPCC-endorsed methodologies, the graph reveals several insights about CO_2 emissions from the cement sector of Pakistan for various estimated for all scopes:

- CO_2 Emissions from Calcination (Scope 1): This traces the carbon dioxide released during the cement's calcination phase, where limestone undergoes thermal decomposition.
- CO_2 Emissions from Fuel Combustion (Scope 1): This category highlights the emissions originating from the combustion of fuels integral to the cement production process. Direct emissions from sources that the industry owns or controls have shown a marked increase in production growth.

- Emissions from Electricity Consumption (Scope 2): Representing the carbon footprint of the industry's electricity consumption, this category has grown significantly, reflecting the energy-intensive nature of cement production.
- Transport Emissions (Scope 3): This data illustrates the emissions from the distribution of cement products across Pakistan and underscores the environmental impact of the logistics involved.

The graph depicts a pronounced growth in emissions from 1990 through the mid-2010s, correlating with the expansion of the cement industry. Notably, the forecasted data post-2020 paints a concerning picture: if the industry continues this trajectory without significant intervention, total emissions could reach alarming levels by 2050.

However, it is imperative to note that a pressing global mandate exists for industries, including the cement sector, to achieve net-zero emissions by 2040. This underscores the urgency for the Pakistani cement industry to make drastic changes in its operational procedures.

This report has meticulously assessed the emissions landscape spanning from 1990 to 2050, with a particular emphasis on the pivotal reference period of 1990 to 2020, which we have defined as the baseline for our analysis. During this foundational three-decade timeframe, we diligently calculated an increase in emissions, a 687% surge, symbolic of the historical industrial landscape, technological advances, and socioeconomic growth. This baseline serves as a crucial contextual benchmark against which all subsequent emissions projections are evaluated, providing invaluable insight into the cumulative environmental impact of industrial activities over the years.

Beyond this historical context, our report also encompasses a forward-looking perspective by projecting emissions for discrete periods—specifically, 2021-2030, 2031-2040, and 2041-2050. Based on the baseline increase, these projections indicate an emissions growth trajectory in the forthcoming decades. In 2030, a projected increase of 172% indicates an intensified environmental impact due to industrial expansion, while in 2040, the projection escalates to 240%, reflecting the consequences of unabated growth trends. Furthermore, the year 2050 culminates in a projected 308% increase in emissions, underscoring the urgency of adopting transformative practices to address the cumulative impact of industrial expansion.

Table 4: Emissions Analysis and Projections (1990-2050)

Year	Emissions (million tonne)	Emissions Increase (%)	Comments
1990-2020	24.92	687	Increase emissions within the baseline period (1990-2020)
1990-2020	11.74	-	Average baseline emissions

2021-2030	31.86	171.5	Projected emissions increase concerning average. Baseline period emissions (1990-2020)
2031-2040	39.89	239.95	
2041-2050	47.92	308.38	

This tabulated representation summarizes the emissions analysis, providing a visual reference that complements the detailed discussion within the report. It is integral to facilitating the comprehension of emissions trends over the specified timeframes. Table 4 elucidates the baseline and projected emissions increases, thus providing stakeholders with an accessible and comprehensive overview of historical and anticipated environmental impacts due to industrial growth. This analytical framework empowers decision-makers to align strategies and initiatives with an awareness of the long-term implications of industrial expansion, promoting informed and strategic decision-making in pursuing a sustainable future.

This analysis signifies that the industry's current direction necessitates immediate attention. Sustainable practices are no longer optional but essential. By exploring alternative fuels, investing in energy-efficient technology, and optimizing transportation methods, the cement industry can curb its escalating emissions and work towards the crucial goal of net-zero emissions by 2040, ensuring a harmonious balance between growth and environmental stewardship.

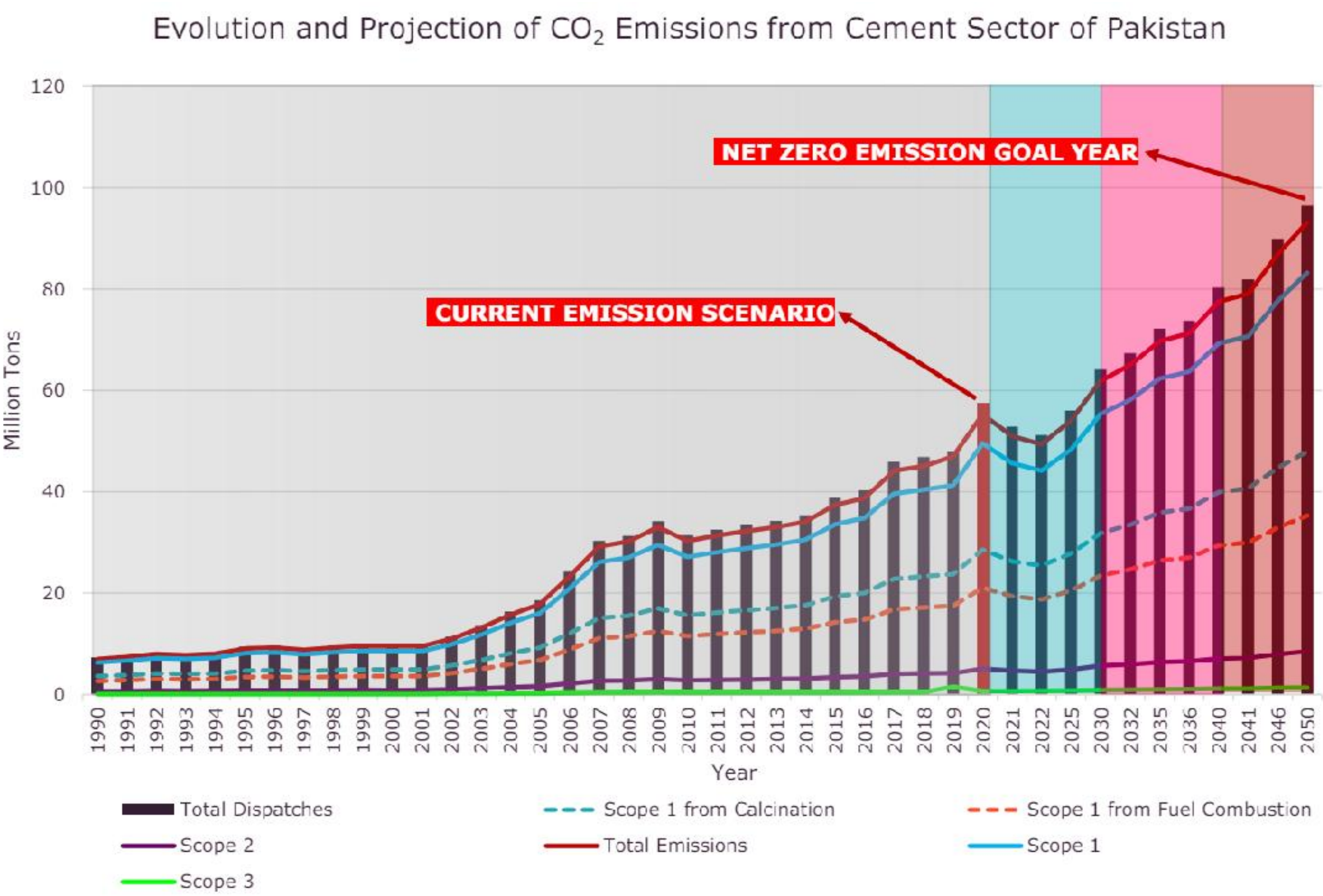


Figure 11: Baseline and projected emissions of the cement sector in Pakistan.

03

Available Tech-Solutions and Alternatives

Design and Effective Capacity

A Strategic Approach

The cement industry in Pakistan is actively exploring various strategies to reduce its CO_2 emissions. Ongoing adjustments in production processes and a transition from conventional fossil fuels to low-CO_2 energy sources have already begun to facilitate a reduction in CO_2 emissions. When combined with Carbon Capture, Utilization, and Storage (CCUS) technologies, even more substantial emissions reductions become feasible.

Key emissions reduction strategies available worldwide and being considered in Pakistan include:

- Innovative Cement Formulations: Developing novel cement formulations incorporating reduced clinker quantities or alternative materials to minimize the carbonates' calcination process.
- CO_2 Capturing & Utilization (CCU): Capturing and utilizing CO_2 emissions from cement production to manufacture basic chemicals, synthetic fuels, and cement carbonation. This can occur during curing or at the end of a cement product's life cycle.
- Carbon-Negative Cement: Recognizing the urgency of addressing climate issues and the challenges of achieving full decarbonization, carbon-negative cement is being explored as a valuable contribution to emissions reduction.

Efforts to decarbonize the cement industry must prioritize emission sources from largest to smallest. Figure 12. indicates the potential of multiple control measures to reduce CO_2 emissions during various steps of cement production. In the context of Pakistan, the most significant emissions sources include:

- Process Emissions from calcium carbonate calcination: These can be addressed by implementing CCUS technologies or mitigated by adopting alternative cement compositions emphasizing circularity.
- Process Emissions from Thermal Processes: These result from the combustion of fuels in kilns and can be managed by transitioning to kiln electrification or improving fuel efficiency.
- Indirect Emissions from electricity consumption: a transition to a decarbonized electricity system is essential to address these.

Efficiency improvements

In Pakistan's cement industry, it is crucial to consider efficiency improvements to address the high energy demand and emissions associated with cement production. As per the European Cement Research Academy (ECRA), the theoretical minimum thermal energy demand for cement clinker production is estimated to range between 1.59 and 1.84 GJ/t clinker. However, the corresponding figures for Pakistan and the global average in 2019 stand at 3.81 and 4.2 GJ/t clinker [20]. This notable disparity signifies an opportunity to significantly reduce fuel consumption and emissions within the Pakistani cement industry. A noteworthy projection for the global average, provided by ECRA and the World Business Council for Sustainable Development (WBCSD)/ Cement Sustainability Initiative (CSI) [25], suggests that the global average energy consumption for cement production could be enhanced to 3.15-3.215 GJ/t clinker by the year 2050. In contrast, the best-case scenario for 2019 already demonstrated a remarkable 23% reduction in energy consumption, with figures as low as 2.7 GJ/t clinker [101]. This reduction highlights the potential for substantial energy efficiency improvements. Reports from the International Energy Agency (IEA) and WBCSD/CSI [26] indicate the possibility of achieving efficiency improvements of 10-11% globally by 2050. However, it is essential to note that these improvements may exhibit regional disparities due to various factors, including differences in technology adoption and operational practices. These enhancements are particularly significant since thermal processes occur within kilns, which are substantial combustion facilities. The scope for further improvements is inherently constrained by factors such as thermal losses, implementing CO_2 capture and storage measures, co-generation options, underutilization of plant capacity [102], and ongoing efforts to adopt the best available techniques. These considerations are pivotal in pursuing sustainable and efficient cement production in Pakistan.

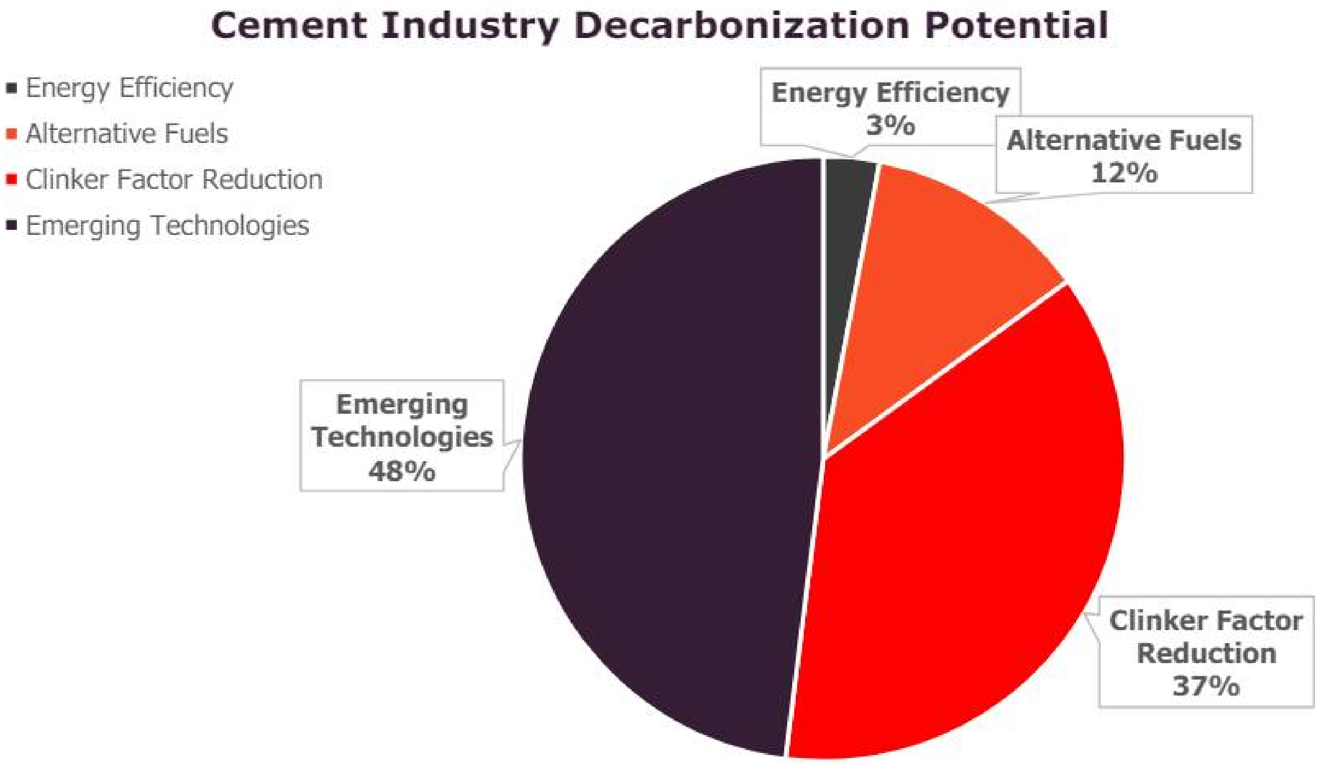


Figure 12: Decarbonization potential in cement Industry.

Total capacity utilization, denoting a utilization rate of 100%, signifies that cement producers are operating at their maximum potential output based on fully utilized production capacity. In contrast, overcapacity characterizes a market scenario where not all potential products can be effectively sold, reducing production by operating facilities at lower utilization rates. Research from Global Cement [27] underscores the strong connection between high utilization rates and improved profitability and sustainability.

Economic performance in the cement industry is significantly influenced by the utilization rate of existing production capacities, as emphasized by the European Commission in 2018. A healthy level of profitability is achievable with a kiln utilization rate of 75% or higher, according to the International Finance Corporation (IFC) [27]. It is worth noting that maximum energy efficiency is attained when operating at maximum design continuous loads [26], while operating at half capacity is considered energy-inefficient [28]. Given that the industry operated at a 70% utilization rate between 2015 and 2020, the pandemic and economic slowdown are expected to exacerbate overcapacity [29]. Nevertheless, this overcapacity presents an opportunity to phase out the least efficient cement plants, aligning with recommendations from Chatham House [30] and the International Energy Agency (IEA) [31]. Various measures are being investigated and implemented to enhance the cement industry's thermal efficiency. These include the modernization of processes and kilns [26], [32],

[33], as well as the adoption of waste heat recovery systems [27], [34], [26]. Valuable insights can also be drawn from the lime sector, which, in addition to these approaches, focuses on efficient insulation lining to minimize shell heat losses, improved process and input control, and proactive maintenance practices [35]. These measures are pivotal for achieving enhanced thermal efficiency within the cement industry and aligning with global sustainability and emissions reduction objectives.

The most advanced technology for clinker production involves the utilization of dry-process kilns equipped with multistage preheating and pre-calcination. In such installations, waste heat is harnessed to preheat and pre-calcine the raw material feed before it enters the kiln, resulting in a substantial reduction in energy consumption, with potential energy savings of up to 10% [26]. This ongoing evolution towards more thermally efficient processes, characterized by dry kilns with pre-heaters and pre-calciners, emphasizes the effective use of waste or excess heat [26], thus necessitating the retrofitting of several plants in Pakistan. It is worth noting that this approach challenges the economic viability of further waste heat utilization or other processes reliant on waste heat [25]. Waste heat can be put to "integrated use," such as in drying fuel required for the cement plant [25] or external applications, including heating and power generation.

Waste heat from cement plants has been effectively employed for heating purposes at various locations across Pakistan, including Bestway Cement Mianwali, Bestway Cement Hattar, Bestway Cement Chakwal, Bestway Cement Farooqia, Bestway Cement Kallar Khar, Lucky Cement, Fecto Cement, Karachi Plant, Attock Cement, D.G. Cement D.G. Khan Plant, and D.G. Cement Khairpur Plant.

Waste Heat Recovery (WHR) is an approach that utilizes a portion of the medium-temperature waste heat (ranging from 200-400°C) from kiln flue gases to generate electricity. While it does not directly reduce a cement plant's electricity consumption, it effectively converts excess heat that would otherwise be wasted into electricity for on-site use or export to the grid [34]. Various technologies and systems can be applied in WHR, including heat pumps, steam cycles, Organic Rankine Cycle (ORC), Kalina cycle, or supercritical CO_2 systems [36], [37], [27], [25], [38], [39]. Beyond on-site utilization, waste heat can also find applications in Carbon Capture, Utilization, and Storage (CCUS) [25], providing heat to other industries and contributing to district heating initiatives [35].

From an economic perspective, WHR in the cement industry requires significant capital investment. However, it is characterized by relatively low operational costs [40]. Regarding energy efficiency, a steam cycle reduces the range of 8 to 22 kWh/t clinker. In contrast, ORC and Kalina cycle systems exhibit a minor reduction, ranging from 10 to 20 kWh/t clinker. Installation costs for these technologies typically range between EUR 15 to 25 million, which are expected to remain relatively constant between 2015 and 2050. All three technologies are projected to reduce cement prices, with expected decreases of 0.5 to 1.4 EUR/t in 2015, increasing to 0.7 to 1.9 EUR/t in 2050 [25]. However, these costs may vary depending on factors such as the specific technology used, the size of the installation, and its location. The cost range for electricity generation capacity varies from USD 7,000/kW for 2 MW systems (ORC) to USD 2,000/kW for 25 MW systems (steam) [41]. In the case of ORC, which has broader applications beyond cement, costs are estimated at around USD 1,500/kW [42], with levelized electricity costs ranging from EUR 21 MWh to EUR 45 MWh [43].

