

Decarbonizing Pakistan's Cement Sector: The Role of Carbon Capture and Storage (CCS) Technologies [†]

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Abstract: The cement industry accounts for 7% of total greenhouse gas emissions, with Pakistan's industry emitting 8.9 million tons annually. Existing decarbonization efforts are insufficient due to technological and policy constraints. CCS presents several challenges, including high costs and energy requirements, as well as advanced monitoring requirements. Policy challenges include the lack of clear regulatory frameworks and incentives for CCS deployment. This study uses scenario analysis with the Low-Emission Analysis Platform (LEAP) to investigate the viability of CCS in meeting Pakistan's Nationally Determined Contributions (NDCs) and net-zero targets. According to the results, CCS has the potential to reduce emissions by 18 Mt under the NDC scenario and attain net-zero status by 2050; however, it will require robust policy support, infrastructure, and regulatory frameworks.

Keywords: industrial decarbonization; energy transition; carbon capture and storage; climate change; cement decarbonization



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1. Introduction

The cement sector is globally responsible for 7% of total greenhouse gas emissions [1]. With climate change and low-carbon development now being the heart of global developments, various technological development and policy provisions are being proposed to reduce emissions. The key methods that can reduce these emissions in the cement sector include measures such as energy efficiency, use of alternate materials, integrating circularity, and the integration of renewable energy resources. However, the extent to which these measures can reduce emissions is limited, especially given that around 40% of total emissions come from fuel combustion, while the remaining stem from the process of calcination [2]. Given this, the carbon capture and storage (CCS) technologies must play a substantial role in the decarbonization of cement, particularly for its net-zero pathway.

Carbon capture and storage refers to the use of technology that can capture carbon dioxide (CO₂) from the source of emissions (such as industries or powerplants) and store them to prevent their release into the atmosphere. Carbon capture and storage (CCS) is crucial for meeting climate targets, particularly for decarbonizing power, industry, and heat, as well as removing CO₂ from the atmosphere. Achieving capture rates above 90% will be essential to meet the 1.5 °C target, but current policies are insufficient for widespread, economically viable CCS deployment [3]. Recent studies analyzed the relationship between scale, CO₂ concentration, and process conditions with capture rates, evaluating techno-economic performance at rates up to 99% (IPCC (2005)). As of 2023, all Carbon Capture, Utilization, and Storage (CCUS) projects combined lead to a capture of around 45 Mt CO₂ annually [4]. However, the International Energy Agency (IEA)'s net-zero scenario demands

an annual reduction of approximately 1.2 Gt CO₂ through the deployment of CCUS [5]. While the current developments in the sector are low, progress has gained some momentum in recent years, with over 500 large-scale commercial projects in the development phase. Between January 2022 and 2023, 50 new capture facilities were announced and set to be operationalized by 2030, which would lead to 125 Mt CO₂ reductions each year [6]. Most of the Intergovernmental Panel on Climate Change (IPCC) pathways that limit global warming to 1.5-degree target make use of carbon removal technologies. As per the IPCC reports, if the existing power plants and industries are unabated, they would lead to 600 billion tons of emission reductions over the next 50 years [7].

Several countries, including Norway, Finland, Sweden, Denmark, France, Iceland, Japan, Switzerland, Portugal, Costa Rica, and the UK, announced legally binding net-zero emissions targets, generally requiring anthropogenic greenhouse gas emissions to be offset by corresponding removals. The UK's target is set for 2050 to align with limiting global warming to 1.5 °C. Major companies like Royal Dutch Shell, Total, Equinor, BP, Nestlé, Qantas, Duke Energy, ThyssenKrupp, HeidelbergCement, Vale, Microsoft, and Delta have also announced net-zero targets, with more organizations expected to follow.

