

Article

Framework for Cement Plants Assessment Through Cement Production Improvement Measures for Reduction of CO₂ Emissions Towards Net Zero Emissions

Esraa Khalil * and Mohamed AbouZeid

Department of Construction Engineering, School of Sciences and Engineering, The American University in Cairo, Cairo P.O. Box 74, Egypt

* Correspondence: esraa.ekhalil@gmail.com

Abstract: Recent global strategies highlight the urgency of addressing greenhouse gas (GHG) emissions, particularly CO₂ from energy-intensive industries such as cement production. Studies show that the cement industry contributes around 8% of the global CO₂ emissions, emphasizing the need for innovative and structural mitigation strategies. While advancements in carbon capture technologies, LC3 cement, alternative raw materials, and renewable energy integration are critical for achieving the net zero emissions (NZE) goal, the challenge lies in having a structured and comprehensive approach for systematically categorizing, prioritizing, and assessing various CO₂ improvement measures within cement plants. To address this gap, this study introduces a structured assessment model designed to evaluate and rate proposed CO₂ improvement measures based on their alignment with the global NZE targets and plant-specific milestones, providing an overall cement plant performance score. The assessment tool developed in this study provides a quantitative scoring system for assessing the implementation level and impact of various CO₂ improvement measures within cement plants. The framework integrates the cleaner production concept and the 5Cs approach to the decarbonization of the cement industry, offering a systematic yet flexible method for cement industry decarbonization. To validate the assessment tool, two cement plants with different production scales and located at different geographical locations were analyzed. Plant A achieved an overall performance score of 3.315, while plant B scored 3.68. The assessment identified a potential CO₂ reduction of 20–30% through targeted improvements, highlighting that even well-established cement plants have opportunities for emissions reduction and efficiency enhancement. This study advances existing assessment methodologies by providing an adaptable, data-driven, systematic, and scalable tool that enhances decision-making, strategic modifications, and resource allocation for achieving NZE targets. Additionally, this assessment tool bridges the gap between global targets and plant-level implementation, ensuring effective transition towards sustainability in the cement industry.



Received: 11 January 2025

Revised: 4 February 2025

Accepted: 12 February 2025

Published: 1 April 2025

Citation: Khalil, E.; AbouZeid, M. Framework for Cement Plants Assessment Through Cement Production Improvement Measures for Reduction of CO₂ Emissions Towards Net Zero Emissions. *Constr. Mater.* **2025**, *5*, 20. <https://doi.org/10.3390/constrmater5020020>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: NZE; CO₂ emissions; GHG; rating cement plants; 5Cs; assessment model; cement; improvement measures

1. Introduction

Over the past decade, the construction industry has had the ambitious goal of achieving zero emissions by 2050, which is the motive for undertaking several encouraging initiatives. While efforts to reduce cement usage have been ongoing, the increasing global

threat posed by climate change has amplified the urgency [1,2]. Several leading organizations have established pathways and roadmaps to achieve the 2050 target, including the World Green Building Council (WorldGBC), the International Energy Agency (IEA), United Nations Net Zero Coalition, the European Cement Association (CEMBUREAU), Global Cement and Concrete Association (GCCA), the Intergovernmental Panel on Climate Change (IPCC), Cement Sustainability Initiative (CSI), and Science-Based Targets initiative (SBTi). They have outlined a phased strategy to reach NZEs. This includes a key milestone to achieve a 40% reduction in embodied carbon by 2030, with all new buildings expected to operate in net zero carbon [3–9]. However, this does not imply a halt in construction or reduced building activity due to fast urbanization, which has led the cement industry to become one of the highest consumers of natural resources, energy, land, and water and a major contributor to CO₂ emission worldwide [10,11]. Cement is a key construction material that is in high demand and is produced in large quantities yearly [12]. In 2022, the global production of Portland cement was 4.1 billion tons compared to 3.3 billion tons in 2010 [13]. To illustrate, producing 1 ton of cement requires, on average, approximately 1.5 tons of raw materials, between 3300 and 4300 MJ of fuel energy, and around 100 to 120 kWh of electrical energy, and releases between 0.73 and 0.99 tons of CO₂, depending primarily on the clinker-to-cement ratio [14–17].

Moreover, according to the International Energy Authority (IEA)'s 2022 World Energy Outlook, cement production as a steadily growing and energy-intensive industry is estimated to produce around 1.4 Gt of CO₂ emissions per year, which is roughly 8% of the global GHG emissions [18–20]. According to the Intergovernmental Panel on Climate Change (IPCC), by the year 2050, there should be around USD 1.6 trillion in investments per year to put the planet in a safe climate zone [20]. Environmental policies across the globe are affecting different industrial sectors, and the cement industry is expected to feel this impact [5,21,22]. In the past decades, there have been some international initiatives to reduce cement-generated CO₂, the industry's footprint, and to control emissions. Some of these initiatives include the Greenhouse Gas Protocol by World Resources, the World Resource Institute (WRI), the World Business Council for Sustainable Development (WBCSD), the Kyoto Protocol, and others [23–25]. Moreover, the ambition of limiting climate change to below 2 °C, as established by the Paris Agreement, has pushed the need for major industries, such as the cement industry, to assess, monitor, and modify their production processes [5,24,26]. For this reason, over the last decade, various pathways and strategies have proposed several mitigation and improvement measures for reducing CO₂ emissions in the cement industry, including improving energy efficiency, using alternative raw materials and fuels, and assessing CO₂ performance [26–28]. However, most of these strategies are directed towards available advanced technologies and reduction pathways that are directed towards clinker production rather than structured, systematic assessments to evaluate and rate the improvement measures across the entire cement production system. The introduction of a novel, structured, and data-driven assessment tool that addresses the limitations of the current methodologies by providing a structured, comprehensive, systematic, and quantitative scoring system for evaluating and prioritizing CO₂ improvement measures within the cement value chain will bridge the gap to reach the 2050 NZE targets.