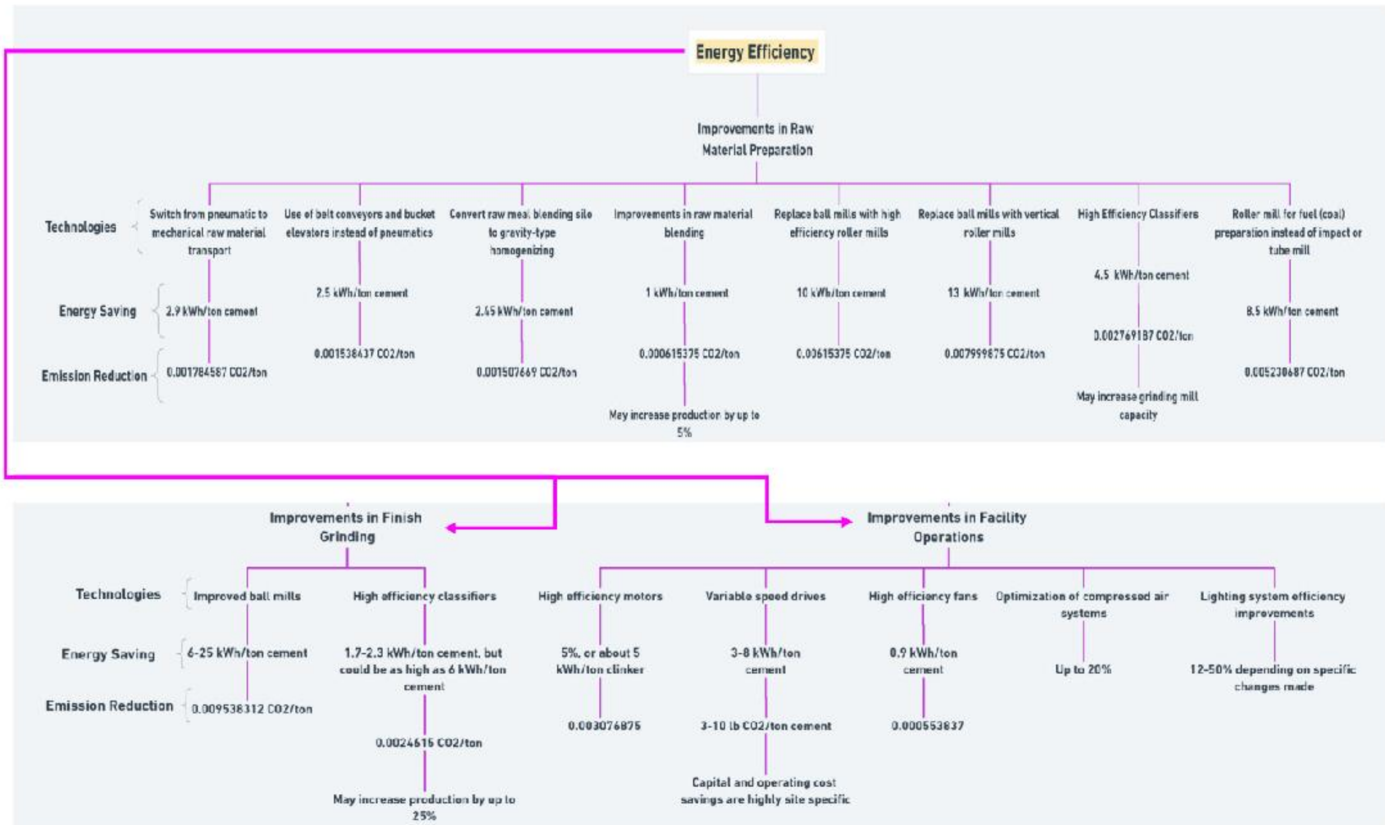
In addition to optimizing thermal efficiency and using production facilities efficiently, improving electric efficiency is another avenue for reducing CO_2 emissions. Electricity is a significant requirement for various processes, including grinding raw materials, cement, additives, and kilns' operation and ancillaries. Approximately 13% of cement production's global final energy consumption is attributed to electricity [26]. Grinding operations, responsible for up to 70% of the electric energy demand in clinker and cement production, present a significant opportunity for efficiency improvements [25]. While the wet process is gradually phased out, various technologies and approaches for handling dry materials are available [44]. These include the use of grinding aids [25] and separate grinding of materials for high-blend cement [45]. However, it is essential to consider the electricity consumption associated with specific decarbonization options, such as CCUS or kiln electrification, as it may affect the overall energy intensity [91].

Electrification for Emissions Reduction

In Pakistan, a significant portion of emissions from process industries can be attributed to using fossil fuels for heating purposes. Shifting towards electric kilns powered by GHG emission-free electricity can curtail emissions in the cement and lime sector by approximately one-third [92]. Electric kilns are presumed to be the most energy-efficient option, boasting a specific energy intensity of 2.68 GJ/t clinker, surpassing the efficiency of the most advanced dry kilns [93]. This transition reduces emissions and enhances exhaust quality compared to fossil fuel combustion, potentially facilitating carbon capture efforts [94].

Various technologies are under exploration for achieving high temperatures based on electricity, including plasma, electrical flow heaters, microwave heating, resistive electrical heating, and induction heating [95],[96],[97]. However, it's important to note that these technologies are still in the developmental phase and require further investigation [98], [46]. The transition to electric kilns will occur in stages, with research programs focusing on foundational aspects [99], complemented by public investments in research and development [100]. This gradual approach will enable the cement industry in Pakistan to embrace electrification while addressing technical challenges and advancing sustainable practices.

Moreover, in the quest for more energy-efficient technologies, additional options are available to reduce electricity consumption and emissions in the cement industry. Various options that can be opted for effective CO_2 emission reductions are described in Figure 13. These technologies have the potential to reduce electricity consumption by up to 130 KWH, thus lessening the load on the grid and contributing to emission reduction effort



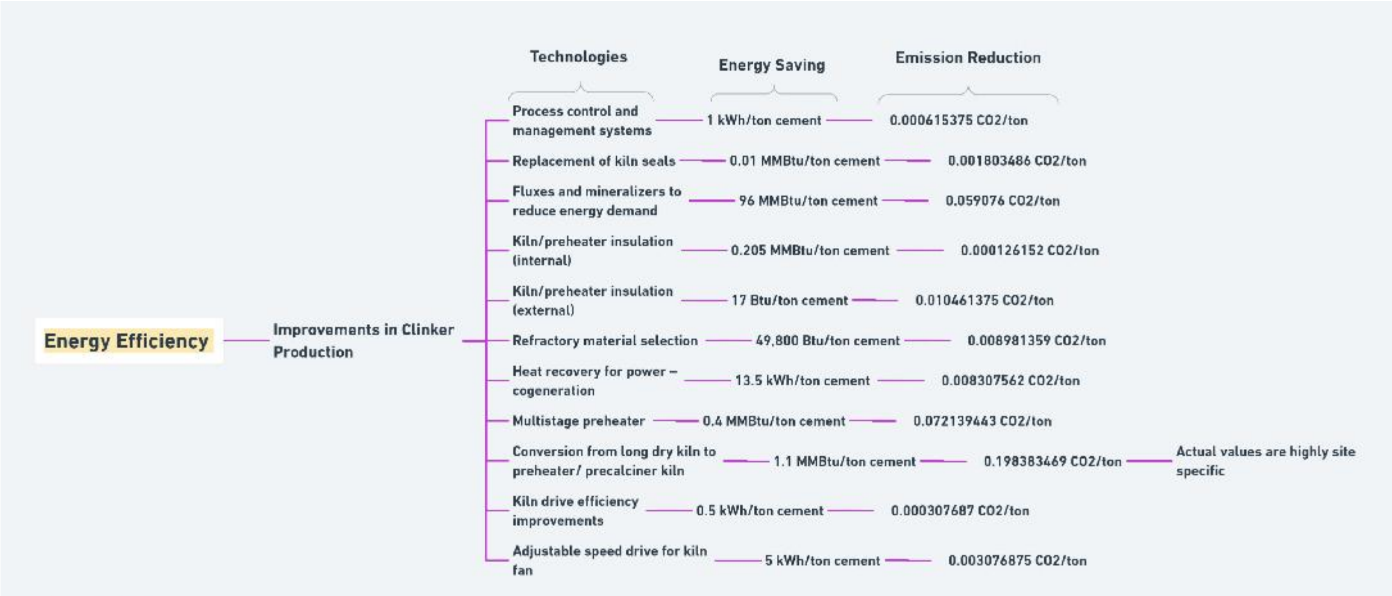


Figure 13: Options available for energy-efficient technologies to improve CO_2 reduction measures.

Table 5: Energy Efficiency Improvements

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Material Handling and Transport	Calculated from energy savings	2.5-2.9kWh/ ton cement	$3.43-$4.1/ ton cement capacity	$0.17/ton cement	New and Existing Facilities with LD, PH, PH/ PC kilns	Yes	
Raw Material Blending and Grinding	Calculated from energy savings	1.0-15 kWh/ ton cement	$2.5-33/ ton cement capacity	Reduction of $0.15/ton cement	New and Existing Facilities with LD, PH, PH/ PC kilns	Yes	May increase production by up to 5%
Classification Systems	Calculated from energy savings	1.7-2.3 kWh/ ton cement, but could be as high as 6 kWh/ton cement	$2/annual ton cement	$0.045/ton cement	Existing and New Facilities. All kilns.	Yes	May increase production by up to 25%

Fuel Preparation	Calculated from energy savings	7-10 kWh/ton coal	The cost of a roller mill is higher than that of an impact or tube mill	Reduction of as much as 20-50%	New and Existing Facilities	Yes	
Process Control and Optimization	7-33 lb CO_2/ ton cement and 1.3 lb CO_2/ton cement from electricity usage reduction	2.5-5% or 42-167 MJ/ ton cement and electricity savings of 1 kWh/ton cement	$0.3/annual ton cement capacity	NA	New and Existing Facilities. All kilns.	Yes	
Kiln Efficiency Improvements	Calculated from energy savings	0.000017 - 1.1 MMBtu/ton cement	$0.8-96/ annual ton cement capacity	Fuel savings may be offset by the cost of fluxes and mineralizers	New and Existing Facilities. All kilns.	Yes	Kiln output increases by 10%, production boosts by 3%, and kiln capacity increases by up to 50%.
Ball Mills Optimization	Calculated from energy savings	1.7-25 kWh/ ton cement	$2-7.3/annual ton cement capacity; or	This may reduce by 10-40%, but the vertical roller mill may increase costs by $0.17/ton of cement.	Existing and New Facilities. All kilns.	Yes	May increase production by up to 25%
Motor and Drive Efficiency	Calculated from energy savings	3-25 kWh/ton cement	$2.3-7.3/ annual ton cement capacity; or	May reduce by 30-40%	Existing and New Facilities. All kilns.	Yes	Capital and operating cost savings are highly site-specific

Fan and Lighting Efficiency	Calculated from energy savings	5-50% depending on specific changes made	$0.46/ton cement	Depends on the plant's needs	Existing and New Facilities. All kilns.	Yes	
Compressed Air System Optimization	Calculated from energy savings	Up to 20%	Depends on the plant's needs	Depends on the plant's needs	Existing and New Facilities. All kilns.	Yes	

In augmenting electrical efficiency within the cement industry, an array of cutting-edge technologies is pivotal in curtailing the electricity demand for producing each ton of cement.Commencing with the conversion of raw meal blending silos into gravity-type homogenizing systems, progressing through refinements in raw material blending, and culminating in the substitution of traditional ball mills with high-efficiency roller mills and vertical roller mills, these methodologies collectively engender a substantive reduction in energy consumption (see Table 5).

The articulated numerical ranges offer a granular understanding of the potential impact each technology can exert. These advancements underscore a concerted endeavor to enhance energy efficiency and ensure a sustainable and resource-conscious trajectory within the landscape of cement manufacturing.

Utilization of Alternative Fuels

The cement industry, known for its significant energy consumption, is responsible for emitting approximately 40% of its total emissions because of fuel consumption. These emissions encompass scope one emissions stemming from thermal processes (precisely, fuel combustion at high temperatures) and two emissions associated with generating electricity used in cement production. While the transition toward decarbonization of the power system is underway, approaches are available to tackle emissions resulting from thermal processes [90].

As depicted in Table 6 below, the industry has various options for diversifying its fuel mix in thermal processes. Notably, using waste and biomass as alternative fuels has gained prominence and is being actively integrated into cement production. In addition to these options, industries are exploring the potential of solar heating, hydrogen integration, and electrification as alternative avenues for reducing emissions and enhancing sustainability.

Table 6: Alternative Fuels for the Cement Industry

AGRICULTURAL BIOMASS RESIDUES		
Fuel	Substitution rate (%)	ΔCO_2 (ton/ton coal replaced)
Rice Husks	35	-2.5
Wheat Straw	20	-2.5
Corn Stover	20	-2.5
Sugarcane Leaves	20	-2.5
Sugarcane Bagasse	20	-2.5
Rapeseed Stems	20	-2.5
Hazelnut Shells	20	-2.5
NON-AGRICULTURAL BIOMASS		
Dewatered sewage sludge	20	-2.5
Dried sewage sludge	20	-2.5
Paper sludge	20	-2.5
Paper	20	-2.5
Sawdust	20	-2.5
Waste wood	20	-2.5
Animal waste (bone, meal, fat)	20	-2.5
PETROLEUM-BASED WASTES		
Tires	<20	-0.8
Polyethylene	unavailable	-1.0
Polypropylene	unavailable	-1.0
Polystyrene	unavailable	-0.9
Waste oils	unavailable	-0.5
Petroleum coke	up to 100	0.2
Miscellaneous wastes		
Automobile shredder residue (ASR)	2	0.05
Carpet residue polypropylene nylon	unavailable	-0.54, -0.15
Textiles	30	0.0
Landfill gas	unavailable	-1.0
Municipal solid waste (MSW)	up to 30	-0.4

The strategic incorporation of these alternative fuel sources is essential for the cement industry's emissions reduction and sustainability journey. The industry can significantly mitigate its environmental impact by diversifying fuel sources and reducing reliance on conventional, high-emission fuels.

The distinction between biomass and waste fuels can sometimes be intricate. For instance, items like diapers are classified as biomass, while impregnated sawdust is categorized as waste. Nevertheless, cement kilns can burn up to 100% of waste or biomass fuels. Several plants worldwide have already embraced or are in the process of upgrading to operate under such conditions. Notable examples include Allmendingen (DE) and Retznei (AT) [85], where these practices are already in operation, and Mannersdorf (AT) [86] and Otterbein (DE) [87], which are undergoing upgrades to achieve fossil-free operation. Other cement plants, such as Montalieu-Vercieu [88] and Mergelstetten [89] actively explore the feasibility of operating without consuming fossil fuels. Notably, successful trials have been conducted, including the use of hydrogen in the fossil-free fuel mix. Adopting these innovative fuel sources is closely tied to their availability and cost. The cost of biomass can fluctuate significantly, ranging from over USD 20 per gigajoule (GJ) for oil crops to USD 1-2/GJ for agricultural residues. It is worth mentioning that municipal waste combustion can even yield financial benefits [82]. However, using municipal waste necessitates addressing the challenge and associated costs of managing chlorine, a requirement already addressed at several cement plants worldwide [83], [84]. Integrating these diverse fuel sources underscores the cement industry's commitment to sustainable and environmentally responsible practices while being influenced by cost considerations and the potential for revenue generation.

Emphasis on Biomass Waste Streams

In biomass utilization, the primary focus is on harnessing waste streams rather than on conventional biofuels. This approach is driven by both economic and environmental considerations [25]. Sustainable biomass resources are expected to range from 539 to 915 million dry tonnes by 2050. This substantial biomass potential could have a profound impact, with the capacity to power 1,212 to 2,061 cement industries like Pakistan's (which consumed approximately 85.5 million tons of oil equivalent in 2019). Of relevance to Pakistan, the controlled combustion of rice husk yields a material akin to pozzolana, which holds a significant interest in the cement production process [30].

Co-processing of Waste and By-products in Cement Plants

The practice of co-processing waste and industrial by-products within cement plants serves to maximize their potential. This involves extracting the energy content and utilizing the remaining residues as raw materials [72]. Waste can encompass various categories, including refuse-derived fuel (RDF), municipal solid waste (MSW), commercial and industrial waste (C&IW), construction and demolition waste (CDW), and solid recovered fuel (SRF) [73]. Waste containing biological material can be further classified as renewable [74].

In middle- and low-income countries, the incorporation of waste processing in cement plants offers an environmentally responsible alternative to the frequent practice of landfilling, contributing to emissions reduction without the need for significant investments in waste-to-energy plants [75]. The utilization of alternative fuels in cement production is positioned to potentially replace 30% of fossil fuels in developing regions and up to 70% in developed regions by 2050 [25], with an emphasis on fostering collaboration between the cement and waste treatment industries at the local level [76] [77].

Waste management is of growing concern in Pakistan due to the substantial volume generated. Households in Pakistan produced approximately 49.6 million tons of solid waste in 2021. This significant waste generation is an important aspect to consider within the context of co-processing waste and industrial by-products in cement plants, as it represents a potential resource for fuel and raw material substitution. Co-processing practices can play a role in addressing the challenges posed by such extensive waste generation, contributing to both environmental sustainability and resource efficiency. .

Bottom ash, although typically associated with coal production [78], is also a by-product of waste-to-energy plants. These ashes are rich in minerals, comprising about 80 to 85% mineral content, making them suitable as substitutes for cement [79]. Ongoing research explores the development of new cement formulations based on processed incineration ash from Municipal Waste Incinerators [80]. Pilot projects have shown promise, treating 90,000 tonnes of bottom ash from 450,000 tonnes of municipal waste, yielding 30,000 tonnes of raw material for clinker production [81] Beyond substituting fossil fuels, mineral ashes contained in waste can replace up to 5% of primary raw materials in clinker production. This conserves primary raw materials for cement manufacturing and reduces the need for landfill minerals [71]. The organic content in these waste materials provides thermal energy, while the non-organic content contributes valuable minerals. The share of non-organic content can be as high as 45% in the case of wastewater sludge, 25% for tires, and 13% for municipal waste [70].