Significance of CCS in Decarbonizing Pakistan's Cement Industry

Pakistan's climate diplomacy over the past few years has significantly changed, given that the country is ranked as the eight-most-vulnerable country in terms of climate change. Pakistan's updated Nationally Determined Contributions (NDCs) were put forward in 2021 and aim to reduce GHG emissions by 50% before 2030 (using 2015 baseline), based on the availability of international finance, and by 15% using the country's own resources. As for the emission profile, a larger portion of emissions in Pakistan comes from the industrial sector (either through manufacturing industries or industrial processes and product use (IPPU)). As per the NDCs, energy and IPPU constitute 50% of Pakistan's total emissions. The cement sector in Pakistan contributes to approximately 8.9 million tons (MT) of greenhouse gas (GHG) emissions annually, which is around 30% of the country's total industrial sector emissions.

Due to technological limitations and high associated costs, discussions on CCS in Pakistan have been sparse. CCS technology demands significant financial investment for the construction and maintenance of capture, transportation, and storage infrastructure, making it economically challenging for widespread adoption [8]. Furthermore, the energy-intensive nature of CCS can offset some of the emission reduction benefits, as it requires substantial power to operate the capture and compression processes [9].

Moreover, Pakistan's recent economic situation further complicates the adoption of CCS. The country is grappling with high inflation, fiscal deficits, and limited public sector funding, making it difficult to allocate substantial resources to new technologies. The economic constraints have led to reduced investment in infrastructure and innovation, hindering the progress of large-scale CCS projects [10]. Additionally, the energy sector in Pakistan faces its own set of challenges, including energy shortages and reliance on imported fuels, which exacerbate the difficulties in implementing energy-intensive CCS technologies. Whilst the Nationally Determined Contributions (NDCs) of Pakistan demands the decarbonization of the cement sector along with other key hard-to-abate sectors, it does not provide short- to medium-term plans for utilizing decarbonization technologies such as CCS implementation [11].

Given the context outlined above, there is currently insufficient evidence regarding the significance and potential of decarbonizing Pakistan's cement sector through CCS implementation. While qualitative assessments exist, there has been a lack of comprehensive long-term modeling or scenario analysis to evaluate its feasibility. This study aims to address this gap by conducting scenario analyses and developing a decarbonization pathway for the cement sector using CCS, in alignment with Pakistan's NDC targets and net-zero plans. The economic viability of CCS remains out of scope for this paper.

2. Methodology

The study uses a mixed-methods approach to developing decarbonization paths. It provides a comprehensive desk review of Pakistan's cement-industry emissions landscape, including baseline levels, emission sources, currently underway operations, and related policies. The analysis is also informed by consultative discussions, such as public-private dialogues and key informant interviews conducted by the Sustainable Development Policy Institute (SDPI). For quantitative data analysis, scenario modeling has been performed using the "Low-Emission Analysis Platform (LEAP)" model. The key scenarios developed in the study include the (i) reference or BAU (business as usual), (ii) the frozen scenario, (iii) energy policy scenario (EPS), (iv) net-zero scenario, and the (v) NDC scenario. The methodological framework of the analysis is indicated in Figure 1 [12].

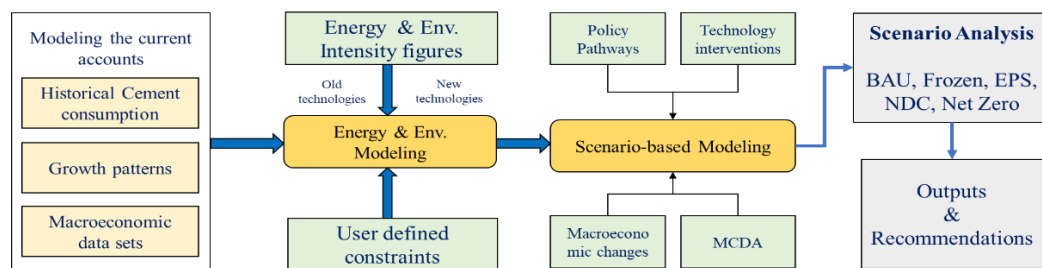


Figure 1. Framework for scenario-based modeling using LEAP.