1.1. Study Aim

Despite the numerous studies on cement production decarbonization and energy efficiency by organizations such as GCCA, CSI, IPCC, and IEA, covering areas on alternative fuels, clinker substitutions, carbon capture technologies, process optimization, and others, there remains a significant gap in developing an integrated assessment model that rates and systematically assesses the performance of cement plants, particularly as concerns CO₂ performance enhancements. The aim of this paper is to address critical gaps in the systematic evaluation of CO₂ improvement measures within cement plants by developing a comprehensive assessment framework and an Excel-based assessment tool for the decarbonization of the cement industry [29]. These gaps include the need for a standardized methodology for evaluating and scoring several proposed CO₂ improvement measures, the absence of a structured yet flexible model for integrating global NZE targets and decarbonization strategies, and the need for quantitative and qualitative decision-making tools that guide the sustainability efforts of plants towards NZEs by 2050. The model is based on the 5Cs approach, enabling systematic identification, collection, evaluation, and rating of the proposed measures that aim to reduce the carbon footprint of cement plants, hence reducing the CO₂ emissions of the cement industry. The target is to incorporate advancements to reduce each of the 5Cs to achieve NZEs by 2050. The developed tool will facilitate resource allocation, future strategic planning, and decision-making supporting the NZE targets. This paper is the second in a series; the first introduced the cement production plan, the assessment tool, and its generic and case-specific application [29].

1.2. Theoretical Concept Behind Model Development

In theory, to systematically establish a framework for evaluating the improvement measures applied to a cement plant, the input and output flows of energy, materials, and others need to be studied. For this, the cleaner production theory and 5Cs approach for decarbonizing the cement industry and its relevant sectors are used for identifying, prioritizing, and setting evaluation targets for the improvement measures proposed as a roadmap for the reduction of CO₂ emissions from cement manufacturing and the carbon footprint of the cement plants [30,31]. These elements are crucial in reducing emissions and promoting sustainability within the construction and related sectors. The 5Cs approach outlines the roadmap to decarbonization, focusing on clinker, cement, carbon capture and storage (CCS/CCU), construction (re)carbonation, and concrete for the assessment of CO₂ improvement measures. It is a comprehensive strategy that seeks to achieve NZEs by 2050 in comparison to the 1990 baseline emissions of 783 kg CO₂/ton of cement through target emissions reduction in the 5Cs across the cement and concrete value chain, as shown in Figure 1 [30]. The concept levers are in the adaption of material and energy efficiency, low-carbon fuel switching, promoting efficiency in material usage, reducing clinker-to-cement ratio, and implementing innovative and advanced technologies. The roadmap to achieve NZEs by 2050 looks at the CO₂ emissions reduction pathways by acting at the different stages of the value chain [30].

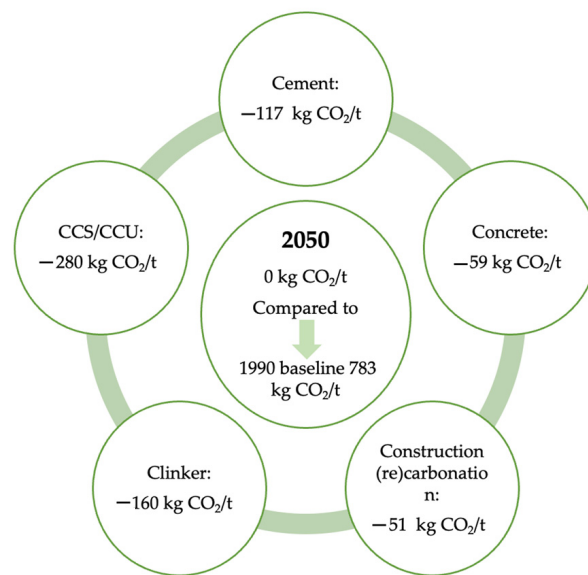


Figure 1. The 5Cs for decarbonizing the cement industry and other relevant sectors [30].

2. Materials and Methods

2.1. Methodological Framework and Structure

The proposed assessment model structure focuses on evaluating the cement plant's sustainability with reference to the performance of improvement measures through the integration of multiple technologies, computations, and metrics. The model is built around key improvement parameters to reduce the CO₂ emissions of the cement plants. This includes five main areas of improvement: process and technology efficiency, alternative fuels and energy management, alternative raw material and clinker production, emission control, and industry innovations and facility operations. In addition to the five main areas, 14 first subareas and 43 s subareas. The structure is designed to assess the impact of these measures on reducing the CO₂ emissions of cement plants, hence reducing their environmental carbon footprint while maintaining efficiency. This model structure facilitates detailed analysis of cement plants while providing flexibility to modify weights and assumptions. Although the quantity of cement produced will directly impact the amount of CO₂ emissions from the cement plant, the proposed evaluation tool remains consistent. The same methodological criteria and computations are used to assess the plant's performance regardless of the amount of cement produced. However, larger cement production volumes will result in higher total emissions, hence lower overall plant performance and improvement measures scores.