However, substituting fossil fuels with waste materials comes with specific requirements. The quality of waste must meet the suitability criteria for co-processing in cement plants, and waste with high moisture, chlorine content, or a high percentage of heavy metals may not be acceptable [69]. Chlorine deposition can deteriorate the stable operation of the kiln, while trace elements may impact clinker quality and environmental performance. Hence, waste materials often undergo pre-treatment, including drying, shredding, or gasification, to enhance their combustion characteristics. An overview of pre-treatment technologies is provided by the International Finance Corporation (IFC) [68].

Exploring Alternative Cement and Materials

While Portland cement is the reference standard, developing alternative cement compositions is well underway. Several driving factors include the availability of alternative raw materials, specific application needs, and the imperative to reduce the carbon intensity of Portland cement. The latter is achieved by minimizing the carbonate content in the raw meal, which contributes to process emissions, and by lowering the thermal process's temperature, which impacts fuel combustion emissions. A crucial consideration in developing alternative cement is ensuring their mechanical properties remain uncompromised. The setting and hardening processes play pivotal roles in identifying suitable low-carbon cement.

Hydraulic cements solidify through chemical reactions between cement and water, resulting in hydrates that are insoluble in water. During this process, over 70 different crystals form in the cement hardening process [66]. In contrast, non-hydraulic cements harden through carbonation reactions involving CO_2 [67]. This approach effectively reverses the calcination of carbonates by mineralizing CO_2 and is, therefore, of interest in CO_2 capture and decarbonization efforts. Carbonation also influences Portland clinker and the products of its hydration, such as calcium hydroxide and calcium silicate hydrate [65]. In addition, pozzolanic materials do not independently solidify when mixed with water. However, they react at average ambient temperatures when finely ground and in the presence of water, forming strength-developing calcium silicate and calcium aluminate compounds through interactions with dissolved calcium hydroxide ($Ca(OH)_2$) [47]. Regardless of the approach, these reactions should result in physical and chemically stable concretes throughout their intended lifetime and various operating conditions. This entails the formation of hydrates and carbonates with low water solubility and high thermal stability to protect the set concrete from water damage, chemical decomposition, or strains resulting from environmental changes. To ensure the quality of the product, these aspects must also be considered during the curing process, which guarantees the physical and chemical stability of the concrete structures as they harden.

For these hydration and carbonation reactions, the right constituents (mineral phases) must be mixed under the correct conditions (stoichiometry, including reactant ratios with water and CO_2, temperatures, etc.), allowing the reactions to progress.

Common Cements:

- Defined in six classes (CEM I to CEM VI) by standard EN 197.
- Contain Portland clinker, which hardens through four main phases: alite, belite, tricalcium aluminate, and tetracalcium aluminoferrite.
- Silicate phases (alite and belite) hydrate in calcium silicate hydrate (C–S–H) and calcium oxide (CH).
- Aluminate phases (tricalcium aluminate and tetra calcium aluminoferrite) hydrate in ettringite using sulfate from gypsum.

Calcium Aluminous Cement (Cac):

- Defined by standard EN 14647.
- Mainly composed of monocalcium aluminate and other mineralogical compounds.
- Hydraulic hardening is due to the hydration of monocalcium aluminate.

Supersulfated Cement:

- Defined by standard EN 15743.
- The main constituent is granulated blast furnace slag (GBFS).
- Hardens through the activation of GBFS by calcium sulfate or Portland cement.

Alternative Cement Chemistries:

- **Reactive Belite Cement:** This is like Portland cement but with different proportions of phases. It is produced at lower temperatures to reduce emissions.
- **Calcium Sulfoaluminate Cement (CSA):** Common in China, with varying compositions containing ye'elimite and other minor phases.
- **Belite-Ye'elimite-Ferrite Cement (BYF or BCSA):** Contains ye'elimite, belite, and tetracalcium aluminoferrite.
- **Carbonate Calcium Silicate Cement (CCSC):** Contains wollastonite, calcium aluminate, and rankinite, which can carbonate into calcium carbonate.
- **Magnesium Oxides Derived from Magnesium Silicates (MOMS) Cement:** Magnesium oxysulfate forms a magnesium carbonate phase after carbonation.

These alternative cement chemistries provide potential pathways for reducing CO_2 emissions in the cement industry. Table 7 summarizes the phases and their principal hardening processes for reference.

Table 7: Overview of cement hardening phases [2]

Phases name and notation	Chemical composition	Cement	Reaction	Product
elite; C3S	$3CaO\cdot SiO_2$	OPC	Hydration	calcium silicate hydrate (CSH)
belite; C2S	$2CaO\cdot SiO_2$	OPC	Hydration	calcium silicate hydrate (CSH)
tricalcium aluminate; C3A	$3CaO\cdot Al2O_3$	OPC	Hydration with sulfate	ettringite ($C_6A\$_3H_{32}$)
tetracalcium aluminoferrite; C4AF	$4CaO\cdot Al2O3\cdot Fe2O_3$	OPC	Hydration with sulfate	ettringite ($C_6A\$3H_{32}$)
monocalcium aluminate; CA	$CaO\cdot Al2O_3$	CA	Hydration	tricalcium aluminate hexahydrate (C_3AH_6)
Granulated blast furnace slag	calcium oxide (CaO), magnesium oxide (MgO), silicon dioxide (SiO_2), aluminum oxide ($Al2O_3$) + other compounds.	SSC	Hydration with sulfate or Portland cement	calcium (C-S-H) silicate hydrate
ye'elimite calcium sulfoaluminate; C4A3$	or $4CaO\cdot 3Al_2O_3\ SO_3$	CSA	Hydration	calcium aluminate mono sulfate ($C_4A\$H_{12}$)
			Hydration with sulfate	ettringite ($C_6A\$_3H_{32}$)
calciumsilicatehydrate (C-S-H)	$3CaO\ 2SiO_2\ 4H_2O$	Hydrated	Carbonation	calcium carbonate ($CaCO_3$)
calcium hydroxide; CH	$Ca(OH)_2$	Hydrated	Carbonation	calcium carbonate ($CaCO_3$)
calcium silicate or wollastonite; CS	$CaO\cdot SiO_2$	CCSC	Carbonation	calcium carbonate ($CaCO_3$)
rankinite; C3S2	$3CaO\cdot 2SiO_2$	CCSC	Carbonation	calcium carbonate ($CaCO_3$)
magnesium oxysulfate	3Mg(OH)2·MgSO4·8H2O	MOMS	Carbonation	magnesium carbonate (MgCO3)

Substitute materials for Portland clinker and their activation methods are vital for reducing energy-related and embodied CO_2 emissions in cement production. These materials, known as supplementary cementitious materials, include:

- **Granulated Blast Furnace Slag:** It consists of at least two-thirds calcium oxide (CaO), magnesium oxide (MgO), and silicon dioxide (SiO_2).
- **Pozzolanas:** Primarily composed of silicon dioxide (SiO_2) and aluminum oxide ($Al2O_3$), with additional iron oxide (Fe2O3) and other oxides. Silica fume and fly ash are examples of pozzolanic materials.
- **Silica Fume:** Fine spherical particles containing at least 85% amorphous silicon dioxide (SiO_2).
- **Fly Ash:** Mainly composed of silicon dioxide (SiO_2) and aluminum oxide ($Al2O_3$), with some iron oxide ($Fe2O_3$) and other compounds. Fly ash can be classified as siliceous (CaO < 10% by mass) or calcareous (CaO > 10% by mass), depending on its reactive calcium oxide content. Calcareous fly ash also exhibits hydraulic properties.
- **Burnt Shale:** Contains clinker phases, mainly dicalcium silicate (belite) and monocalcium aluminate (CA), along with small amounts of free calcium oxide (CaO) and calcium sulfate (CS). It also contains a significant proportion of pozzolanically reacting oxides, particularly silicon dioxide (SiO_2), giving it hydraulic and pozzolanic properties.
- **Limestone:** It mainly consists of calcium carbonate, which, when finely ground, offers beneficial properties for cement and concrete.

Most of these materials result from calcium, aluminum, and silicon oxide combinations. Figure 14 illustrates various raw materials that provide the necessary chemical mix for cement phases. It’s important to note that using raw materials not explicitly mentioned in existing standards is technically feasible.

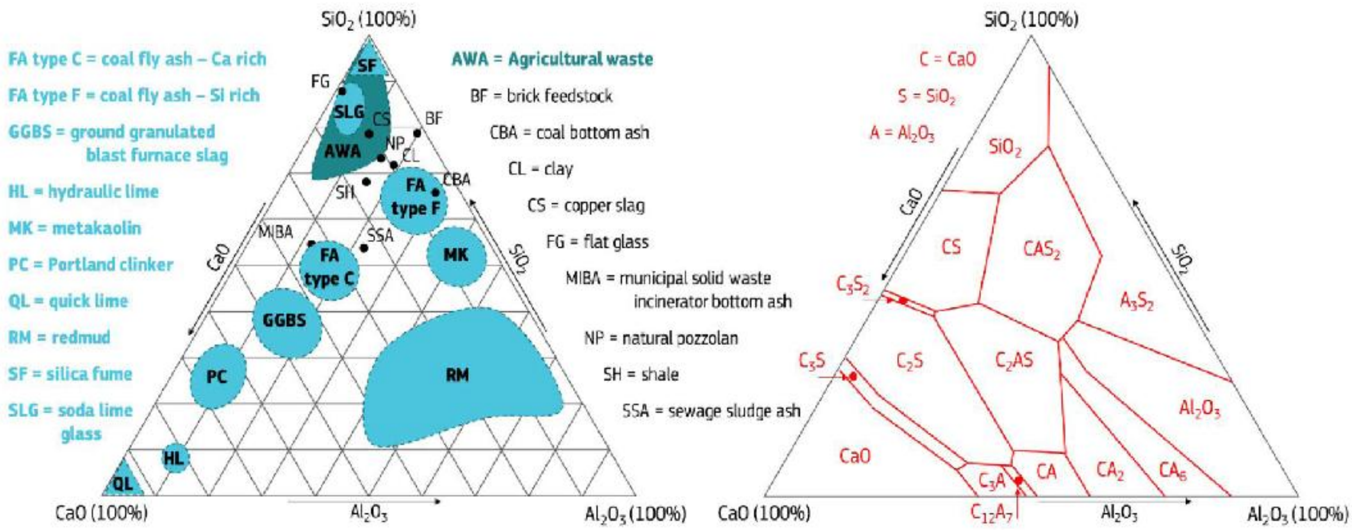


Figure 14: Raw materials (left) and cement phases (right) in the calcium oxide, aluminum oxide and silicon oxide system. [48], [63], [64]

Enhancing material reactivity to facilitate specific reactions such as hydration and carbonation is crucial. Reactivity can be boosted for hydration [25] and carbonation [62] through a combination of activation approaches, as outlined in Table 8. Comminution and chemical activation are the most commonly employed methods for conventional cement production. These strategies are fundamental in optimizing the reactivity of materials and are central to developing alternative cement formulations with enhanced performance.

Table 8: Review of activation methods [61]

Method	Technological features	Advantages	Disadvantages
Chem. additives	Modification of formulations	Wide range of modified formulations	High price
Addition of surface-active substances	Formation of additional crystallization centers and stimulation of growth of neoplasms of secondary generation	Compaction of cement stone structure	Limited range of applications
Grinding of binder by a mill	Different types of mills—ball, vibratory, vario-planetary, etc.	Simplicity	High energy costs
Liquid-phase mechanic activation	The mechanical effect produced by rotary-pulsating apparatus	Hydration occurs more fully, and the mobility of the concrete mix increases	A small amount of the mixture is charged per cycle
Magnetic activation of mixing water	Cycle magnetic water treatment	Energy efficiency	Expensive equipment
Hydro dynamic activation	Synergistically used are the physical and chemical processes occurring in the water flow: aeration, cavitation (cold boiling), collapsing, coagulation	Transfer of dissolved substances in water into insoluble substances and their removal	Relatively low efficiency
High-voltage electrical discharge treatment	The imposition of a constant field of high intensity on a water-cement system leads to phenomena of water electrolysis and electrophoresis, i.e., the motion of charged particles in an electric field.	Significant change in the ion composition of the suspension and the appearance in the water of polarized groups	Technological complexity
Electro physical activation	Electromagnetic action (sometimes followed by steaming)	Improvement elastic strength of concrete	High costs
Microwave (dielectric) heating	The absorption by the material of the energy of the electromagnetic fields of the high-frequency or microwave range and the conversion of this energy to thermal	High speed of technological process	Expensive equipment
Thermal activation	Heating with subsequent cooling according to various schemes	A relatively simple and effective way	High costs
Ultrasonic treatment	Ultrasonic treatment causes the effect of cavitation, grinding of solid particles, and micro-cracks in crystals.	Intensification of cement hydration processes	High energy costs

Thermo acoustic activation	The cement paste is pre-treated in an aerohydrodynamic activator, stirred with aggregates, and heated before being laid at 60–65°C.	Strength increases 1.5 times	Complexity of processing

Carbon Capture, Utilization & Storage (CCUS) for Emission Reduction

In pursuing a low-carbon society, it is imperative to accelerate the development and implementation of options for reducing CO_2 emissions, among other measures [26]. CCUS is recognized as a promising solution to mitigate CO_2 emissions from cement production. The International Energy Agency (IEA) emphasizes the integration of emerging and innovative technologies, including carbon capture, as a pivotal means of achieving significant cumulative reductions in CO_2 emissions. This reduction is projected to reach 48% by 2050 under the 2 Degrees Celsius (2DS) scenarios compared to the Reference Technology Scenario (RTS). A substantial portion of these reductions by 2050 will be attributed to technologies like clean gases, carbon capture, and storage, as well as carbon removal methods, including CCUS technologies and CO_2 storage in materials [European Commission, 2020c]. However, specific data related to the cement sector is currently unavailable. The approach of capturing, utilizing, and storing emissions, instead of addressing them individually at their sources, offers a potentially more convenient and cost-effective means of preventing CO_2 release into the atmosphere. This makes a compelling case for CO_2 capture and storage. Several critical steps are involved in successfully averting CO_2 emissions: CO_2 must be captured at the source, in this context, a cement plant, and then transported to a facility for further handling, either for storage or for transformation and utilization.

Carbon Capture Technologies

While CO_2 capture is technically feasible, widespread implementation is yet to materialize effectively in the fight against climate change. Many approaches and technologies are under development for this purpose [60]. Notably, the cement industry experiences high CO_2 concentrations in exhaust gases, primarily due to emissions from the calcination of limestone, surpassing those of the power generation sector. This underscores the relevance of carbon capture in this industry. CO_2 capture methods primarily rely on separation processes. Oxyfuel combustion and indirect heating for limestone calcination also yield exhaust gases with elevated CO_2 content, rendering them suitable for further processing. Enhancing CO_2 concentration in exhaust gas involves replacing air with pure oxygen in the kiln, which improves combustion and eliminates nitrogen, thereby increasing the CO_2 content in the exhaust gas.

Pure oxygen can be procured through various means, although significant quantities are required for this method [59]. This approach, called oxyfuel or oxy-combustion, demonstrates promise in enhancing CO_2 capture capabilities within the cement industry. Some technologies are shown below in Figure 15.