To support data collection for model development, this study uses the LEAP model developed for Pakistan's SDG7 Roadmap developed by UNESCAP in support of the SDPI and Private Power and Infrastructure Board (PPIB). Under the SDG7 model, CCS has been added as a new element for decarbonization, particularly in the cement sector. Under different scenarios, CCS deployment follows the following pattern: no utilization of CCS in the BAU, frozen, or EPS scenarios, since there are no policy provisions for this in Pakistan. In both the NDC and net-zero scenarios, CCS is optimized to reduce the emission levels to the specific policy target, i.e., zero emissions in net zero and 50% emission reductions in the NDC scenario. Further, the key detriments used for the modeling (base year as well as future projections) are summarized in Table 1.

Table 1. Baseline profile and growth patterns for cement industry in model development [12].

Parameter	Value	Parameter	Value
Thermal Energy Consumption for Cement	3.9 GJ/t-cl	Electrical Energy Consumption for cement	90 kWh/t Cement
Clinker-to-Cement Ratio	0.95	Emission Intensity	0.79 t-CO ₂ /t-cl
Energy Mix (2022)	Coal (80%), Natural Gas (12%), Electricity (1.2%), Others (6.8%)	Share of Cement in Industrial Emissions	61%
Economic Growth	4.3% (as per IGCEP)	Population Growth Rate	2%
Energy Demand (2022)	7.1 Mtoe	Commercial Floor-Space Increase	Direct Index of GDP

As for the rest of the data sets, the setting of the current scenario is the same as that used in SDG7 Roadmap development, with detailed data attached in its annexure. While this study specifically focuses on the role of CCS, the overall model also analyses the potential reductions achieved through other strategies such as energy efficiency improvements, renewable energy integration, use of alternate fuels, and the clinker substitution.

3. Results

This section explains the key findings from the LEAP model, particularly in the context of the role of CCS in decarbonization pathways for the cement industry. The overall emission profile of Pakistan's cement industry is shown in Figure 2.

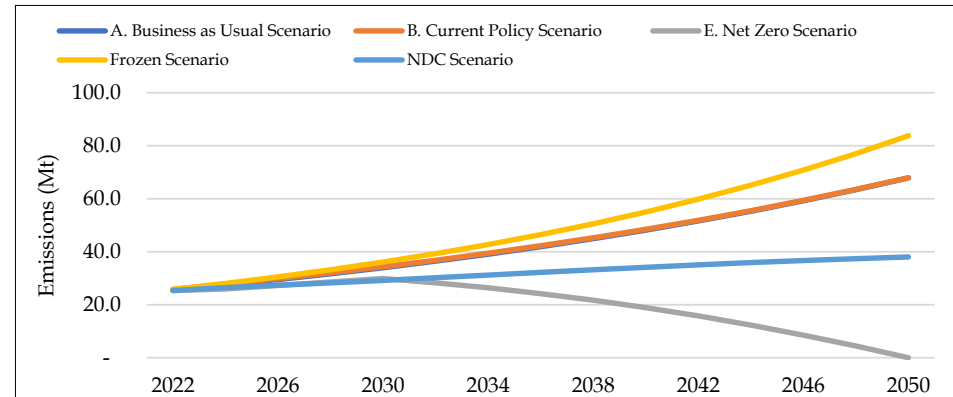


Figure 2. Emission profile of Pakistan's cement sector under different scenarios.

Figure 2 shows that in a BAU scenario, emissions from Pakistan's cement sector are projected to exceed 34 Mt by 2030 and reach approximately 70 Mt by 2050. In contrast, under the NDC scenario, emissions are expected to rise to 29.5 Mt by 2030 and 38 Mt by 2050, representing reductions of 14% and 44% compared to the BAU scenario, respectively. In the net-zero scenario, the emission trajectory mirrors that of the NDC scenario until 2030 but declines to zero by 2050. Figure 3 illustrates the impact of CCS in reducing these emissions through an optimized modeling approach.