A comprehensive methodology for rating cement plants based on their mitigation measures is developed. The three sustainability pillars on which the proposed improvement measures are based are the economy, environment, and society. This rating model is generic enough to be applied to a wide range of plants and is not site-specific or country-specific. Comparing green building and sustainability rating platforms with the developed cement-specific assessment tool in this study highlights that the platforms enable a broad, corporate-level sustainability evaluation that assesses corporate environmental, social, and governance (ESG) performance [32,33]. On the other hand, the developed assessment tool is tailored to the specific decarbonization needs of the cement industry, focusing on technical, process, and emission reduction improvement measures in the value chain by providing actionable insights and performance benchmarks. The developed assessment tool enables plant operators and decision-makers to implement targeted strategies to achieve decarbonization of the cement production process. The niche focus of the created assessment tool allows us to provide detailed guidelines as a roadmap for reducing CO₂ emissions. One of

the key strengths of this assessment tool is its ability to provide benchmarking capabilities against standards. This tool allows cement plants to compare their CO₂ emission reduction measures against global best practices through the evaluation of weightage and significance factors. By applying this tool, cement plants can track the progress of the improvement measures to identify areas for improvement and areas that need implementation of best practices to reduce CO₂ emissions. This quantitative approach differentiates the created tool from other sustainability frameworks. The main focus of the created tool is carbon emissions reduction, unlike other methods where carbon management is part of broader environmental criteria. A detailed comparison between the use of sustainable rating systems and a cement-specific assessment tool for achieving NZEs by 2050 showed that the created tool is different in the following ways:

- Purpose: it focuses on assessing decarbonization measures for cement plants to achieve NZEs by 2050, while other systems evaluate sustainability performance.
- Scope and assessment criteria: It covers improvement measures related to CO₂ emissions reduction, energy efficiency, alternative fuels and raw materials, technology innovations, product improvements, and facility operations efficiency. On the other hand, the rating systems cover broad ESG factors.
- Targeting: it is designed for cement plant decision-making and for operators to evaluate the performance of the plant, whereas companies across the industry use the rating system.
- Certification: It offers scores for each improvement measure based on an evaluation key, with action plans and detailed results reporting to improve the plants' performance across different improvement measures. Rating systems provide sustainability ratings of silver, gold, platinum, or bronze based on environmental performance.
- Methodology: it uses quantitative and qualitative models with the needed KPIs and global targets as references to track the plant's progress towards NZEs and is not based on questionnaires only.
- Focus on carbon emissions: it focuses primarily on carbon emissions reduction in cement production facilities by evaluating CO₂ emissions improvement measures, while the other rating systems include carbon emissions as one of many environmental criteria and do not specialize in cement-specific decarbonization strategies.
- Benchmarking: it allows cement plants to compare the various CO₂ emission reduction measures against global best practices and NZE targets. However, the other evaluation methods allow companies to compare their performance against industry peers.
- Action plans: it offers technical insights tailored to specific cement plants to achieve the NZE targets based on scores, bar charts, and historical data logging across the supply chain in the cement industry.

The model framework is presented in stages and sub-stages that should be followed to complete the evaluation. Figure 2 demonstrates the assessment framework. The model has three main phases: the first phase is the design and framework development phase, the second phase is the implementation and evaluation phase, and the third phase is the monitoring and reporting phase.