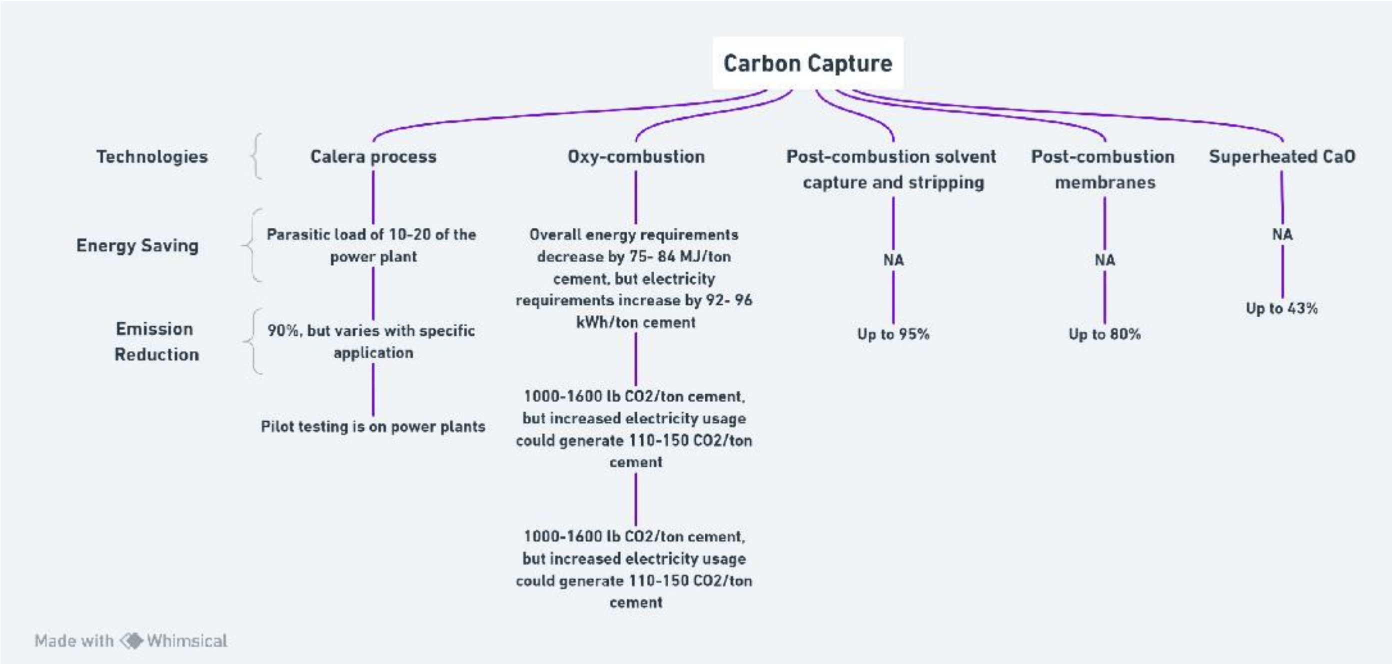
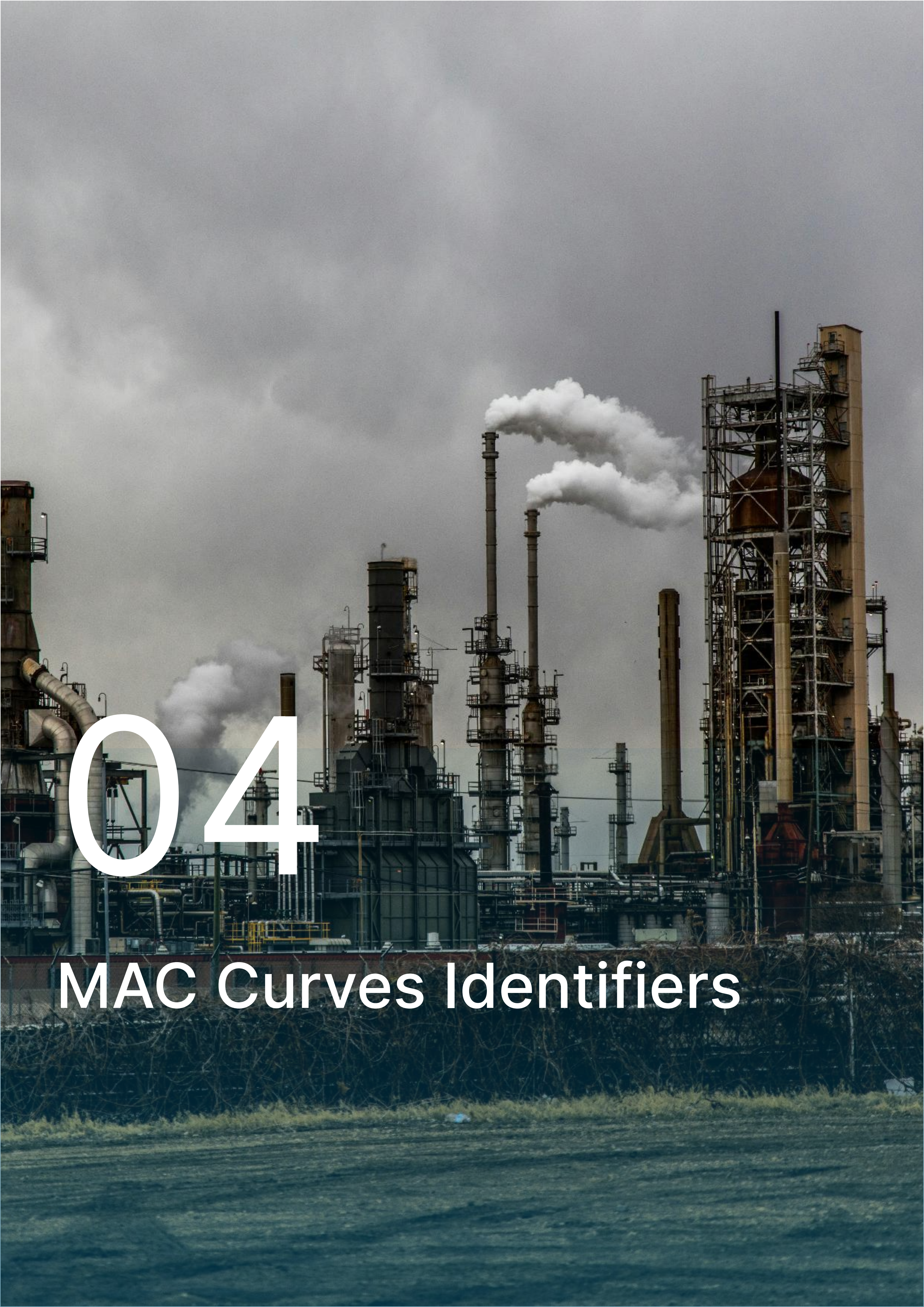


Figure 15: CCUS Technologies options and their potential to mitigate CO_2.



04

MAC Curves Identifiers

Understanding MAC curves

Marginal Abatement Cost Curves (MACCs) are powerful analytical tools in environmental economics designed to help policymakers and businesses make informed decisions about reducing greenhouse gas emissions while optimizing economic efficiency. These curves graphically represent the cost-effectiveness of various emission reduction measures, providing valuable insights into how to tackle climate change. At their core, MACCs illustrate the relationship between the cost of reducing emissions and the quantity of emissions reduced. Not all emissions reductions come at the same price, and by identifying the lowest-cost options, MACCs help allocate resources more efficiently. By ranking emission reduction strategies from least expensive to most expensive, decision-makers can prioritize actions that offer the most significant environmental benefit for the least cost.

MACCs also highlight the abatement potential, the maximum amount of emissions that can be reduced at a given cost. This information is crucial for setting emission reduction targets and designing effective climate policies. Businesses can use MACCs to identify cost-effective ways to reduce their carbon footprint. At the same time, governments can set carbon pricing mechanisms and regulations that encourage emission reductions while minimizing economic disruption.

Key features of MAC curves include:

- Descending Curves: MAC curves generally slope downward from left to right, indicating that the first emissions reductions are often less expensive, while subsequent reductions become progressively more costly.
- Abatement Potential: They show the maximum emissions that can be reduced at different cost levels. This information is crucial for setting emission reduction targets.
- Cost-Effectiveness: Decision-makers can use MAC curves to prioritize strategies that offer the most significant emissions reductions for the least cost, thereby maximizing cost-effectiveness.
- MACCs help ensure that efforts to combat climate change or reduce pollution are economically efficient and aligned with environmental goals.

Methodology

The Marginal Abatement Cost Curves (MACCs) can be calculated using the following formula:

- Marginal Abatement Cost ($/t$CO_2$e)= (Net Present Value ($))/(Total CO_2 emissions abated over the life of the project)
- Where, Net Present Value (NPV)= (Total project costs- Total project savings)/((1 + discount rate)^(project lifetime))

Net Present Value (NPV), adjusted for the time value of money, measures a project's overall worth. When project expenses exceed savings, the NPV is negative, indicating a net cost. Conversely, when savings surpass expenses, the NPV is positive, signaling a return on investment. To determine the Marginal Abatement Cost, we multiply the NPV by -1. A negative Marginal Abatement Cost denotes economically feasible initiatives that yield cost savings. A favorable Marginal Abatement Cost implies a negative NPV and represents an actual cost per tonne of CO_2e abated. Notably, a negative Marginal Abatement Cost ($/t CO_2e) signifies emissions reduction and financial benefits, while a positive ($/t CO_2e) indicates emissions reduction without financial gains.

Table 9 outlines current initiatives for decarbonizing the cement sector. The first 16 entries cover globally adopted technologies, while entries 17 to 55 focus on alternative fuels in Pakistan for replacing coal in cement production. These options are applied to the annual production of the XYZ (anonymous name) cement plant in Pakistan. The following assumptions were used for these calculations:

- The cement factory will continue to produce 0.6 million metric tons of cement over 20 years.
- A 10% discount rate is used for calculating NPV.
- CO_2 emission reductions are calculated by multiplying the emission reduction per ton for each option by the annual production of 0.6 million tons.
- 1unit of electricity (1 KWh) = PKR 34.8
- Exchange rate of 1 $ USD = PKR 286
- Projected horizon = 20 years

The results indicate that some options reduce emissions and result in cost savings. For example, 'Use of belt conveyors and bucket elevators instead of pneumatics' reduces emissions by 0.00154 t CO_2e per ton of cement, saving 2.5 kWh/ton (equivalent to $0.12 per kWh) and incurring a capital cost of $3.43 per ton. This leads to operating cost savings of $0.17 per ton. All these values are calculated based on an annual production of 0.6 million metric tons of cement over 20 years, with NPV calculated at a 10% discount rate. The Emission Reduction ($/t$CO_2e$) is derived by dividing the NPVs by the emission reductions for the 20 years. A harmful Emission Reduction ($/t$CO_2e$) value indicates that 'Use of belt conveyors and bucket elevators instead of pneumatics' reduces emissions and has a financial benefit. In contrast, a positive Emission Reduction ($/t$CO_2e$) value indicates emissions reduction without financial gain, making the option costly financially. For clarity purposes, the data in Table 9 is separated into MACCs for Technology (Figure 16) and MACCs for Alternate Fuels (Figure 17).

MACCs for technology

Figure 16 below showcases the marginal abatement costs for various technologies relevant to the cement sector. Notably, 'Decarbonated feedstocks (steel slag or fly ash)' and 'Conversion from the long dry kiln to preheater/ pre-calciner kiln' exhibit highly favorable marginal abatement costs at ($83.82) and ($82.35), respectively. This indicates that these options can lead to cost savings of approximately $83.82 and $82.35 per ton of CO_2 reduced, making them economically attractive due to their monetary benefits. Over 20 years, these options reduced 2,380,602 tons and 2,423,885 tons of CO_2 emissions, surpassing most other options except for 'blended cement.'

Blended cement, while a more costly option with a marginal abatement cost of $0.53, delivers the highest CO_2 emission reductions, amounting to 2,583,360 tons over 20 years. Although marginally expensive compared to the two options discussed earlier, it provides superior CO_2 emission reductions. When contrasted with these three options, the remaining options yield comparatively lower CO_2 emission reductions, making them less favorable from a cost-effectiveness standpoint.

Table 9: MACCs for Sample Cement Industry

Sr. #	Control Technology	Emission Reduction (t CO2e)	Energy Savings (KWh /MT)	Capex Costs ($/ MT)	Opex Saving ($/ MT)	Energy Savings ($/ year)	Operating Costs ($/ year)	Capital Costs ($)	NPV ($)	Emission Reduction (tCO2e / 20-year)	Marginal Abatement Costs ($/ tCO2e)
1	Use of belt conveyors and bucket elevators instead of pneumatics	0.00154	2.5	3.43	0.17	182,517	102,000	2,058,000	364,258	18,461	(19.73)
2	Improvements in raw material blending	0.00062	1	2.5	(0.02)	73,007	(12,000)	1,500,000	(980,613)	7,384	132.79
3	Replace ball mills with vertical roller mills	0.00818	13	33	0.17	949,091	102,000	19,800,000	(10,851,471)	98,160	110.55
4	Heat recovery for power – cogeneration	0.01231	13.5	3	0.25	985,594	150,000	1,800,000	7,867,955	147,690	(53.27)
5	Conversion from long dry kiln to preheater/ precalciner kiln	0.19838	322.3781	7.9	0.08	23,535,856	48,000	4,740,000	196,042,658	2,380,602	(82.35)
6	Air mixing technology	0.01000	(0.23)	0.867	-	(16,792)	0	520,200	(663,156)	120,000	5.53
7	Improved ball mills	0.01538	15.5	4.8	(0.17)	1,131,608	(102,000)	2,880,000	5,885,637	184,612	(31.88)
8	High-efficiency classifiers	0.00369	2	2	(0.05)	146,014	(27,000)	1,200,000	(186,767)	44,307	4.22
9	High-efficiency motors	0.00308	5	0.67		365,035	0	402,000	2,705,748	36,922	(73.28)
10	Decarbonated feedstocks (steel slag or fly ash)	0.20199	328.23952	0.75	(0.08)	23,963,780	(48,000)	450,000	203,158,520	2,423,885	(83.82)
11	Calcareous oil shale	0.01262	20.51497	1	(0.08)	1,497,736	(48,000)	600,000	11,742,422	151,493	(77.51)

12	Convert to reciprocating grate cooler.	0.0253	(0.3)	2.8	0.11	(21,902)	66,000	1,680,000	(1,304,570)	303,120	4.30
13	High-temperature heat recovery for power generation (for long dry kilns)	0.0114	2.5	3.3	0.27	181,982	162,000	1,980,000	948,514	136,920	(6.93)
14	Upgrading of a preheater kiln to a preheater / precalciner kiln	0.0427		18	(1.10)	0	(660,000)	10,800,000	(16,418,952)	512,520	32.04
15	Blended cement	0.2153	(1.0)	0.72	(0.06)	(73,620)	(36,000)	432,000	(1,365,257)	2,583,360	0.53
16	rice husks-Anthracite	0.0258	0	0	3.37	0	2,023,242	0	17,225,001	309,600	(55.64)
17	wheat straw-Anthracite	0.0106	0	0	1.55	0	930,435	0	7,921,317	127,200	(62.27)
18	corn stover-Anthracite	0.0245	0	0	4.07	0	2,443,067	0	20,799,207	294,000	(70.75)
19	sugarcane bagasse-Anthracite	0.0190	0	0	4.08	0	2,449,168	0	20,851,146	228,000	(91.45)
20	rice paddy-Anthracite	0.0363	0	0	5.50	0	3,297,010	0	28,069,306	435,600	(64.44)
21	paper sludge-Anthracite	0.0093	0	0	(13.83)	0	(8,299,132)	0	(44,348,042)	111,600	397.38
22	sawdust-Anthracite	0.0107	0	0	0.14	0	85,982	0	732,012	128,400	(5.70)
23	waste wood-Anthracite	0.0206	0	0	(0.48)	0	(290,614)	0	(2,474,159)	247,200	10.01
24	tires-Anthracite	0.0315	0	0	(0.56)	0	(333,282)	0	(1,780,944)	378,000	4.71
25	paper-Anthracite	0.0219	0	0	(3.96)	0	(2,375,192)	0	(12,692,291)	262,800	48.30
26	rice husks-Bituminous	0.0208	0	0	3.69	0	2,215,694	0	11,840,008	249,600	(47.44)
27	wheat straw-Bituminous	0.0077	0	0	1.73	0	1,040,325	0	5,559,196	92,400	(60.16)
28	corn stover-Bituminous	0.0216	0	0	4.26	0	2,554,359	0	21,746,695	259,200	(83.90)

29	sugarcane bagasse-Bituminous	0.0162	0	0	4.27	0	2,560,020	0	21,794,897	194,400	(112.11)
30	rice paddy-Bituminous	0.0313	0	0	5.82	0	3,490,241	0	29,714,385	375,600	(79.11)
31	paper sludge-Bituminous	0.0064	0	0	(13.65)	0	(8,190,858)	0	(69,733,391)	76,800	907.99
32	sawdust-Bituminous	0.0079	0	0	0.33	0	195,263	0	1,662,386	94,800	(17.54)
33	waste wood-Bituminous	0.0178	0	0	(0.30)	0	(182,034)	0	(1,549,759)	213,600	7.26
34	tires-Bituminous	0.0288	0	0	(0.38)	0	(225,410)	0	(1,919,045)	345,600	5.55
35	paper-Bituminous	0.0190	0	0	(3.78)	0	(2,265,222)	0	(19,285,113)	228,000	84.58
36	rice husks-Sub Bituminous	0.0229	0	0	7.19	0	4,311,506	0	23,039,389	274,800	(83.84)
37	wheat straw-Sub Bituminous	0.0089	0	0	3.73	0	2,239,381	0	19,065,111	106,800	(178.51)
38	corn stover-Sub Bituminous	0.0228	0	0	6.26	0	3,753,544	0	31,956,034	273,600	(116.80)
39	sugarcane bagasse-Sub Bituminous	0.0173	0	0	6.27	0	3,759,413	0	20,089,168	207,600	(96.77)
40	rice paddy-Sub Bituminous	0.0333	0	0	9.31	0	5,587,530	0	47,569,791	399,600	(119.04)
41	paper sludge-Sub Bituminous	0.0076	0	0	(11.68)	0	(7,007,729)	0	(59,660,748)	91,200	654.17
42	sawdust-Sub Bituminous	0.0090	0	0	2.32	0	1,393,624	0	11,864,703	108,000	(109.86)
43	waste wood-Sub Bituminous	0.0189	0	0	1.69	0	1,015,170	0	5,424,763	226,800	(23.92)
44	tires-Sub Bituminous	0.0299	0	0	1.51	0	908,051	0	7,730,754	358,800	(21.55)
45	paper-Sub Bituminous	0.0202	0	0	(1.78)	0	(1,069,786)	0	(9,107,691)	242,400	37.57

46	rice husks-Lignite	0.0295	0	0	15.06	0	9,035,517	0	76,924,447	354,000	(217.30)
47	wheat straw-Lignite	0.0127	0	0	8.22	0	4,934,852	0	26,370,349	152,400	(173.03)
48	corn stover-Lignite	0.0266	0	0	10.78	0	6,470,652	0	55,088,309	319,200	(172.58)
49	sugarcane bagasse-Lignite	0.0211	0	0	10.80	0	6,477,326	0	55,145,127	253,200	(217.79)
50	rice paddy-Lignite	0.0400	0	0	17.22	0	10,331,817	0	87,960,587	480,000	(183.25)
51	paper sludge-Lignite	0.0114	0	0	(7.39)	0	(4,433,556)	0	(37,745,361)	136,800	275.92
52	sawdust-Lignite	0.0128	0	0	6.80	0	4,078,853	0	21,796,120	153,600	(141.90)
53	waste wood-Lignite	0.0227	0	0	6.16	0	3,694,454	0	31,452,968	272,400	(115.47)
54	tires-Lignite	0.0335	0	0	5.75	0	3,450,960	0	29,379,971	402,000	(73.08)
55	paper-Lignite	0.0240	0	0	2.63	0	1,580,846	0	13,458,635	288,000	(46.73)