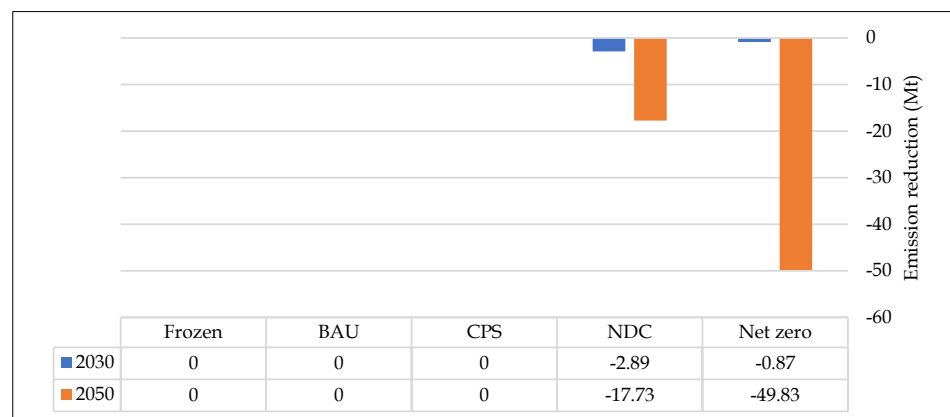


Figure 3. Potential of emission reductions through CCS in different scenarios.

Figure 3 illustrates that no emission reductions through CCS were identified under the three scenarios (frozen, BAU and CPS). The mapping of CO₂ emissions to CO₂ sinks will be an important step to accelerate CCS projects in Pakistan, with potential CO₂ storage sites including coal deposits, gas fields, oil fields, and saline aquifers. However, techno-economic assessments, such as those for open-pit coal mines, are necessary to determine their suitability for permanent CO₂ storage, which applies similarly to oil and gas fields.

Under the NDC and net-zero scenario, CCS is projected to contribute emission reductions of up to 18 Mt and 50 Mt by 2050. Under both scenarios, CCS deployment is optimized to achieve the desired policy targets (50% reductions as per the NDCs and 100% for net zero). The rest of the emission reductions come from other decarbonization levers, as per the international 2030 and 2050 targets and policy provisions for them in Pakistan. Figure 4 further illustrates the role of CCS in relation to other levers or strategies.

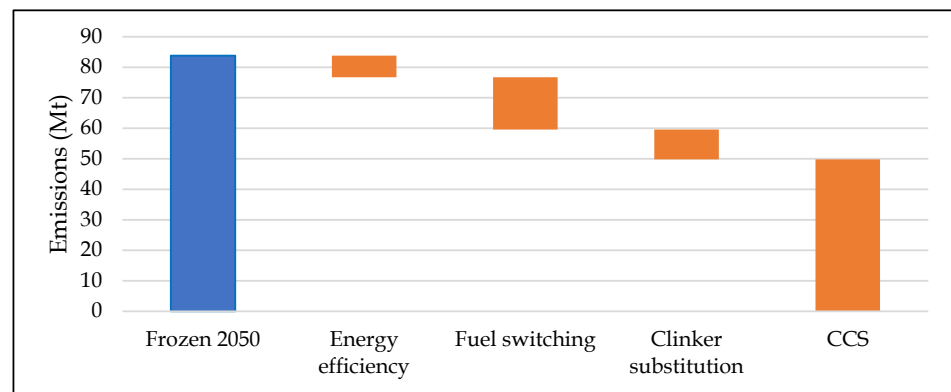


Figure 4. Potential of decarbonization levers to achieve net-zero emissions in cement sector.

4. Discussion

The results underscore the critical role of CCS in achieving net-zero emissions in the cement sector, representing a promising pathway to decarbonize the cement industry in Pakistan by significantly reducing CO₂ emissions. However, its successful implementation requires a coordinated effort across policy, infrastructure development, technology deployment, economic assessment, capacity building, and stakeholder engagement to overcome challenges and realize its full potential in contributing to sustainable development goals.