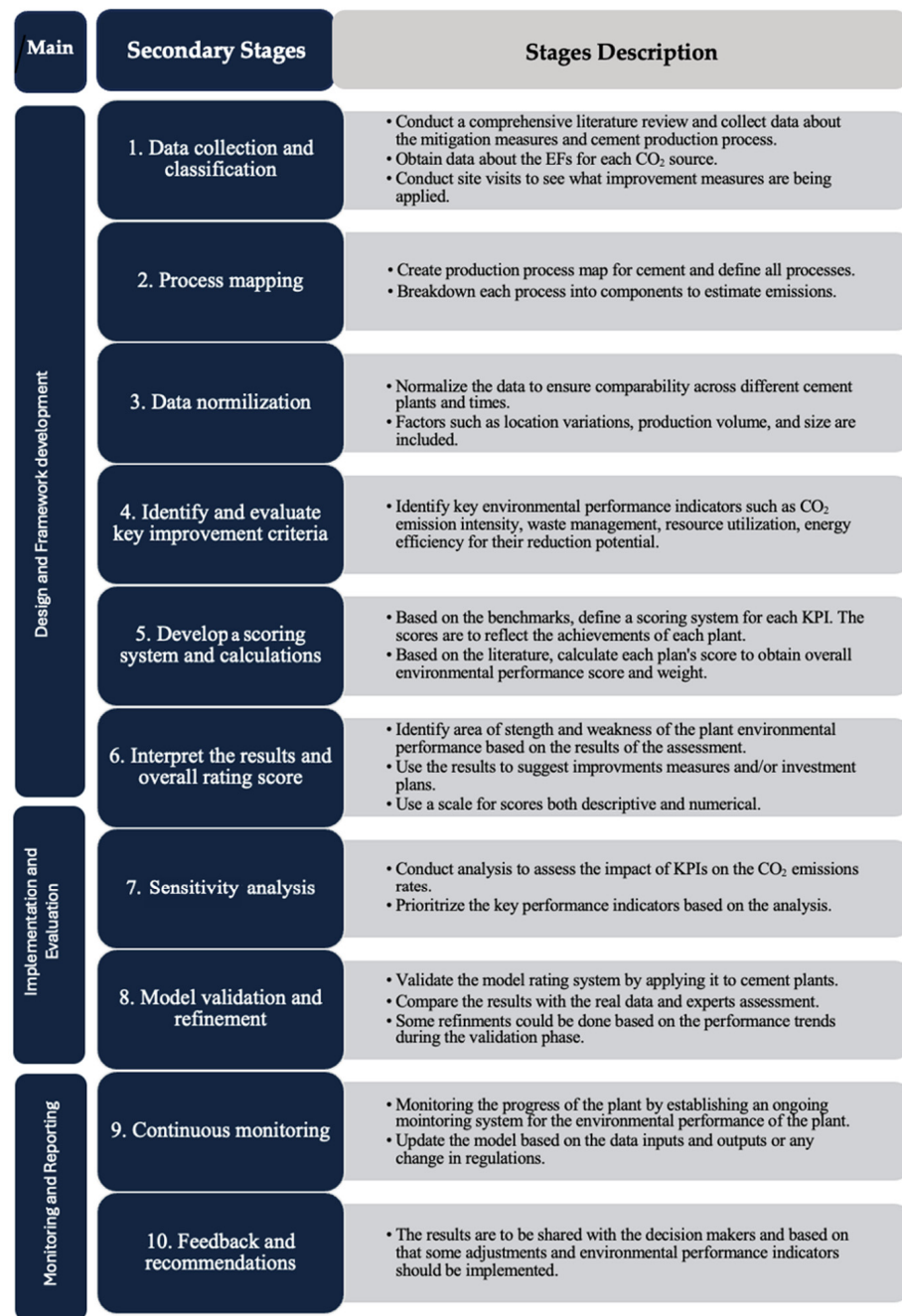


Figure 2. Study assessment framework for CO₂ emissions reduction by cement plants.

2.2. Data Collection and Classification

All necessary data on the cement production processes from inputs and outputs along the material and energy streams of cement production, including fuel consumption, energy usage, raw material consumption, and transportation, were gathered from five cement plants operated by leading national and international manufacturers. Their selection represented a diverse range of production capacities, different geographical locations, operational methods, and regulations. The data collection sources included sustainability reports, literature reviews, and site visits, ensuring comprehensive CO₂ improvement measures compilation and assessment across different configurations and environments. This selection process allows for a broader applicability of the assessment tool developed in this study. To ensure the accuracy and comprehensiveness of the survey, interviews and site visits were conducted. This step includes the collection of data on any issues that

emerge during the site inspection, from instant air emissions levels, waste management, water wastage, energy consumption, transparency levels regarding compliance with the regulations and environmental performance, and others. The site visit survey and the collected data on the environmental performance of the cement facility are gathered and organized in a sheet based on the recommendations of the GCCA, EBRD, IEA, CSI, WBCSD, and the European Cement Research Academy (ECRA) [3–6]. This sheet contains plant information, including plant name, company of ownership, country of the facility, plant type, kiln types, clinker capacity, verifications, and CO₂ and energy protocol versions used. The survey ends with general comments and notes about this stage of the facility. Table 1 summarizes the parameters and data used for CO₂ emissions calculations. The units of measurement and the proposed sources of data are indicated in the table. The data are measured preferably at the plant level; however, when this is not possible, default values are used.

Table 1. Data collected and emission sources by scope.

Emission Sources	Component	Unit of Calculation	Data Source
Scope 1			
CO ₂ from Calcination	Clinker produced	Tons	Plant measured
	Dust calcination	Tons	Plant measured, reports
	CKD emission	g/t clinker	Plant measured
CO ₂ from fuel combustion	NCV	GJ/t fuel	Plant measured
	EF	kg CO ₂ /GJfu	Calculated or default IPCC/CSI
	Fuel consumption	Tons	Calculated, plant, reports
CO ₂ from mobile sources	EF	kg CO ₂ /km	Calculated or default
	Fuel consumption	Liters	Calculated or plant
Scope 2			
CO ₂ from external sources	Power Consumption	kWh	Plant level or reports
	EF	gCO ₂ /kWh	

In addition, a generic sheet is created for the plant data collection and classification phase. This sheet includes data inputs and records. It is a baseline for data documentation to normalize and unify data classification and collection. The data collection method, unit of record, basis of classification, tool rating, and improvements are recorded. It gives a clear overview of where the cement plant stands. This table provides a structural and unified format for documenting and organizing the data in categories based on the cement plant's operational process. Figure 3 shows a model sample sheet for data inputs and recording where ratings are computed using the tool software.

Date/../20..						
2. Data Inputs and Recording						
Seq	Data categories	Collection Method	Unit	Basis of Classification	Rating	Improvements and comments
1	Energy Consumption					
1a	Electricity	Manual , Smart meters, Automated data logging	kWh, GJ	production process	1 to 5	
1b	Fuel	Sensors, Automated data logging , smart meters	T/kg	Equipment and production process		
2	Raw material usage					
2a	clay	Manual, smart meters	tons	Environmental impact, Material type, production process, operation, quality	Poor/Fair/Good/Excellent	
2b	sand	Sensors, Automated data logging	tons, m3	Quality, grade		
2c	limestone	Metering, Automated data logging	ppm, g/m3	production process		
2d	Gypsum	Metering, Automated data logging	tons, kg	Equipment and production process		
2e	Others	Manual, smart meters	tons, kg	Operation		
3	Production outputs					
3a	Clinker	Sensors, Automated data logging	tons, m3	Volume, process, energy consumption, emissions, Environmental impacts, quality	Poor/Fair/Good/Excellent	
3b	Cement	Manual, smart meters				
4	Waste generation		tons			
4a	Solid waste	Manual, smart meters	tons, kg	Environmental impact, Sources, Quantity, Management process	Negligible/Low/Moderate /High	
4b	Liquid waste	Sensors, Automated data logging	ppm, g/m3			
4c	Gaseous waste	Metering, Automated data logging	ppm, g/m3			
5	Emissions					
5a	CO2	Manual, calculation , smart meters	ppm, g/m3	Production process and environmental impact	Low/Medium/High	
5b	Nox	Sensors, Automated data logging	tons, kg	Equipment used and environmental impact		
5c	Sox	Metering, Automated data logging	ppm, g/m3	Operation and environmental impact		
5d	Air	Manual, smart meters	ppm, g/m3	Production process and environmental impact	Yes/No	
6	Alternatives					
6a	Fuels	Metering, Automated data logging	ppm, g/m3	production process	Low/Medium/High	
6b	Raw material	Sensors, Automated data logging	tons, kg	Operation and environmental impact		
General comments						

Figure 3. Sample assessment tool sheet for framework data input and recording at cement plants.