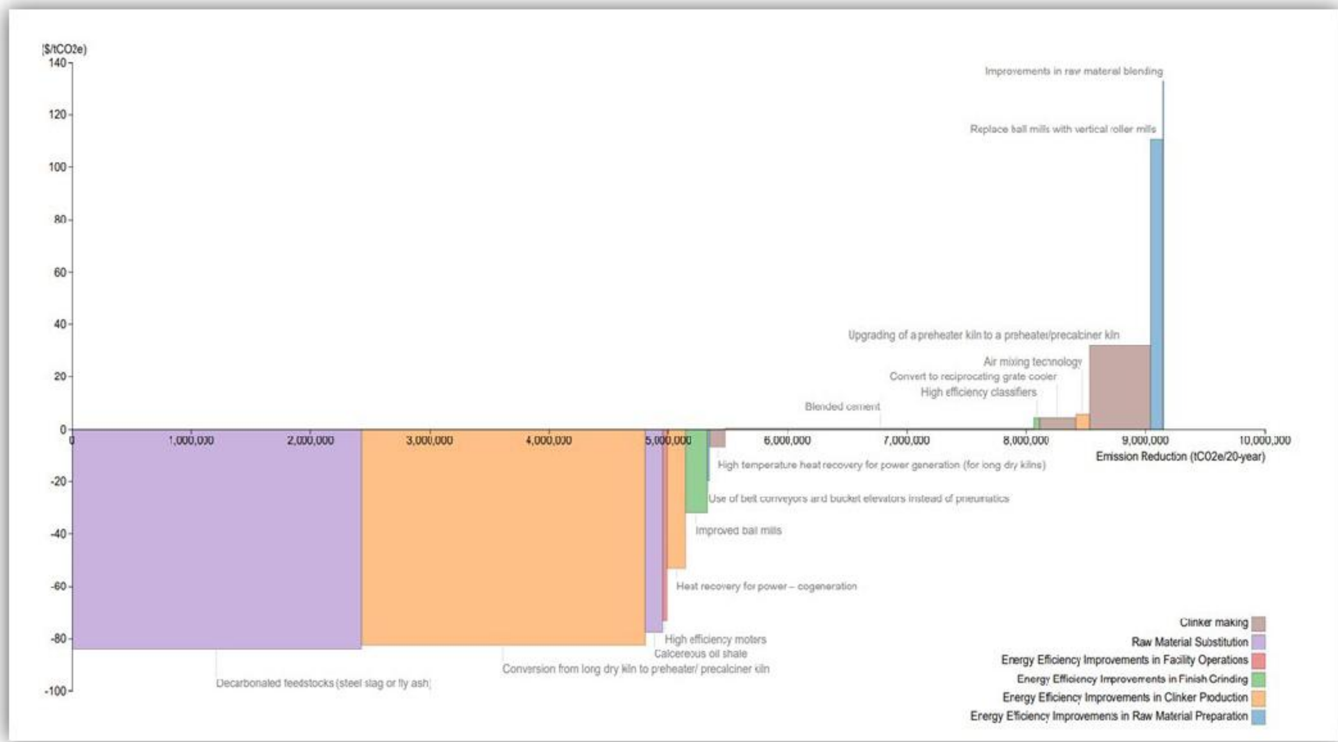


Figure 16: MACCs for Technology Options

MACCs for Alternate Fuels

Figure 17 showcases the marginal abatement costs for various alternative fuels in Pakistan. It can be noted that rice paddy, if mixed with different types of coal, the CO_2 reduction in tons of 480,000 for lignite, 435,600 for anthracite, 399,600 for bituminous, and 375,600 Bituminous, which is the highest among available options in the context of CO_2 reduction. Whereas the marginal abatement costs per ton of CO_2 reduced are ($183.25) for lignite, ($64.44) for anthracite, for Sub-Bituminous ($119.04), and ($79.11) for Bituminous, which means that this option will not only reduce emissions but will also benefit in saving cost to the industry. However, in the case of rice husk, if mixed with different types of coal, the CO_2 reduction in tons is 354,000 for lignite, 309,600 for anthracite, 274,800 for bituminous, and 249,600 for Bituminous, which is the 2nd highest among available options in the context of CO_2 reduction. In contrast, the marginal abatement costs per ton of CO_2 reduced are ($217.30) for lignite, ($55.64) for anthracite, and ($83.84) and ($47.44 for bituminous, making them economically attractive due to the monetary benefits they offer. Being 3rd highest on the list of CO_2 reduction, corn stover, if mixed with different types of coal as an alternative fuel, emissions are reduced by 319,200 for lignite, 294,000 for anthracite, 273,600 for bituminous, and 259,200 Bituminous, which is the 3rd highest among available options in the context of CO_2 reduction. In contrast, the marginal abatement costs per ton of CO_2 reduced are ($172.58) for lignite, ($70.75) for anthracite, for Sub Bituminous ($116.80) and ($83.90) Bituminous, making them economically attractive due to the monetary benefits they offer. Wheat straw, despite contributing less emission compared to the options discussed above as it has a 20% replacement ratio with different types of coal, is still a viable option as the supply of wheat straw is available in ample amounts. Considering wheat straw, if mixed with different types of coal, the CO_2 reduction in tons is 152,400 for lignite, 127,200 for anthracite, 106,800 for bituminous, and 92,400 for Bituminous; in contrast, the marginal abatement costs per ton of CO_2 reduced are ($173.03) for lignite, ($62.27) for anthracite, for Sub Bituminous ($178.51) and ($60.16 for bituminous, which indicates the cost of production will be reduced in a more significant number using wheat straw.

If used as alternative fuels, such as waste tires, paper waste, sugarcane bagasse, and waste wood, the other options will contribute to a considerable CO_2 reduction. Still, some options with favorable marginal abatement costs are more costly due to less supply availability. Tire waste has a high calorific value and reduces CO_2 emissions in a more significant number, but they are considered not a viable option due to less availability. Sugarcane bagasse is also not considered a sugar mill, and local farmers mostly use it to create brown sugar. The remaining options, such as paper sludge and paper waste, have a favorable marginal abatement cost per CO_2 positive, and emission reduction is also meager compared with other options, making it not a favorable option to be used as an alternative fuel.

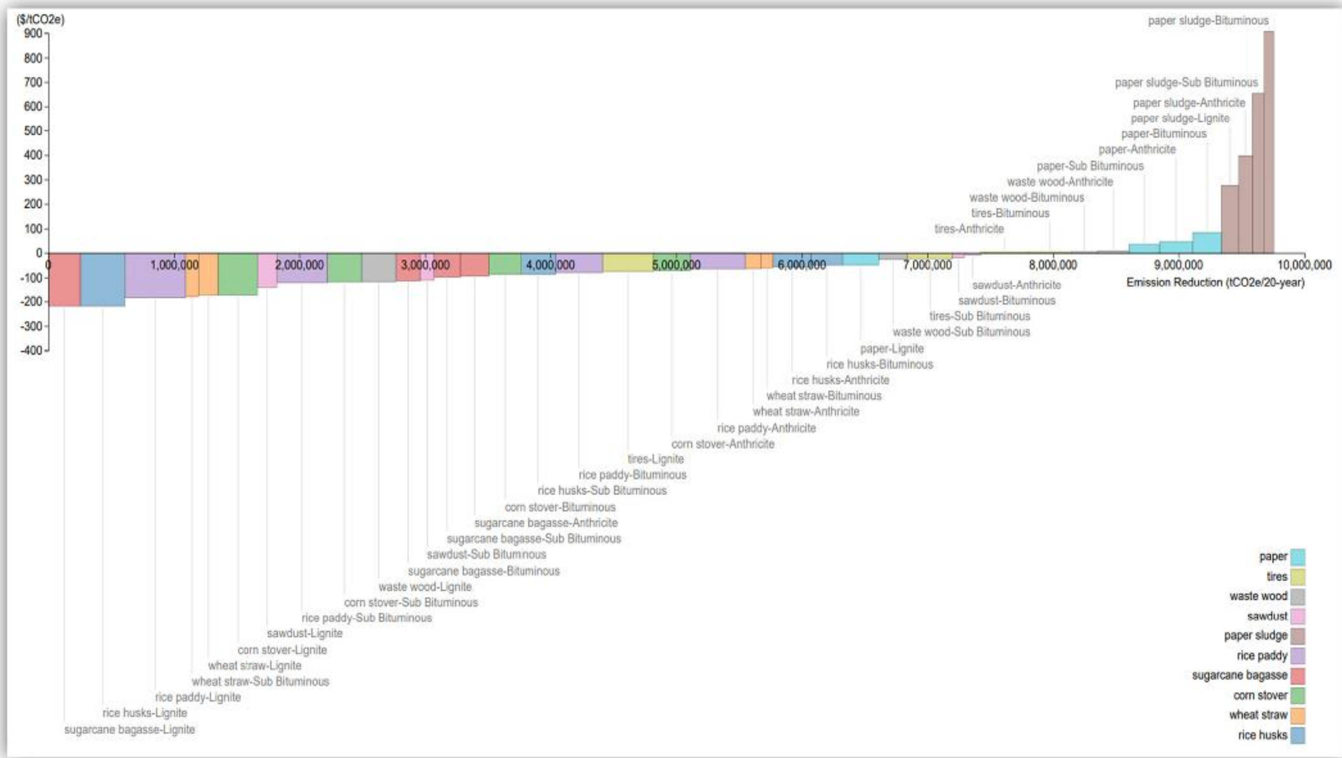


Figure 17: MACCs for Alternate Fuels

MAAC Curves Findings

The above results were attained based on data from a cement plant that produced 600,000 tons annually. If no intervention is made, the cement plant with the same production level in the next 20 years will emit 9,600,000 tonnes of CO_2. From the MAAC curves discussed in the above sections, a summary of Table 10 is presented below. This table presents the savings in cost and CO_2 emissions using the three most critical technological interventions and the four most important alternative fuels that can partially replace coal burning in Kilns.

Table 10: MAAC Curves Findings Summary table

Sr. #	Control Technology	Capital Costs ($)	Net Present Value ($)	Emission Reduction (tCO_2e)	Emission Reduced (%)	Marginal Abatement Costs ($/ tCO_2e)
1	Conversion from long dry kiln to preheater / precalciner kiln	4,740,000	196,042,658	2,380,602	24.8 %	(82.35)
2	Decarbonated feedstocks (steel slag or fly ash)	450,000	203,158,520	2,423,885	25.2 %	(83.82)
3	Blended cement	432,000	(1,365,257)	2,583,360	26.9 %	0.53
4	Rice husks-Bituminous	0	11,840,008	249,600	2.6 %	(47.44)
5	Corn stover-Bituminous	0	21,746,695	259,200	2.7 %	(83.90)
6	Wheat straw-Bituminous	0	5,559,196	92,400	0.96 %	(60.16)
7	Rice paddy-Bituminous	0	29,714,385	375,600	3.9%	(79.11)

It is evident that technological solutions are capital-intensive, especially the “Conversion from the long dry kiln to preheater / precalciner kiln.” However, all three technological interventions result in significant environmental benefits by reducing CO_2 emissions. In terms of costs, the “Conversion from the long dry kiln to preheater / precalciner kiln” and “Decarbonated feedstocks (steel slag or fly ash)” recover the capital expense and result in a positive NPV. On the other hand, “Blended cement” cannot recover the capital expense and has a negative NPV.

Using alternate fuels, rice husk, corn stover, wheat straw, and rice paddy, results in emission reductions of 2.6%, 2.7 %, 0.96%, and 3.9%, respectively. While these emission reductions appear substantially less than those given by technological interventions, it is pertinent to note that adopting alternate fuels requires no capital expense. Hence, they are the easiest and quickest source of CO_2 emissions reduction.

The above analysis was done for one cement plant. If the results are extrapolated to 73 million tons of annual cement production over 20 years, it will result in 1.168 billion tons of CO_2. The above techniques can reduce CO_2 emissions, as shown below.

Table 11: Best available technologies according to MACCs

Sr. #	Control Technology	Emission Reduction (tCO_2e)	Emission Reduced (%)
1	Conversion from long dry kiln to preheater / precalciner kiln	289,639,865	24.8 %
2	Decarbonated feedstocks (steel slag or fly ash)	294,906,044	25.2 %
3	Blended cement	314,308,800	26.9 %
4	Rice husks-Bituminous	30,368,000	2.6 %
5	Corn stover- Bituminous	31,536,864	2.7 %
6	Wheat straw-Bituminous	11,242,000	0.96 %
7	Rice paddy-Bituminous	45,699,252	3.9%

05

Case Study: Sustainable Solution for Cement Production in Pakistan

Pakistan ranks 20th globally amongst the countries with coal reserves, with a proven coal reserve of 3,377 million metric tonnes (MMT). However, Pakistan's local coal reserves are relatively low quality and have high sulfur content. Most of the coal in Pakistan is lignite or sub-bituminous, which has a lower energy content than higher-quality bituminous or anthracite coal. This lower quality can impact efficiency and environmental performance in terms of emissions. Due to these concerns, Pakistan relies on imported coal to meet the consumption requirements of different sectors of the economy.

The total consumption of coal by different sectors of the economy stood at 15.418 MMT during the period under consideration, out of which 9.402 million metric tons were mined indigenously while the remaining 6.576 million tons were imported from various international countries like Indonesia, South Africa, and Afghanistan. The coal from Afghanistan is transported via trucks (40 tonnes capacity), while imported coal from other countries is transported via maritime transport to the port in Karachi. This coal is transported to the hinterland via Railways and then trucks. Thus, Pakistan's cement industry has a high potential to reduce reliance on coal in general and imported coal in particular by replacing some coal with locally available biowaste/fuels. This will create a win-win situation by simultaneously reducing costs and CO_2 emissions.

Agriculture accounts for roughly 25 percent of GDP, and Pakistan is among the world's top producers of crops such as wheat, cotton, sugarcane, rice, etc. The waste of these crops can be used as biofuel for the cement industry to be mixed with coal in kiln operations. Based on the discussion of Chapter 4, the most viable crops are wheat, rice, and corn. Not only are these crops readily available in both the north and south regions, but refuse/waste of these crops have sufficient high heat content for cement production.

Sustainable Supply Chain Solution

In this section, we have proposed a supply chain solution for alternate biofuels that can be mixed with coal for kiln operations. This would reduce the coal used and help decarbonize the cement industry.

ASSUMPTION:

During cost and energy emission calculation, the following assumptions were used:

- Bituminous coal is used as the benchmark for these calculations.
- A negative cost savings shows that using these biofuels increases cost.
- The average transport cost for 10 MT of biofuel is PKR 50,144.
- The purchase cost of rice huck, rice addy, corn stover, and wheat straw were taken from the market survey and assumed not to be impacted by inflation, etc.
- 35% of coal can be replaced with rice husk and rice paddy, while only 20% can be replaced with wheat straw and corn stover.
- The cement industry will not expand for the next twenty years. However, it is assumed to be operating at its total capacity of 73 MMT in 2040.

To develop a sustainable supply chain for biofuels to replace coal partially, the crop chosen must fulfill three major requirements – (1) have the necessary calorific value to replace coal partially, (2) relatively cheaper procurement costs as compared to the coal, and (3) availability of the required amount of the biofuel, as otherwise cement plants will not be interested in using them.

Table 11 provides the calorific value, replacement ratio (how many kgs of biofuel are required per kg of coal), and cost-saving (per ton of cement produced).

Table 12: Features of the biofuels

Sr. #	Name of Biofuel	Calorific Value	Replacement ratio	Cost Saving ($/MT)	Emissions Saving (CO_2/MT)
1	RICE HUSK	16.2 GJ/dry ton	1.648	3.69	0.0208
2	WHEAT STRAW	18.2 GJ/dry ton	1.467	1.73	0.0077
3	CORN STOVER	15.4 GJ/dry ton	1.734	4.26	0.0216
4	SUGARCANE BAGASSE	19.4 GJ/dry ton	1.376	4.27	0.0162
5	RICE PADDY	15.9 GJ/dry ton	1.679	5.82	0.0045
6	PAPER SLUDGE	8.5 GJ/dry ton	3.141	-13.65	0.0064
7	SAWDUST	16.5 GJ/dry ton	1.618	0.33	0.0079
8	WASTE WOOD	17.4GJ/dry ton	1.534	-0.30	0.0178
9	TIRES	37 GJ/dry ton	0.722	-0.38	0.0288
10	PAPER	22 GJ/dry ton	1.214	-3.78	0.019

The most beneficial biofuels are rice paddy ($5.82/MT), sugarcane bagasse ($4.27/MT), corn Stover ($4.26/MT), rice husk ($3.69/MT), and wheat straw ($1.73/MT). Sugarcane bagasse is primarily available for 2-3 months of the year and has high utilization in local factories; thus, it is not considered a viable option for the cement industry.

A 5-year average production (2018-19 to 2022-23) for rice, wheat, and corn shows an annual production of 7.53 MMT, 25.71 MMT, and 8.723 MMT, respectively. Punjab accounts for 52% of the national rice production, 77% of the national wheat production, and 85% of the national corn production. On the other hand, Sindh contributes 38% of the national rice production, 15% of the national wheat production, and less than 1% of corn production. There are 13 cement plants in Punjab and four in Sindh, indicating that rice, wheat, and corn are ideal crops for alternative fuel in the cement industry. Figure 18, Figure 19, and Figure 20 highlight the geographical location of rice, wheat, and corn production in Pakistan.