The potential of adoption of CCS and transition hinges on several key approaches:

- Long-term planning, monitoring, development and regulatory support:** The government can establish clear and ambitious targets for emissions reduction and CCS deployment within the cement sector along with other industrial sector targets, which should be aligned with national climate goals, such as net-zero emissions, by mid-century. This should involve developing monitoring and reporting mechanisms to track CO₂ emissions, capture rates, and storage integrity. Moreover, this should be supported with robust regulatory frameworks that provide certainty and stability for CCS investments. This includes streamlined permitting processes for CCS projects, clear guidelines for CO₂ storage site selection and operation, and frameworks for liability and monitoring.
- Role of finance and investment:** CCS projects, including those in the cement sector, are capital-intensive due to the costs associated with capturing, transporting, and storing CO₂. Financial support is essential to bridging the gap between upfront investment costs and long-term operational savings and environmental benefits. This implies the crucial role of various financial instruments, such as direct funds in the form of grants, incentives, and subsidies, and implementing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, in creating financial incentives to help offset the high initial costs and encourage early adopters in the cement industry. Similarly, the government should harness the potential of carbon pricing mechanisms such as carbon taxes and cap-and-trade systems. CCS projects can generate revenue streams through carbon offset credits or enhanced oil recovery (EOR) operations. Cement manufacturers can monetize captured CO₂ by selling carbon credits or using CO₂ for EOR, providing additional financial incentives for CCS deployment. These mechanisms encourage industries to reduce emissions and invest in low-carbon technologies like CCS. Governments and international financial institutions can offer risk mitigation instruments, such as guarantees or insurance, to reduce the perceived financial risks associated with CCS investments. This helps attract private-sector capital and facilitates project financing. This includes attracting investments from financial institutions, venture capital firms, and private equity funds that recognize the potential long-term returns from CCS technology development and deployment.
- International collaboration:** Given the techno-economic nature and implications of CCS, it is imperative to engage in international collaboration to share experiences, best

practices, and lessons learned from CCS projects in other countries. Participating in knowledge-sharing platforms and partnerships to accelerate technology development and deployment can help build the capacity of human resources. This includes educating engineers, technicians, and policymakers on CCS technologies, operational best practices, and regulatory compliance.

- **Technology innovation and R&D support:** This refers to the need to invest in research and development (R&D) to advance CCS technologies tailored to the cement industry's specific needs. It is critical to support pilot projects and demonstrations to validate technologies and scale them up for commercial deployment.
- **Public-private partnerships:** These can help share risks, leverage expertise, and accelerate technology development and deployment. Hence, it remains significant to foster collaboration between government, industry stakeholders (including cement manufacturers), research institutions, and international organizations to allow for the better integration of R&D, policies, regulations and the mobilization of finances and investment.

5. Conclusions

This study highlights the critical role of CCS technologies in the decarbonization of the cement industry, particularly their contribution to achieving Pakistan's Nationally Determined Contributions (NDCs) and net-zero goal by 2050. Scenario-based modeling using LEAP analysis indicated that while energy efficiency, fuel substitution, and alternate fuels are going to be critical in emission reduction trajectories, the inclusion of CCS is most crucial for such a transition. Going forward, this inclusion requires a strong and multi-faceted approach. Long-term planning while exploring the alternate financing mechanisms would remain critical to make CCS a viable option. Ultimately, the transition to a low-carbon cement industry in Pakistan hinges on coordinated efforts across government, industry, and international stakeholders. The journey ahead will require sustained commitment and collaboration, but the potential benefits for the environment, economy, and society are profound.

Supplementary Materials: The supporting information can be downloaded at: Energy transition pathways for the 2030 agenda: SDG 7 roadmap for Pakistan | ESCAP (unescape.org) (accessed on 1 January 2024). model data sets and driving factors for other decarbonization levers.

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