2.3. Process Mapping and Data Normalization

In this step, the cement production process is visually represented, and the various stages and steps are mapped. This stage includes quarrying, crushing, grinding, blending, calcination, clinker production, grinding of clinker, packaging, and transportation of the final product. In addition, each process step is broken down into individual components for accurate determination of the energy and materials needed for each stage and estimation of CO₂ emissions and other air emissions. This stage helps to streamline operations, optimize operations, improve efficiency, and identify inefficiencies. An Excel sheet with the cement production process covering the main steps is created relative to the energy consumption and emissions of each step. The scoring is given as an evaluation using yes, no, or n/a points, where

- Yes means the emissions and energy consumption of each step of production are reported as planned;

- No means emissions are generated, and the energy consumption of each step of production is not reported as planned. This should be explained in the comments cell;
- N/A means emissions are not generated or this step or does not exist at this plant.

The data collected in the first step and the process mapping step are normalized. The normalization helps with data completeness across different cement plants and regions based on standard sheets to be filled. The normalization stage standardizes the variations in different categories during the rating and evaluation process. Data normalization is based on the standards and protocols of the GCCA, EEAA reporting, IEA, ECRA, and others, as mentioned. Figure 4 is a simplified model sheet developed to summarize the assessment tool's automatically rated efficiency of the cement production process in the cement plant based on the emissions generated as well as the energy consumed. This can be used as a guideline for determining the general efficiency of each step in the process of cement production to visualize the areas that need improvement to reach the 2050 goal.

Date		.././20..	
------	--	-----------	--

3. Process mapping											
Seq	Main process steps	Reporting	Efficiency score	Years							
				2024	2025	2026-2029	2030	2031-2039	2040	2041-2049	2050
1	Raw material supply	yes, no, n/a	(1–5)								
1a	Raw material preparation	yes, no, n/a	(1–5)								
2	Cement production (kiln operation)	yes, no, n/a	(1–5)								
3	Power generation on site	yes, no, n/a	(1–5)								
4	Heating and cooling process	yes, no, n/a	(1–5)								
5	Transportation	yes, no, n/a	(1–5)								
5a	Internal on site	yes, no, n/a	(1–5)								
5b	External off site	yes, no, n/a	(1–5)								
6	Add extra detailed processes	yes, no, n/a	(1–5)								
General comments											

Figure 4. Sample assessment tool sheet used in the model framework development for rating the efficiency of the plant's cement production process.

2.4. Identifying and Evaluating Key Improvement Measures

At this stage of model development, each category is analyzed to identify the key improvement measures for evaluating the CO₂ reduction potential of each plant. Due to the uncertainties and limitations surrounding the availability of the needed data, the results may lead to inaccurate results, undermining future risk identification, causing inaccurate prediction, limiting generalization for future global goals, and leading to ineffective policies and decision-making. This includes the following:

- Accessibility: Accessing comprehensive and up-to-date data with respect to the study objective, especially in international cement plants;
- Reliability: The accuracy of the data is subject to the source's creditability;
- Completeness: The parameters of systematic collection and reporting affect the depth of the analysis. Incomplete datasets could affect the results;
- Confidentiality: Some data may be sensitive, with limited access and agreements needed for data provision. This could restrict the analysis of certain parameters;
- Identification of key environmental performance indicators, including CO₂ emission intensity, waste management, resource utilization, and energy efficiency for reduction potential.

Qualitative assessment based on a scoring system is used to select the best measures that have low, high, and medium potential for the reduction of CO₂ emission by the cement plant. Table 2 presents the scale used to assess the parameters' impact on improving emissions. This scale is assessed based on the improvements made to one of the major reduction potential measures, such as the following:

- Energy consumption from clinker and cement production;
- Process efficiency of each stage of cement production, waste generation, and water consumption;
- Avoiding CO₂ emissions by replacing or incorporating CO₂ emissions;
- Fuel from the calcination process.

Table 2. Qualitative scale and level of impact on CO₂ emission reduction.

CO ₂ Reduction Potential	Impact Level	Estimated % of Reduction
The measures cannot reduce CO ₂ emissions from the major sources but can significantly reduce CO ₂ emissions from at least one source.	low	<20%
The measures can effectively reduce CO ₂ emissions from at least one source.	Medium	20% to 50%
The measures can effectively improve CO ₂ emissions from one or more sources.	High	>20%

Table 3 shows the improvement measures proposed for rating and scoring by the assessment tool in the application phase of this study based on a numerical rating scale. Each aspect is presented and given an abbreviation. The measures are selected and prioritized into categories, concentrating on the main area from the 5Cs approach. Additionally, the weight of each improvement measure, obtained from the literature review as well as observations from site visits, surveys, and industry experts, is based on a weighting matrix and mean values [8,9].

Table 3. Detailed classification of CO₂ emissions reduction and improvement measures used during cement production and plant operations.

Category	Abb.	Sub-Category	Abb.
1. Process and technology efficiency			
E	Energy efficiency	Electrical efficiency	EEE
		Thermal efficiency	EET
		Variable speed drives	EED
	Process efficiency	Process control systems	EPC
		Operational efficiency	EPO
		Recycle and reuse	EPR
		Pollution control and prevention	EPP
	Kiln technology upgrade	Kiln drive improvements	EKK
		Insulation improvements	EKI

Table 3. Cont.