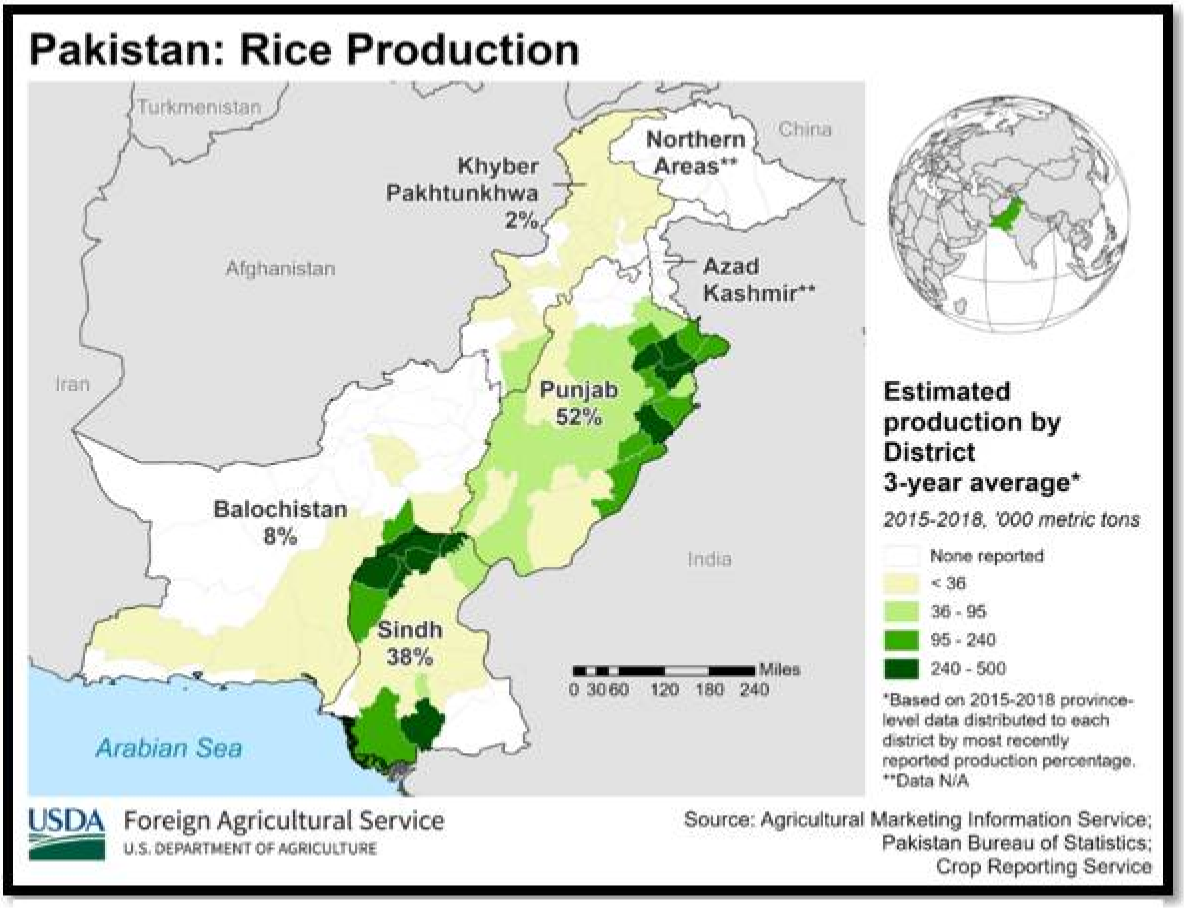


Figure 18: Area Wise Rice Production in Pakistan

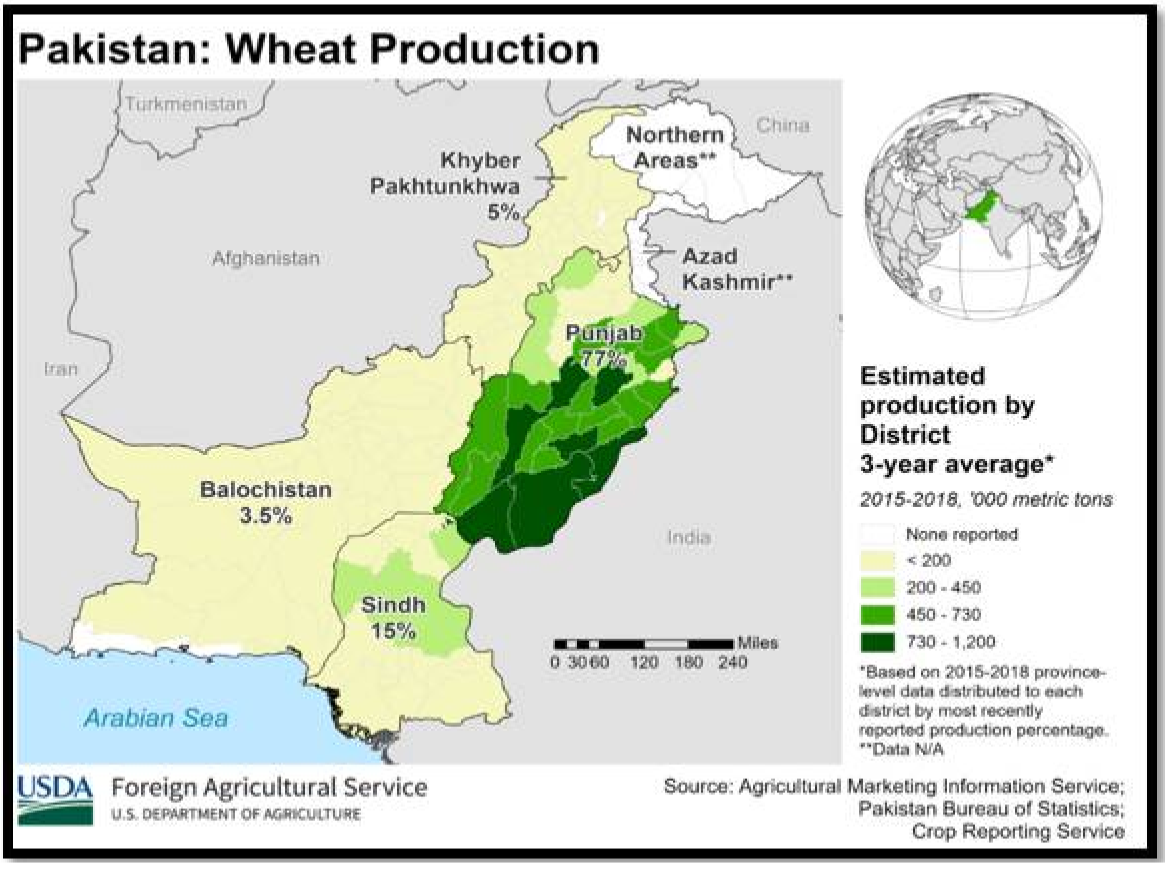


Figure 19: Area-wise wheat Production in Pakistan

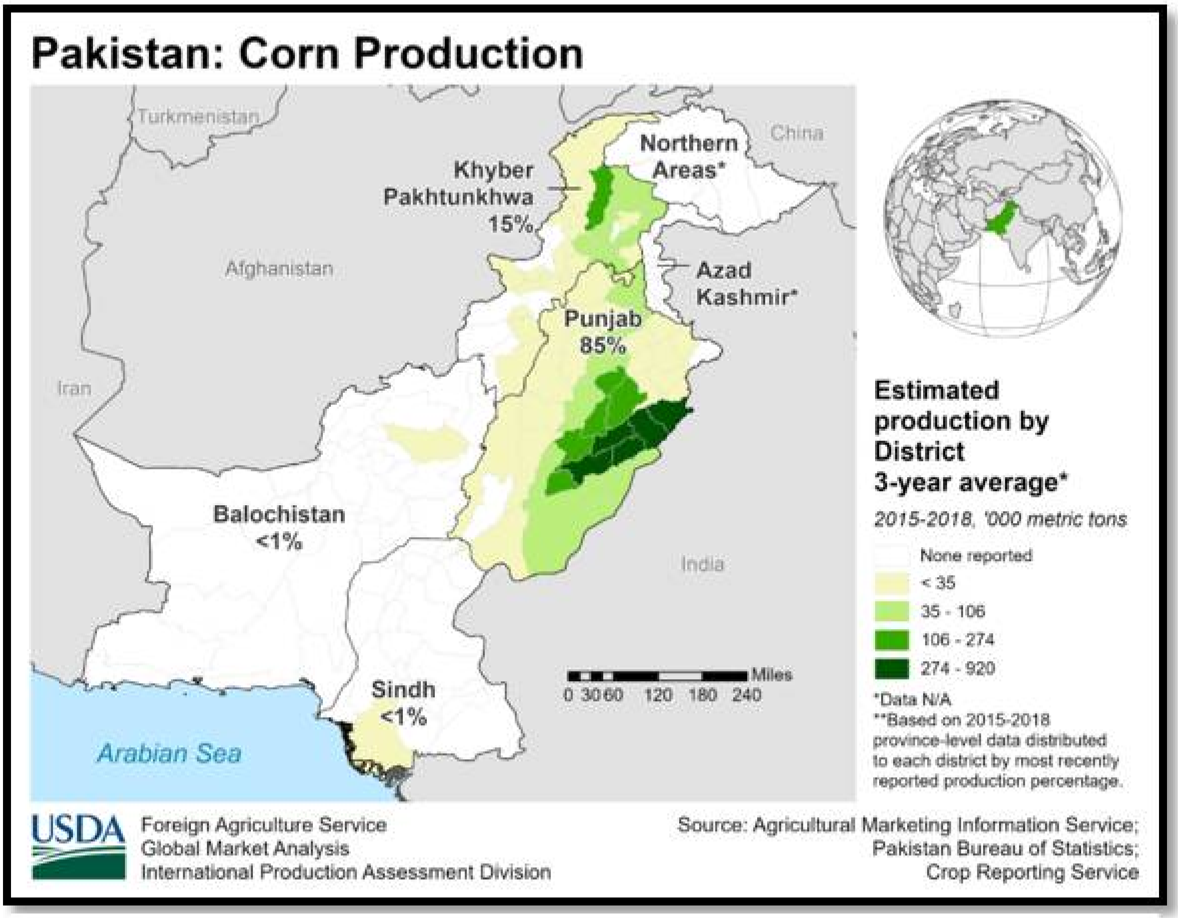


Figure 20: Area wise Corn Production in Pakistan

Availability Analysis of Alternate Biofuels:

To be a viable alternative fuel, the biofuel chosen must be available for round-the-year operations; otherwise, cement plants will not be interested in using it. Thus, the first requirement is to calculate the amount of biofuel needed for one-ton production of cement. 150 kg of Bituminous coal is required to produce 1 tonne of cement.

Table 13: Fuel requirement for producing one tonne of cement

FOR PRODUCING 01 MT OF CEMENT	RICE HUSK	WHEAT STRAW	CORN STOVER	RICE PADDY
Amount of Standalone Coal required (kg)	150	150	150	150
Total amount of coal and biofuel mixture (kg)	181.13	162.54	170.25	182.71
Coal in the mixture (kg)	97.50	120.00	120.00	97.50
Alternate fuel in the mixture (kg)	83.63	42.54	50.25	85.21
Reduction in coal (kg)	52.5	30	30	52.5

To replace coal alternative fuels with coal to produce each ton of cement, around 83.63 kg of rice husk, 85.21 kg of rice paddy, 42.54 kg of wheat straw, and 50.25 kg of corn stover are required. Two scenarios can be developed for the cement industry's round-the-year operations. Firstly, the amount of biofuel required to meet last year's production, i.e., 44.58 MMT of cement, and secondly, the amount required to meet the accumulated production capacity of all cement plants in Pakistan, i.e., 73 MMT. Both these scenarios are discussed in Table 12.

Table 14: Scenario Analysis

SR. #	RICE HUSK	WHEAT STRAW	CORN STOVER	RICE PADDY
SCENARIO 1: MEET THE PRODUCTION REQUIREMENT OF LAST YEAR (2022-2023) I.E., 44.58 MMT				
Alternate fuel required to meet year 22-23 requirement (MMT)	3.73	1.9	2.24	3.8
Availability of crop (MMT) *see annex A for calculations)	3.47	16.8	6.32	18.83
Demand percentage to available crop	107%	11%	35%	20%
Raw material sufficient	No	Yes	Yes	Yes
SCENARIO 2: MEET THE FULL PRODUCTION CAPACITY OF THE CEMENT INDUSTRY, I.E., 73 MMT				
Alternate fuel required to meet capacity demand (MMT)	6.11	3.11	3.67	6.22
Availability of crop (MMT) *see annex A for calculations)	3.47	16.8	6.32	18.83
Demand percentage of available crop	176%	18%	58%	33%
Raw material sufficient	No	Yes	Yes	Yes

Based on the above analysis, it is evident that rice husk alone is not sufficient to meet the current or capacity production requirements. However, wheat straw, corn stover, and rice paddy are adequate to meet these requirements. It is important to note that maize/corn and rice are Kharif crops, while wheat is a Rabi crop. Hence, year-round operations require a combination of Rabi and Kharif crops, assuming a 6-month storage of biofuel inventory.

It is important to note that rice husks have already established a supply chain and are used in the energy generation industry. Thus, the cement industry will find it challenging to procure rice husks. On the other hand, rice paddy (a significant byproduct of rice crops) may be a more viable option. Rice paddies are not only sufficient to meet the demand of the cement industry, but their use as fuel will have a significant impact on the environment. Typically, farmers burn rice paddies to clear their fields for subsequent cultivation, which causes severe harm to the environment as a consequent smog is a recurring phenomenon that afflicts socio-economic activities across Punjab and Sindh [58], [59]. Developing a supply chain for rice paddy will allow the burning of rice paddies in a more controlled environment than in an open field and cause environmental havoc.

06

Way Forward

Challenges

Heavy Dependence On Coal

Pakistan's cement industry's reliance on coal as a primary energy source is a significant hurdle for decarbonization. Coal constitutes 51.4% of the energy used in the industrial sector, with cement alone consuming nearly 36% of the industrial sector's coal usage. (Nation, 2023). Moreover, the trend of coal consumption has been on an upward trajectory, with an annual compound growth rate exceeding 20% since 2016. This heavy dependency on coal makes transitioning to lower-carbon alternatives challenging, given the established infrastructure and processes centered on coal usage. The cement sector in Pakistan finds itself on unstable ground, mainly owing to its heavy reliance on coal. The soaring prices and unpredictable supply of imported coal have forced many plants to dial down operations or shut down temporarily, casting a long shadow on the industry's export growth during the fiscal year of 2022-23. The sector's tether to foreign shores for over 66% of its coal supply, mainly from South Africa and Indonesia, leaves it at the mercy of the ebbs and flows of the global market. While coal keeps the kilns burning, it also stokes the flames of environmental concern. The cement industry's sizable appetite for coal significantly contributes to the country's carbon emissions—a fact often overshadowed in national dialogues around carbon footprint, even as new plants mushroom across the country, further fanning these emissions. Regulatory headwinds are also blowing in, with an increasing emphasis on trimming down CO_2 emissions, nudging the sector towards a greener energy tableau. Amidst the swirling energy market tempest, some cement producers in the northern reaches of Pakistan are casting their nets towards Afghanistan's coal reserves. However, this new avenue comes with supply chain modifications and quality assurance challenges. Beyond the coal problem, the sector also grapples with broader economic tremors triggered by dwindling demand in the wake of natural calamities or political unease and the ripple effects of a global economic slowdown. Navigating this complex landscape calls for a concerted effort to unearth sustainable energy alternatives, ramp up energy efficiency, and bolster domestic coal production to lessen the tether to foreign coal supplies. This multi-pronged approach could pave the way towards steadier ground for Pakistan's cement industry, blending economic robustness with environmental responsibility.

Limited Fiscal Space And Investment:

In the pursuit of decarbonizing Pakistan's cement industry, formidable challenges emerge, with limited fiscal space and investment resources standing out as significant hurdles. In scientific terms, this translates into the struggle to secure the necessary financial means for adopting cutting-edge green technologies and implementing sustainable practices to curb emissions. Pakistan's fiscal landscape is constrained by many factors, including high public debt and competing budgetary priorities, encompassing healthcare, education, and infrastructure development. Such fiscal constraints impede the government's ability to allocate substantial resources to incentivize the transition to low-carbon cement production. Moreover, the cement industry faces the problem of making substantial initial investments in sustainable technologies and practices, often with long payback periods. This capital-intensive nature, coupled with the private sector's reluctance to embrace these technologies, presents challenges that necessitate creative solutions, international collaboration, and the mobilization of financial and technological resources to navigate the intricate path toward a more environmentally responsible cement industry in Pakistan.

Impact Of Interest Rates

Interest rate, defined as the amount charged by lenders to borrowers for the use of money, expressed as a percentage of the principal, plays a crucial role in the economic landscape of a country, influencing the cost of borrowing and the return on savings. The recent retention of a high % interest rate of 22% by the Central Bank of Pakistan poses a notable challenge to the decarbonization endeavors within the cement industry. Firstly, the elevated cost of borrowing, exacerbated by high-interest rates, deters the essential capital investment required for transitioning to low-carbon technologies or upgrading existing infrastructures to greener alternatives. The financial commitment towards such transitions is substantial, and with the augmented financing costs, the anticipated Return on Investment (ROI) diminishes, making sustainable investments less appealing. Secondly, the operational costs of cement companies could rise if they are subjected to variable-rate loans, thereby straining financial resources and leaving less room for investment in decarbonization initiatives. Furthermore, access to capital, a lifeline for operational and strategic shifts towards sustainability, may be constrained. High-interest rates could deter investors, whose apprehensions might be fueled by the eroded profits due to increased interest costs or the perceived financial barriers to reducing carbon emissions in the industry. This financial milieu could also disincentivize innovation and research into cleaner production methods, potentially hindering collaborations with other sectors or entities striving for sustainability. Lastly, cash flow constraints induced by high-interest rates limit the funds available for reinvestment into decarbonization initiatives. The compounded effect of these financial hurdles could significantly hamper the pace at which the cement industry can adopt more sustainable, low-carbon operations, undermining the broader decarbonization agenda.

Technical Innovation And Inflation

The journey toward decarbonization in the cement industry is loaded with numerous challenges, among which the lack of technical innovation and prevailing inflation are substantial. The lack of local technical innovation stifles the industry's ability to transition to cleaner and more energy-efficient production methods. Despite the availability of alternative, greener technologies, the adoption rate within the industry is notably sluggish due to a shortage of technical advancements that would otherwise drive down the costs and improve the efficiency of these technologies. This technological stagnation hampers the industry's ability to meet decarbonization goals and exacerbates its vulnerability to the adverse financial implications of high inflation rates. Inflation, characterized by a general price increase and a fall in the purchasing value of money, further compounds the cement industry's financial challenges. The high inflation rate escalates the cost of raw materials, energy, and other operational expenses, thereby straining the already thin profit margins of companies within the industry. In a high inflation scenario, the cost of financing also rises, making it exceedingly difficult for companies to secure the necessary funds for investing in greener technologies or upgrading existing infrastructures to meet environmental standards.

Furthermore, the interaction between inflation and lack of technical innovation creates a feedback loop that further deters decarbonization efforts. High inflation rates could deter research and development investments, a crucial technical innovation driver. The resulting lack of innovation hampers the industry's ability to reduce production costs and improve efficiency, making it less resilient to the financial strains imposed by inflation. This vicious cycle impedes the industry's transition to greener operations and threatens its financial sustainability significantly when the high-interest rate exacerbates the cost of borrowing. Moreover, the potential loss scenario projected due to these factors significantly deters the industry stakeholders from committing to the capital-intensive transition toward decarbonization. The apprehension of entering a loss phase due to high operational and financing costs, exacerbated by inflation and lack of technical innovation, forms a formidable barrier to adopting greener, low-carbon technologies. In conclusion, the intertwined challenges of lacking technical innovation, rampant inflation, and high-interest rates pose significant hurdles to the cement industry's decarbonization efforts. A multi-faceted approach encompassing financial, technological, and policy interventions is imperative to navigate these challenges and propel the industry toward a sustainable, low-carbon trajectory.

Opportunities for Pakistan

An intricate array of control measures will play a pivotal role in the quest for net-zero CO_2 emissions in Pakistan's cement industry from 2020 to 2050. The initial phase, slated for 2024 -2030, will concentrate on laying a solid foundation for decarbonization. During this period, the industry will optimize the existing waste heat recovery (WHR) systems with strict control measures to ensure these systems operate at peak efficiency. Monitoring and controlling these WHR systems will be paramount to extracting the maximum waste heat, boosting energy efficiency, and simultaneously curbing CO_2 emissions. Concurrently, the industry will integrate renewable energy sources, especially solar panels, during 2024-2030. Advanced control strategies will be employed to oversee the efficient generation and utilization of solar energy, thus reducing the industry's reliance on conventional electrical grids during daylight hours. Between 2024 and 2030, the cement industry will make strides in enhancing electrical efficiency and emissions reduction through technology upgrades. This phase will introduce advanced process control and management systems supported by stringent control measures. These systems encompass various vital technologies, including transitioning from pneumatic to mechanical raw material transport, substituting ball mills with high-efficiency or vertical roller mills, utilizing high-efficiency classifiers, installing adjustable speed drives for kiln fans, and incorporating oxygen enrichment and air mixing technology. These technologies will be meticulously controlled to maximize energy efficiency while reducing the carbon footprint. Moving into the subsequent phase, from 2031 to 2040, the industry underscores its commitment to decarbonization and sustainable practices. This period's Control measures will include establishing an integrated system for monitoring and controlling emissions. This system will enable systematic carbon credit accumulation, with stringent control measures for precise emissions tracking, ensuring compliance and transparency. Exploring alternative fuels and materials from 2024 to 2030 will necessitate rigorous control measures. Cement plants must implement advanced control systems to ensure the safe and efficient use of alternative fuels like biomass and alternative raw materials such as steel slag and pozzolanic materials. These control systems will monitor and regulate combustion processes, optimizing energy efficiency while mitigating emissions.

The journey towards advanced clinker production technologies, such as oxy-combustion, carbonate looping, and syngas co-production from 2030 to 2035, demands precise control systems. These systems will be responsible for ensuring the efficient operation of these innovative technologies, minimizing emissions, and advancing the sustainability of cement production. In the final phase, from 2041 to 2050, the industry will intensify its efforts to achieve net-zero CO_2 emissions. Advanced control measures will be enacted for emissions-reduction technologies such as reciprocating grate coolers, suspension preheater low-pressure drop cyclones, and the transition from long dry kilns to preheater/pre-calciner kilns. Stringent control measures for carbon capture systems and fuel switching will also be implemented, ensuring these technologies' safe, efficient, and optimized operation. The primary objective will be to minimize emissions while facilitating a seamless transition to low or zero-carbon fuels. Throughout the journey, a real-time emissions monitoring and reporting system, fortified by stringent control measures, will ensure continuous accountability and transparency. Through these meticulously designed and executed control measures, Pakistan's cement industry will endeavor to effectively work toward achieving net-zero CO_2 emissions by 2050. This steadfast commitment to control and sustainability will not only enhance the industry's efficiency. Still, it will also steadily reduce its carbon footprint, marking a significant step towards environmental responsibility and sustainability.

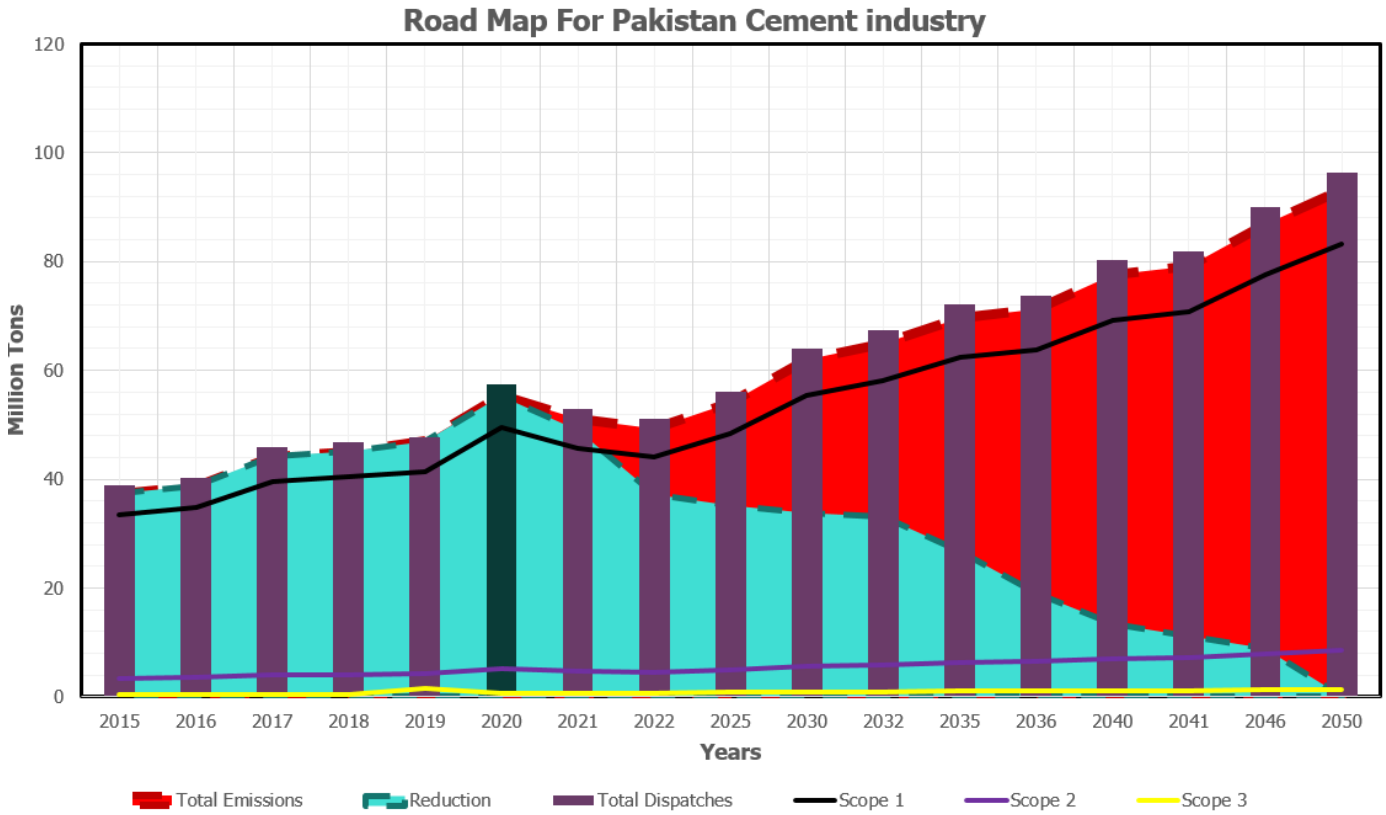


Figure 21: RoadMap for NET Zero Emission Scenario for Pakistan's Cement Sector

Green Financing

In 2019, the European Commission stipulated that the EU would become climate-neutral by 2050. This ambitious goal required significant investments from both the public and private sectors. According to the European Commission in 2021, the EU estimated that around €350 billion of additional investment would be needed in the energy system annually until 2030 to meet the 55% emission reduction target. This step by the EU indicates a significant push toward implementing green financing initiatives within the cement industry.

These initiatives reflect a broader commitment to sustainability and environmental responsibility. A notable approach involves issuing green bonds, which provide cement companies with funds to invest in projects to reduce the industry's carbon footprint. These investments often focus on cutting-edge technologies such as energy-efficient kilns and adopting cleaner fuels, all of which contribute to more environmentally friendly cement production. The EU has also embraced carbon pricing mechanisms, including emissions trading, offering financial incentives for cement manufacturers to curb their emissions. This encourages the adoption of innovative solutions like carbon capture, utilization, and storage, which have the potential to reduce emissions in the sector significantly.

Moreover, the EU requires rigorous environmental impact assessments for new cement projects. This provides investors with confidence that the industry is actively addressing sustainability concerns. Additionally, the EU supports research and development in the field, helping to advance low-carbon cement production technologies. Public procurement policies prioritize using sustainable cement products, creating a market for eco-friendly options, and incentivizing companies to adopt environmentally responsible practices. Lastly, the European Investment Bank has played a critical role by providing financial support for projects that improve energy efficiency, reduce carbon emissions, and enhance overall sustainability in the cement sector.

Promoting green financing initiatives in a developing country like Pakistan demands a flexible approach, with government policies at its core. Firstly, Pakistan should establish a robust green bond framework that lays down clear guidelines for issuing green bonds that align with international standards. Tax breaks and subsidies for green bond issuers should be introduced to incentivize companies, reducing regulatory costs and financial burdens associated with going green. Moreover, environmental impact assessments should be mandated for all industrial projects, ensuring alignment with sustainability objectives and identifying potential environmental risks. Introducing a carbon pricing mechanism, such as a carbon tax or cap-and-trade system, is crucial for encouraging emissions reduction, with the generated revenue reinvested into green financing programs. Public procurement policies can be leveraged to prioritize using sustainable cement products in government projects, creating a market for green cement and supporting the sector's transition. Additionally, funds should be allocated for research and development programs in sustainable cement production technologies, fostering innovation through collaboration between research institutions, academia, and the private sector. Capacity building through workforce development, training, and public awareness campaigns is critical to equipping the industry and the public with the necessary knowledge and skills. International collaboration, monitoring and reporting mechanisms, and private sector engagement should also be necessary. By implementing these policies, Pakistan can pave the way for a greener, more sustainable industrial landscape and earn more revenue through carbon credit trading.

Recommendations

From the operational perspective, the most viable strategy in the short term to curtail CO_2 emissions from the cement industry involves substituting coal-fueled kiln operations with biofuels, including but not limited to rice husk, rice paddies, corn stover, and wheat straw. This alternative effectively replaces 20-35% of coal in kiln operations. In the long term, the cement manufacturer can consider converting to precalciner kilns and using alternate raw materials to reduce CO_2 emissions significantly. While these technologies can be capital intensive, the cement plants will recuperate their capital cost as they lead to significant energy and production cost savings. Furthermore, we can advocate for cement manufacturers lacking waste heat recovery plants to promptly install such systems, emphasizing their potential to enhance energy efficiency and substantially decrease emissions. Concurrently, cement manufacturers already equipped with these plants are encouraged to explore upgrading options. This proactive approach across sectors can substantially improve overall energy efficiency, aligning industrial practices with sustainability goals and mitigating environmental impact.

The Pakistani government should proactively institute its carbon tax policy to incentivize domestic emissions reduction rather than being subject to specific global carbon tax instruments such as the EU's Carbon Border Adjustment Mechanism (CBAM). This tax should target industries and plants with higher carbon footprints that are not yet transitioning towards sustainable practices aligned with the nation's climate commitments. The revenue generated can be channeled into subsidies, incentives, and green financing programs to accelerate decarbonization efforts across sectors. Self-administering a carbon tax allows Pakistan to exercise greater control and autonomy in managing its environmental policy and industrial regulation. However, the design of such a tax must balance competitiveness concerns while creating a robust price signal for curbing emissions.

On the policy side, it is recommended that the Government of Pakistan (GOP) take several initiatives to encourage cement manufacturers to adopt green practices. For example, the GOP can incentivize cement manufacturers' use of renewable energy by lowering import duty on solar panels. Similarly, the GOP can offer low interest rates on loans so that industries invest in green technologies and sustainable practices. This can alleviate the financial burden on industries and encourage more investments in eco-friendly and energy-efficient technologies. GOP can implement a more robust carbon tax structure to discourage high emissions while offering tax incentives for industries that adopt greener practices or technologies. Furthermore, the GOP can legislate for regular energy efficiency audits for industries and certifications for those meeting high energy conservation and sustainable practices standards.

All mainstream industries, especially cement producers, are recommended to collaborate with academic/research institutes and allocate a certain percentage of their revenue towards research and development in green technologies, fostering innovation and new solutions for producing green cement.

Further, it is strongly recommended that there is a need for a structured dialogue between industrial sectors and the Ministry of Climate Change and other relevant industries and stakeholders to foster mutual understanding and collaborative efforts towards emissions reduction. Furthermore, there is a need for widespread adoption of indigenously developed technologies such as "CO_2 - Arrestor, CO_2 - Bin, etc." developed by NUST in industrial settings, including installation on chimneys, indoor spaces, and vehicles, to tackle Scope 1 and 3 emissions directly from the source. This technology represents a significant advancement in emissions control and should be leveraged to its fullest potential.

As highlighted in the stakeholder consultation summary annexed to this report, a multi-pronged approach involving technological upgradation, regulatory reforms, capacity building, incentivization mechanisms, and cross-sector collaboration is crucial for achieving meaningful decarbonization in Pakistan's cement industry.

07

References

References

1. IPCC, Global Warming of 1.5°C. Cambridge University Press, 2022. doi: 10.1017/9781009157940.

2. D. R. Sakhamuru, Techno-economic Analysis and Strategic Decarbonization of the Indian Cement Industry. Massachusetts Institute of Technology, 2022. [Online]. Available: https://books.google.com.pk/books?id=3IKjzwEACAAJ

3. IPCC, "2006 IPCC guidelines for national greenhouse gas inventories," 2006. Accessed: Aug. 13, 2023. [Online]. Available: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

4. IPCC, Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge, UK and New York, NY, USA, 2018. doi: 10.1017/9781009157940.

5. W. T. Choate, "Energy and Emission Reduction Opportunities for the Cement Industry," Dec. 2003. doi: 10.2172/1218753.

6. W. Shen, L. Cao, Q. Li, W. Zhang, G. Wang, and C. Li, "Quantifying CO_2 emissions from China's cement industry," Renewable and Sustainable Energy Reviews, vol. 50, pp. 1004–1012, Oct. 2015, doi: 10.1016/j.rser.2015.05.031.

7. WBCSD, "Low Carbon Technology Roadmap for the Indian Cement Sector: Status Review 2018," 2018. Accessed: Jul. 13, 2023. [Online]. Available: https://www.wbcsd.org/contentwbc/download/6071/84963/1

8. S. Bhardwaj, D. Tewari, and B. Natarajan, "Emission Reduction Approaches for the Cement Industry," Alliance for an Energy Efficient Economy, 2021.

9. U.S. Geological Survey, "Mineral commodity summaries 2022: U.S. Geological Survey," 2022. doi: 10.3133/mcs2022.

10. Z. Cao et al., "The sponge effect and carbon emission mitigation potentials of the global cement cycle," Nat Commun, vol. 11, no. 1, p. 3777, Jul. 2020, doi: 10.1038/s41467-020-17583-w.

11. S. Pauliuk et al., "Global scenarios of resource and emission savings from material efficiency in residential buildings and cars," Nat Commun, vol. 12, no. 1, p. 5097, Aug. 2021, doi: 10.1038/s41467-021-25300-4.

12. E. Worrell, L. Price, N. Martin, C. Hendriks, and L. O. Meida, "CARBON DIOXIDE EMISSIONS FROM THE GLOBAL CEMENT INDUSTRY *," 2001. [Online]. Available: www.annualreviews.org

13. J. Liu et al., "Carbon and air pollutant emissions from China's cement industry 1990–2015: trends, evolution of technologies, and drivers," Atmos Chem Phys, vol. 21, no. 3, pp. 1627–1647, Feb. 2021, doi: 10.5194/acp-21-1627-2021.

14. F. Belaïd, "How does concrete and cement industry transformation contribute to mitigating climate change challenges?," Resources, Conservation & Recycling Advances, vol. 15, p. 200084, Nov. 2022, doi: 10.1016/j.rcradv.2022.200084.

15. T. Lacerda Prazeres and Z. Xie, "What is a carbon border tax and what does it mean for trade? ," World Economic Forum, 2021. Accessed: Apr. 26, 2023. [Online]. Available: https://www.weforum.org/agenda/2021/10/what-is-a-carbon-border-tax-what-does-it-mean-for-trade/#:~:text=A%20carbon%20border%20adjustment%20tax%20is%20a%20duty,a%20trade-related%20measure%2C%20it%20affects%20production%20and%20exports.#:~:text=A%20carbon%20border%20adjustment%20tax,it%20affects%20production%20and%20exports

16. M. Larch and J. Wanner, “Carbon tariffs: An analysis of the trade, welfare, and emission effects,” J Int Econ, vol. 109, pp. 195–213, Nov. 2017, doi: 10.1016/j.jinteco.2017.09.003.

17. Harvard Law Review, “The Promise and Perils of Carbon Tariffs,” in Developments in the Law, 6th ed., vol. 135, 2022. Accessed: Apr. 26, 2023. [Online]. Available: https://harvardlawreview.org/print/vol-135/the-promise-and-perils-of-carbon-tariffs/#:~:text=Carbon%20tariffs%20can%20help%20to,incentivizing%20action%20in%20 nonregulating%20jurisdictions

18. M. Springmann, “Carbon tariffs for financing clean development,” Climate Policy, vol. 13, no. 1, pp. 20–42, Jan. 2013, doi: 10.1080/14693062.2012.691223.

19. J. Paez, “The European Union Launched the World’s First Carbon Tariff The Carbon Border Adjustment Mechanism as the next step in its climate journey,” Frost, Oct. 12, 2023.

20. PACRA, “Cement Sector Study,” 2023. Accessed: May 13, 2023. [Online]. Available: https://www.pacra.com/view/storage/app/Cement%20-%20PACRA%20Research%20-%20Mar%2723_1680173738.pdf

21. The State of Pakistan’s Economy, “Third Quarterly Report for FY18,” 2018.

22. All Pakistan Cement Manufecturars Association, “Statement of Cement Production Capacity .”

23. United Nations Environment Programme, “Greening Cement Production has a Big Role to Play in Reducing Greenhouse Gas Emissions -UNEP Global Environmental Alert Service (GEAS),” Nov. 2010, Accessed: Apr. 29, 2023. [Online]. Available: https://wedocs.unep.org/20.500.11822/8832.