Category		Abb.	Sub-Category	Abb.
2. Alternative fuels and energy management				
A	Alternative fuels	AF	Biomass	AFB
			Waste materials	AFW
			Non-traditional fuels	AFN
	Renewable energy	AR	Solar energy	ARS
			Wind energy	ARW
			Hydropower	ARH
			Hybrid solar panels	ARP
	Waste heat recovery	AH	Heat exchanger	AHH
			Combined heat and power	AHC
3. Alternative raw material and clinker production				
R	Alternative raw materials	RA	Decoronated feedstocks	RAD
			Blending raw materials	RAB
			Preprocessing of materials	RAP
	Clinker substitution	RC	Calcareous oil shale	RCC
			Supplementary materials	RCS
			Low-temperature clinkers	RCT
	Product development	RP	Blended cement	RPI
			New product technologies	RPN
4. Emission control and industry innovations				
I	CO ₂ and heat control	IC	Carbon capture and storage	ICS
			Selective non-catalytic reduction (SNCR) systems and CRS	ICR
			Synergistic heating	ICH
	Innovative technology and integration	II	Advanced process technologies	IIT
			Developing CO ₂ reduction innovations	IIR
			Waste treatment integration	IIW
			Power plant integration	IIP
			Power plant/cement plant carbonate looping	IIC
			Syngas co-production	IIS
			5. Facility operations	
O	Best practices in operation	OB	Staff training and public relations	OBT
			Maintenance and program enhancing	OBM
			Water management	OBW
	Standards and compliance	OS	Regulatory compliance	OSR
			Sustainable material standards	OSS
			Environmental impact assessment	OSE
			Research and CO ₂ reduction innovations	OIR
	Breakthrough innovations	OI	Environmental strategies	OIE

2.5. Develop a Scoring System and Calculations

This model stage involves developing a unified scoring system for evaluating the cement plants. After the last step, identifying the key improvement measures, the next step is to set targets or benchmarks for each measure based on specific plant standards, requirements, and sustainability targets. These measures are then given scores based on efficiency and effectiveness. A weightage factor is assigned relative to its significance. In addition, score calculation is assigned based on a comparison between actual performance against the established targets and assigned weight, deviation, and score. A generic template for scoring and comparing the performance indicators in a given cement plant is developed to help with the prioritization of improvement measures and to identify the most effective measures. Figure 5 Provides a sample of the sheet to be used in this stage of the evaluation model.

Date		.././20..					
4. Scoring of Performance Measures.							
Seq	Data categories	Target/ Benchmark	Scoring Criteria	Weighting factor	Actual performance	Score (1–5)	Improvements and comments
1	Energy Consumption		kWh/ton of cement				
2	Raw material usage		Efficiency				
3	Production outputs		Tons of cement/ period				
4	Waste generation		Ton of waste/ ton of cement				
5	Emissions		Kg CO ₂ / ton of cement				
6	Water Usage		Liters /ton of cement				
7	Alternatives		Efficiency in utilization				
General comments							

Figure 5. Sample sheet for scoring and weighting performance measures.

2.6. Interpreting the Results and Overall Rating Scores

The results are automatically interpreted to identify areas of weaknesses and strengths at each point for future improvement and/or investments. To evaluate the performance of each measure, a score from 1 to 5 is assigned to each measure. A visual representation of the rating scale representing the level of maturity and/or completeness is shown in Table 4; 5 is the highest implementation level and 1 represents a poor implementation level. These color-coded scores are programmed automatically to be displayed by the assessment tool.

Table 4. Assessment tool’s automated visual representation of the performance indicators, with scores from 1 to 5.

Poor	Low	Average	On Track	Optimal

2.7. Sensitivity Assessment

This stage of assessment of improvement measures in cement plants is conducted to understand their impact on certain parameters, such as effectiveness, viability, and results. In this stage of the model, technical maturity, sensitivity, and economic viability are analyzed to assess the applicability of the implementation of CO₂ emission reduction measures. It gives a general guideline for checking the viability of an improvement measure to be implemented in a cement plant. In this framework, key factors that can determine the

applicability of a CO₂ emission reduction measure are technological viability, sensitivity, and maturity. This step assesses the feasibility of implementing a proposed improvement measure with respect to the plant's available technology, resources, and infrastructure. Some of the factors considered at this stage include technological compatibility with the existing processes and equipment, the availability of the needed materials and energy resources, and the implementation of this technology within the existing operational state. In addition, the level of technological maturity affects the decision of whether or not to implement the measure. For this, a scale of the level of maturity is used to verify the technological maturity of the mitigation measure to be used. Table 5 outlines a qualitative scale for categorizing the various measures of technological maturity and sensitivity.

Table 5. Qualitative scale for assessing technology maturity and sensitivity.

Sensitivity Level	Maturity Level	Description
Low	High	The technology is well established and not easily affected by external factors.
Medium	Medium	The technology is emerging and involves moderate complexity on external factors. May have moderate sensitivity to external factors.
High	Low	The technology is in the early development stages. It is affected by technological complexity and is sensitive to external factors and conditions.

Additionally, economic viability is significant for determining the implementation of an improvement measure and its relationship to the plant's business approach. This aspect evaluates the financial applicability of a certain measure and involves analyzing the implementation cost of each measure, the initial investment in the case of new or emerging technologies, and the operational costs. In addition, economic viability is impacted by the complexity of the plant's business approach. Table 6 defines the qualitative scale for evaluating the economic viability and business approach complexity of implementing improvement measures in cement plants to reduce CO₂ emissions.

Table 6. Qualitative scale for evaluating the economic viability and complexity of business approaches required by CO₂ reduction measures.