24. EN 206, Concrete - Specification, performance, production and conformity. 2021.

25. ECRA and WBCSD/CSI, “Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead.,” 2017. Accessed: Sep. 17, 2023. [Online]. Available: www.ecra-online.org

26. IEA and CSI/WBCSD, “Technology Roadmap - Low-Carbon Transition in the Cement Industry,” 2018. Accessed: Jul. 29, 2023. [Online]. Available: https://www.wbcsd.org/contentwbc/download/4586/61682/1

27. Global Cement, “Global Cement Alternative Fuels Special Issue.,” 2021. [Online]. Available: https://www.cemfuels.com/reports

28. IFC, “Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis.,” 2014. Accessed: May 09, 2023. [Online]. Available: https://www.ifc.org/content/dam/ifc/doclink/2014/ifc-waste-heat-recovery-report-ifc-2023.pdf

29. Climate Strategy, “Carbon Control and Competitiveness Post 2020: The Cement Report.,” 2014. Accessed: Jun. 03, 2023. [Online]. Available: https://climatestrategies.org/wp-content/uploads/2014/02/climate-strategies-cement-report-final.pdf

30. IFC, “The Impact of COVID-19 on the Cement Industry.,” 2020. Accessed: Apr. 29, 2023. [Online]. Available: https://www.ifc.org/en/insights-reports/2020/covid-19-impact-on-cement-industry

31. Chatham House, “Making Concrete Change Innovation in Low-carbon Cement and Concrete.,” 2018, Accessed: May 29, 2023. [Online]. Available: https://www.chathamhouse.org/sites/default/files/publications/2018-06-13-making-concrete-change-cement-lehne-preston-final.pdf

32. IEA, “An energy sector roadmap to carbon neutrality in China Title of the Report,” 2020. Accessed: May 29, 2023. [Online]. Available: www.iea.org/t&c/

33. Z. Cao, E. Masanet, A. Tiwari, and S. Akolawala, “Decarbonizing Concrete Deep decarbonization pathways for the cement and concrete cycle in the United,” Evanston, IL, 2021. Accessed: Aug. 29, 2023. [Online]. Available: https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf

34. Mistra Carbon Exit., "Technical roadmap - cement industry.," 2020. Accessed: Jun. 19, 2023. [Online]. Available: https://static1.squarespace.com/static/59497bb66b8f5bd183c75745/t/5ecb9fa55060ad27ee20de31/1590402994302/MistraCarbonExit_Roadmap_Cement_v4.pdf

35. Global Efficiency Intelligence, "Deep Decarbonization Roadmap for the Cement and Concrete Industries in California," 2019. Accessed: Aug. 02, 2022. [Online]. Available: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/65dc33328033512b9dc83d80/1708929870913/Decarbonization+Roadmap+CA+Cement-+Final-Spet+2019rev.pdf

36. ECOFYS on behalf of EULA., "Competitive and Efficient Lime Industry-Cornerstone for a Sustainable Europe," 2014. Accessed: Oct. 21, 2023. [Online]. Available: https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Technical-report-by-Ecofys_0.pdf

37. TASIO project, "Waste Heat Recovery for Power Valorisation with Organic Rankine Cycle Technology in Energy Intensive Industries.," 2014, Accessed: May 07, 2023. [Online]. Available: https://cordis.europa.eu/project/id/637189

38. Heatleap project, "VALORIZING WASTE HEAT FOR ENHANCED ENERGY EFFICIENCY," 2014, Accessed: May 01, 2023. [Online]. Available: https://heatleap-project.eu/wp-content/uploads/2023/11/HEATLEAP_project_summary_E1.4.pdf

39. CO_2OLHEAT, "Supercritical CO_2 power cycles demonstration in Operational environment Locally valorising industrial Waste Heat. H2020 grant agreement N° 101022831.," 2021. Accessed: Aug. 30, 2023. [Online]. Available: https://CO_2olheat-h2020.eu/

40. AC2OCem project Del. 4.1., "Accelerating Carbon Capture using Oxyfuel technology in Cement production.," 2021. Accessed: Mar. 14, 2023. [Online]. Available: https://ac2ocem.eu-projects.de/Portals/32/D4.1_Waste%20heat%20recovery%20systems%20for%20oxyfuel%20cement%20plants.pdf?ver=5cf0irZvun92RuoXOBRtsQ%3d%3d

41. B. Vanderborght, F. Koch, L. Grimmeissen, S. Wehner, P. H. Heersche, and J.-P. Degré, "Low-Carbon Roadmap for the Egyptian Cement Industry -- Project "Egypt: Technology and Policy Scoping for a Low-Carbon Egyptian Cement Industry," 2016.

42. IFC, "Improving thermal and electric energy efficiency at cement plants: international best practice.," 2018. Accessed: Nov. 07, 2023. [Online]. Available: https://www.ifc.org/content/dam/ifc/doc/mgrt-pub/elect-enrgy-effic-cement-05-23.pdf

43. T. Tartière and M. Astolfi, "A World Overview of the Organic Rankine Cycle Market," Energy Procedia, vol. 129, pp. 2–9, Sep. 2017, doi: 10.1016/j.egypro.2017.09.159.

44. S. Santarossa, "Shrinking energy bills with ORC technology. In World Cement magazine," Jul. 2022. Accessed: Apr. 01, 2023. [Online]. Available: https://issuu.com/palladianpublications/docs/world_cement_march_2024

45. Frauke. Schorcht, Ioanna. Kourti, B. Maria. Scalet, Serge. Roudier, Luis. Delgado Sancho, and Institute for Prospective Technological Studies., Best available techniques (BAT) reference document for producing cement, lime and magnesium oxide : Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control). Joint Research Centre of the European Commission, 2013. doi: doi:10.2788/12850.

46. M. Lord and Beyond Zero Emissions, Zero Carbon Industry Plan - Rethinking Cement. 2017. Accessed: Apr. 07, 2023. [Online]. Available: https://d2v-fh04.na1.hubspotlinksstarter.com/Ctc/W+113/d2v-fH04/VXghPw6r8rlpW2NmC-74RjNmYW61z83B5cljRmN5VHnSj5kBVqW50kH_H6lZ3nZW24wJT86vNRk3N643BS7CscMhW7nGbS46GlYfSW8br7kj1zp6M-W253b9V23_10XW2MWhTP942zdqW4B4K2I5VlX7QW48FvDQ8ZPh2TN1V4ckKQL2xKW1SfZF91sNpVsW8DK3m95G-f0WW3wWVX792_-dxW2xDPCF6R187_W85cYwB7c399WW2FMmhW8VqKvxW1dy74X6H5S-RW2nr-Hk1z8RwvW8rZ3GX5Hcm8GW2p5N-n8XPqMJVTLTcn58Gd7qW37GcnY27Db-

cW5c0kZr2RvxCBVWhsS-72CS_QN7dwR9VRVfLYW7t7Hx147-DsW6YCvG58W3_67W6jVIP56SWWtWW2hnCc74
D6TwbW81JDr26qzvVLN95D8jjvNCzDN1fpVHbP9y2dW3xsv6R44kMjfd7XN9g04

47. Global Cement, “Update on electric cement kilns,” 2022, [Online]. Available: https://www.globalcement.com/news/item/14256-update-on-electric-cement-kilns?utm_source=newsletter&utm_medium=email&utm_content=567926&utm_campaign=gcw561

48. EN 197-1, Cement - Part 1: Composition, specifications and conformity criteria for common cements. https://standards.iteh.ai/catalog/standards/cen/64d327b1-d5ac-45e3-8b04-fafec9e0698e/en-197-1-2011, 2011.

49. A. Marmier, “Decarbonisation options for the cement industry,” 2023. doi: 10.2760/174037.

50. G. Habert et al., “Environmental impacts and decarbonization strategies in the cement and concrete industries,” Nature Reviews Earth and Environment, vol. 1, no. 11. Springer Nature, pp. 559–573, Nov. 01, 2020. doi: 10.1038/s43017-020-0093-3.

51. EN 206, Concrete - Specification, performance, production and conformity. 2021.

52. T. Nation, “Decarbonisation the way forward for Pakistan’s cement industry,” 17 Feb 2023. [Online]. Available: https://www.nation.com.pk/17-Feb-2023/decarbonisation-the-way-forward-for-pakistan-s-cement-industry.

53. IPCC, “2006 IPCC Guidelines for National Greenhouse Gas Inventories,” Published: IGES, Japan., 2006.

54. “State Bank of Pakistan,” [Online]. Available: https://www.sbp.org.pk/reports/quarterly/fy18/Third/SpecialSection-1.pdf.

55. “All Pakistan Cement Association,” [Online]. Available: http://apcma.com/.

56. “PACRA,” [Online]. Available: https://www.pacra.com/sector_research/Cement%20-%20PACRA%20Research%20-%20Mar’23_1680173738.pdf.

57. “Pakistan Economic Survey,” [Online]. Available: https://www.pacra.com/sector_research/Construction%20-%20PACRA%20Research%20-%20Mar’22_1648744436.pdf.

58. M. F. Khokhar et al., “Countries of the Indo-Gangetic Plain must unite against air pollution,” Nature, vol. 598, no. 7881, pp. 415–415, Oct. 2021, doi: 10.1038/d41586-021-02829-4.

59. M. F. Khokhar et al., “Recurring South Asian smog episodes: Call for regional cooperation and improved monitoring,” Atmos Environ, vol. 295, p. 119534, Feb. 2023, doi: 10.1016/j.atmosenv.2022.119534.

60. ECRA. (2016b). ECRA CCS Project Phase IV.A. Available at: https://ecraonline.org/fileadmin/redaktion/files/pdf/ECRA_Technical_Report_CCS_Phase_IV_A.pdf

61. GlobalCCSInstitute. (2021). Technology readiness and costs of CCS. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf

62. Fediuk. R., Mochalov, A., & Timokhin, R. (2018). Review of methods for activation of binder and concrete mixes. AIMS Materials Science 2018, Volume 5, Issue 5: 916-931. doi: 10.3934/matersci.2018.5.916

63. Wang, T., Yi, Z., Guo, R., Huang, H., Garcia, S., & Maroto-Valer, M. (2021). Particle carbonation kinetics models and activation methods under mild environment: The case of calcium silicate. Chemical Engineering Journal, Volume 423, 2021, 130157, ISSN 1385-8947, https://doi.org/10.1016/j.cej.2021.130157.

64. https://www.cementequipment.org/home/quality-composition-of-cement-clinker/attachment/img_5cb17d65c88c6/

65. Taylor, H. F. W. (2007). Cement Chemistry. Thomas Telford Publishing, London, UK, 2nd edn, 1997. ISBN

66. Ylmén, R., & Jäglid, U. (2013). Carbonation of Portland Cement Studied by Diffuse Reflection Fourier Transform Infrared Spectroscopy. International Journal of Concrete Structures and Materials, 7, 119-125. https://doi.org/10.1007/s40069-013-0039-y

67. The Graphene Council. (2021). Graphene in Cement & Concrete Applications.

68. Climate Strategy. (2014). Carbon Control and Competitiveness Post 2020: The Cement Report.

69. IFC. (2017). Increasing the Use of Alternative Fuels at Cement Plants.

70. CMA & IIP. (2016). Action Plan for Enhancing the Use of Alternate Fuels and Raw Materials in the Indian Cement Industry

71. ECRA. (2016). Evaluation of energy performance in cement kilns in the context of co-processing.

72. ECOFYS. (2016). Market opportunities for use of alternative fuels in cement plants across the EU - Assessment of drivers and barriers for increased fossil fuel substitution in three EU member states: Greece, Poland and Germany.

73. Cembureau. (2013). The role of cement in the 2050 low carbon economy. Available at: https://cembureau.eu/media/cpvoin5t/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf

74. ECRA. (2016). Evaluation of energy performance in cement kilns in the context of co-processing.

75. Eurostat. (2019). Renewables annual questionnaire 2017-2021 and historical revisions. Available at: https://ec.europa.eu/eurostat/documents/38154/10015688/Ren-Instructions-2018.pdf/bc81e198-d1fc-4799-bb35-f5f4f252e19b

76. Khan, M. M. H., Havukainen, J., & Horttanainen, M. (2021). Impact of utilizing solid recovered fuel on the global warming potential of cement production and waste management system: A life cycle assessment approach. Waste Management & Research, 39(4), 561–572. https://doi.org/10.1177/0734242X20978277

77. Schenckprocess. (2022). Alternative Fuel Feeding Line. Available at: https://www.schenckprocess.cz/cizkovice-cement-plant/

78. STADLER. (2021). STADLER renovates the CITR waste management facility managed by FCC Medio Ambiente in Las Marinas, El Campello (Alicante) in Spain. Available at: https://stadler-engineering.com/company/news/detail/stadler-renovates-the-citr-waste-management-facility-managed-by-fcc-medio-ambiente-in-las-marinas-el-campello-alicante-in-spain

79. ETH. (2018). A sustainable future for the European Cement and Concrete industry - Technology assessment for full decarbonisation of the industry by 2050.

80. CEWEP. (2018). Bottom Ash Factsheet. Available at: https://www.cewep.eu/wp-content/uploads/2017/09/FINAL-Bottom-Ash-factsheet.pdf

81. ASH-CEM (2016). ASH-CEM: Novel Cements & Building Materials from Incineration Ashes. Available at: https://www.sim-flanders.be/projects/ash-cem-icon/

82. INDAVER project. (2022). Twee projecten geselecteerd na open oproep om circulaire economie in Antwerps havengebied te stimuleren. Available at: https://www.indaver.com/be-nl/nieuws-media/nieuws-detail/twee-projecten-geselecteerd-na-open-oproep-om-circulaire-economie-in-antwerps-havengebied-te-stimule/

83. ETC. (2018). Mission Possible, Reaching Net-Zero carbon emissions from harder-to-abate sectors by mid-century.

84. ATEC. (2019). References cement. Available at: https://www.atec-ltd.com/images/Reference_List_IN_PROGRESS_01_2019.pdf

85. FLSmidth. (2021). FLSmidth delivers MissionZero flagship solution to Cimpor Cement. Available at: https://www.flsmidth.com/en-gb/company/news/news-and-events/2021/chlorine-bypass-solution-cimpor-cement

86. Cembureau. (2020c). Cementing the European Green Deal, reaching carbon neutrality along the cement and concrete value chain by 2050. Available at: https://cembureau.eu/media/kuxd32gi/cembureau-2050-roadmap_final-version_web.pdf

87. ATEC. (2022). LafargeHolcim, Mannersdorf (AT). Available at: https://www.atec-ltd.com/en/references/lafargeholcim-mannersdorf-at/496.html

88. ZKW Otterbein. (2022). Hintergrundinformationen zum Maßnahmenpaket "OTTERBEIN ZEMENT ECO-PLUS 2023". Available at: https://www.zkw-otterbein.de/nachbarschaftsdialog/hintergrundinformationen-otterbein-zement-eco-plus-2023

89. Vicat. (2021b). Meteor: augmentation de la part de combustibles alternatifs à Montalieu-Vercieu. Available at: https://www.vicat.fr/actualites/meteor-augmentation-de-la-part-de-combustibles-alternatifs-montalieu-vercieu

90. Catch4climate. (2021). Bericht über Informationsforum Mergelstetten (vorgezogene freiwillige Bürgerbeteiligung). Available at: https://catch4climate.com/wp-content/uploads/2022/02/Bericht_Informationsforum_Catch-for-Climate_Mergelstetten_Synopse-Version-3.pdf

91. Sandalow, D., Friedmann, J., Aines, R., McCormick, C., McCoy, S., & Stolaroff J,. (2019). ICEF Industrial Heat Decarbonization Roadmap. Bonn, Germany: ICEF. Available at: https://www.icef.go.jp/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf

92. Climate Action Tracker. (2017). Manufacturing a low-carbon society: How can we reduce emissions from cement and steel?

93. A.Spire. (2020). P4Planet 2050 Roadmap. Available at: https://www.aspire2050.eu/sites/default/files/users/user85/p4planet_07.06.2022._final.pdf

94. Dhas, S. (2021). Decarbonisation pathways for the cement industry.

95. Agora Energiewende and Wuppertal Institute. (2021). Breakthrough Strategies for Climate- Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition. www.agora-energiewende.de.

96. Cembureau. (2020b). Powering the Cement Industry. Available at: https://cembureau.eu/media/ckkpgrg1/cembureau-view-cement-sector-electricity-use-in-the-european-cement-industry.pdf

97. CemZero project. (2018). A feasibility study evaluating ways to reach sustainable cement via the use of electricity. Available at: https://www.cementa.se/sites/default/files/assets/document/65/de/final_cemzero_2018_public_version_2.0.pdf.pdf

98. Hodges, R., & Woods, D. (2020) Support to Sino-German Cooperation on NDC Implementation: Sectoral Best Practice. Available at: https://climatecooperation.cn/wp-content/uploads/2021/01/Ricardo-Industrial-decarbonisation_cement_FINAL.pdf

99. Sandalow, D., Friedmann, J., Aines, R., McCormick, C., McCoy, S., & Stolaroff J,. (2019). ICEF Industrial Heat Decarbonization Roadmap. Bonn, Germany: ICEF. Available at: https://www.icef.go.jp/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf

100. A.Spire. (2020). P4Planet 2050 Roadmap. Available at: https://www.aspire2050.eu/sites/default/files/users/user85/p4planet_07.06.2022._final.pdf

101. Hasanbeigi, A., Nilsson, A., Mete, G., Fontenit, G., & Shi. D. (2021). Fostering industry transition through green public procurement: A "How to" guide for the cement & steel sectors. Available at: https://www.

industrytransition.org/content/uploads/2021/08/1-fostering-industry-transition-through-green-public-procurement.pdf

102. GCCA. (2019). Getting the Numbers Right Project, Emissions Report 2019.

103. Thierry Lecomte, José Félix Ferrería de la Fuente, Frederik Neuwahl, Michele Canova, Antoine Pinasseau, Ivan Jankov, Thomas Brinkmann, Serge Roudier, Luis Delgado Sancho; Best Available Techniques (BAT) Reference Document for Large Combustion Plants; EUR 28836 EN; doi:10.2760/949

104. U.S. Geological Survey. (2002-2019). Data for annual publication Minerals Yearbook, Cement, XLS Format, 2002 to 2019. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-andinformation

PRIED

Policy Research Institute
for Equitable Development

www.priedpk.org

+92 51 8440512

Second Floor, Plot No. 5-N. Sitara Market, G-7/2 Islamabad