Economic Viability	Business Approach Complexity	Description
High	Low	The implementation of each measure offers significant cost savings and can easily be integrated with the existing plant processes.
Medium	Medium	The implementation of each measure offers moderate cost savings and requires organizational adaption. It can be integrated with the existing plant processes but needs planning and coordination.
Low	High	The implementation of each measure offers limited cost savings and high risk. It requires substantial external support to be integrated with the plant processes.

The second step in the implementation and evaluation phase is the model validation and refinement. During this stage of the model, a thorough examination is applied to evaluate the model's effectiveness and applicability by using a specific cement plant and considering the application and constraints associated with an improvement measure. This validation should be performed by a group of experts and a technical team. In addition, this

phase considers three main aspects during the evaluation: site constraints and applicability, organizational readiness and resource allocation, and organizational implementation level.

2.8. Site Constraints and Applicability

This aspect assesses whether a certain improvement measure is applicable to a specific site. It evaluates the technical feasibility and compatibility with the cement plant's existing infrastructure. It involves the evaluation of the technological compatibility of the improvement measure with the available equipment and systems. Table 7 provides a qualitative and quantitative scale for evaluating the site constraints and applicability of an improvement measure to a given cement plant.

Table 7. Qualitative and quantitative scale for validating CO₂ emissions reduction by mitigation measures through site constraints and applicability.

Level	Feasibility Percentage	Description
Low	<50%	The proposed mitigation measure is not feasible given the current site conditions and constraints. Lack of infrastructure and resources. Significant obstacles in the environment.
Medium	50–75%	The proposed mitigation measure could be implemented given the current site conditions and constraints. Infrastructure and resources need to be modified. Moderate obstacles in the environment.
High	>75%	The proposed mitigation measure is feasible and well suited given the current site conditions and constraints. Infrastructure and resources are well aligned. Environmental conditions are aligned and support the implementation.

Another parameter of significance is the organizational position of implementation of certain measures. This aspect examines the degree to which the current state of the cement plant is implementing a certain improvement measure. If an improvement measure is already established in the plant and is at a level of implementation that leaves no room for improvement, then the evaluation states this and refers to the next measure based on the prioritized benchmarks and targets. In addition, it involves assessing the degree of appearance of similar measures in the plant. It also assesses their effectiveness and performance. Table 8 defines the qualitative scale for evaluating the organizational position of the mitigation measures for reducing CO₂ emissions.

By studying the impact of improvement measures on the facility's existing level of adaption, the know-how about that measure, and the changes that will occur in case of implementation, company decision-makers can identify opportunities for expansion and improvements. In addition, they will be able to prioritize the measures and allocate funds and resources. Cement plant decarbonization and evaluation will be based on evaluations to assess the level of progress of a certain measure.

Table 8. Qualitative scale for evaluating the organizational position.

Level	Description
Low	The measure is not being implemented, and/or no similar measures are currently in practice. Existing measures are ineffective and/or implemented poorly. Significant room for improvement. The know-how is not available at the plant level.
Medium	The measure is being implemented, and/or some similar measures are currently in practice but with variable effectiveness. Existing measures are implemented but are inconsistent or lacking in some areas. Moderate room for improvement. The know-how is relatively available at the plant level.
High	The measure is implemented, and/or many similar measures are currently in practice. Existing measures are effective and implemented substantially and consistently. Strong foundation for improvements. The know-how is available at the plant level.

2.9. CO₂ Emissions Calculations

Calculation of the CO₂ emissions of the cement plant is conducted using equations based on the IPCC formula and recommendations as well as the literature. Emissions estimation involves two emission factors (EFs), one for clinker production and the other for cement kiln dust (CKD) [34–37]. Equation (1) is the formula for CO₂ emission from clinker production and is a product of the lime fraction in the clinker and the factor 0.785, which is the theoretical CO₂ emissions (by weight) associated with the production of 1 unit weight of CaO in the clinker [37].

$$Ef \text{ clinker} = \text{fraction CaO} \times 0.785. \quad (1)$$

A general approach to estimating CO₂ emissions during clinker production is based on the guidelines of the IPCC; thus, the basic equation for estimating CO₂ emissions from clinker production is as follows [37]:

$$\text{CO}_2 \text{ Emissions from Clinker} = \text{Production Data} \times \text{CKD Corrections Factor} \quad (2)$$

The third equation used to calculate emissions is the total emissions that occur due to the manufacturing process, fuel emissions, and electricity emissions [37].

$$\text{Total emissions} = \text{Process emissions} + \text{Fuel emissions} + \text{Electricity emissions}. \quad (3)$$

The ratios used are based on the standard values in the industry. The clinker-to-cement ratio of Portland cement is taken as 95%, the raw material-to-clinker ratio is taken as 1.5, and the CaCO₃-to-raw material ratio is taken as 78% based on the GHG Protocol guidelines. EFs are measured either from the cement plant level or default values provided in Table 1.

3. Results

After developing the assessment framework, the model is applied for analysis of improvement measures based on generic market analysis and two case-specific cement plants to evaluate the implementation level of the improvement measures proposed. Cement plant A is one of the largest production facilities in Egypt. The plant is located on the northern coast and has a production capacity of around 2 million tons per year and 6000 tons per day. On the other hand, company B is a leading international company that

operates more than 65 cement plants worldwide. The studied cement plant B is located in Germany and has an approximate production capacity of 10 Mton per year.

Table 9 demonstrates the results of the quantitative analysis of plant A. Data input and output from the sustainability report for the year 2023, along with the estimated performance by the years 2025 and 2030, were used to calculate the expected percentage change in CO₂ emissions according to the reporting standards of the GCCA, UNGC, IEA, IPCC equations, and IEA [3–9].

Table 9. Current and estimated (until 2030) environmental performance and CO₂ emissions of plant A.

Performance Measures	Units	2023	Estimated		
			2025	2030	%/yr
OPC Production	Mton	1.04	0.9	0.5	(11)
Clinker–cement ratio	%	78.8	71.41	54.3	(4.8)
Thermal energy	TJ	9756	9198.3	7939.7	(2.9)
Electrical energy	TJ	1235	1194.8	1100	(1.63)
Natural raw material	MM tons	4.4	4.02	3.21	(4.42)
Alternative raw material	%	6.4	12.26	52.51	38.42
Substitution fuel	%	19.2	29.12	81.67	23.2
Alternative fuel consumption	ton	118	127.4	154.4	57.33
Water consumption	MM ³	0.66	0.545	0.34	(9.13)
Scope 1 emissions	Kg/t	647.6	612.2	529.4	(2.78)
Scope 2 emissions	Mtons	0.16	0.1471	0.1196	(4.12)
Scope 3 emissions	Kg/t	83	79.6	72.1	(2.05)
Green products	%cem	13.0	36.8	238.8	68.17
Dust emissions	g/t Clinker	59.9	79	150.9	14.88
NOx emissions		1255	1249.5	1167.7	(0.3)
Recycled waste	tons	20.7	27.8	61.1	16
RDF	% heat	10.5	13.1	24.1	11.7
Total CO ₂ emissions	Mt	2.1	2.07	1.99	(0.72)

3.1. Industry Evaluation of Improvement Measures

The improvement measures proposed in Table 3 for evaluating the reduction potential of CO₂ emissions and their categorization are qualitatively analyzed at this stage of the study to relate the most effective categories and sub-categories to be implemented and evaluated at the plants to assess the feasibility of their application. In this step of the study, the results of the analysis, data collection, and assessment of the CO₂ emission reduction measures are presented based on the methodology in Section 2. The scale used to evaluate each improvement measure is from 1 to 5, where 1 is the least developed and implemented and 5 is the most developed and implemented level.

Table 10 shows the assessment of the cement plant's performance in reducing CO₂ emissions and the other performance factors based on generic industry analysis of each performance measure in relation to the technological maturity and economic viability applied in the plant. It also evaluates the performance measures based on their sensitivity to change and as a reference to site constraints, applicability, position, and readiness as a market comparison. It gives an indication of the position of the plant in relation to the market. The correlation between each measure and its improvement potential is determined for future improvements. This table was filled using data from the sustainability reports

of the plant, site visits, official facility goals, and targets. It was verified by interviewing experts at the facility and re-evaluated during a major event in Egypt.

3.2. Analysis of the Proposed Improvement Measures in Two Case Studies (Plants A and B)

There are various sustainability measures that the plants are implementing to reduce CO₂ emissions and the environmental impacts of the cement plants' production. These measures are part of their broader strategies that align with the global decarbonization goals of the cement industry. Some of these measures, which align with those in Table 3 and have medium-to-high impacts, are as follows:

- **Alternative fuels (AF):** Both plants are incorporating alternative fuels such as RDF, TDF, used oil, and biomass to reduce reliance on fossil fuels. For instance, the use of substitutional fuels in plant A was 13.1% in 2022 and 19.5% in 2023. In addition, alternative fuel utilization was recorded at 33.17%. Cement plant A has achieved a thermal substitution rate (TSR%) exceeding 30%. This is an indication of the percentage of thermal energy derived from alternative fuels that reflects the cement plant's environmental performance and reliance on non-conventional fuels. The increased use of alternative fuels reduces CO₂ emissions [38]. In 2023, cement plant A made significant efforts in improving its sustainability initiatives by safely utilizing RDF. This milestone helps to significantly reduce CO₂ emissions by promoting co-processing.

The use of alternative fuels in cement plant B reached 25.7% of total fuel consumption in 2020 and increased to around 28% in 2022. In 2023, plant B successfully increased the use of AF to 29.9%, with waste-based biomass accounting for around 13% of this. The target is to increase the percentage of AF in the fuel mix to over 40% by 2030, with biomass accounting for 20% of this.

- **Energy Efficiency (EE) and Kiln technology upgrade (EK):** Energy efficiency is a key factor in the decarbonization plans of both plants. In 2023, the consumption of thermal energy and electrical energy by plant A were 9756 TJ and 1235 TJ, respectively.

Cement plant B is implementing EE measures such as reducing electricity consumption and using waste to generate electricity to reach the NZE target, which has resulted in a 10% reduction in energy consumption. Also, to reduce CO₂ emissions, the plant decreased the ratio of clinker in cement; clinker production is the intermediate and most energy-intensive process. There are some key energy-efficient measures being undertaken in both plants, including the following:

1. Upgrading kiln technology by modernizing kiln operations to optimize thermal energy consumption. This was performed by upgrading their preheater and calciner systems. Also, plant B is working on a novel kiln technology that will be able to capture more than 500,000 tons of CO₂ emissions by 2025.
2. Waste heat recovery systems are implemented in some facilities to capture and reuse heat generated from kiln and clinker production, which helps in electricity generation and supplies energy for other processes, reducing overall energy consumption and, hence, the CO₂ emissions of the plants.
3. Clinker-to-cement ratio is optimized using additives such as fly ash and slag in the cement production process. This leads to a significant reduction in CO₂ emissions.
4. The use of modern, efficient grinding mills has contributed to the reduction in electricity consumption and led to the reduction in CO₂ emissions. Vertical roller mills are more energy-efficient than traditional ball mills.
5. Cement plants A and B are ISO certified with ISO 50001, the energy management system certification [39]. In addition, plant A has invested 97% of its resource allocations in environmental strategies, where 27% are invested in environmental manage-

ment, and 70% are invested in environmental technologies, for example, as shown in Figure 6.

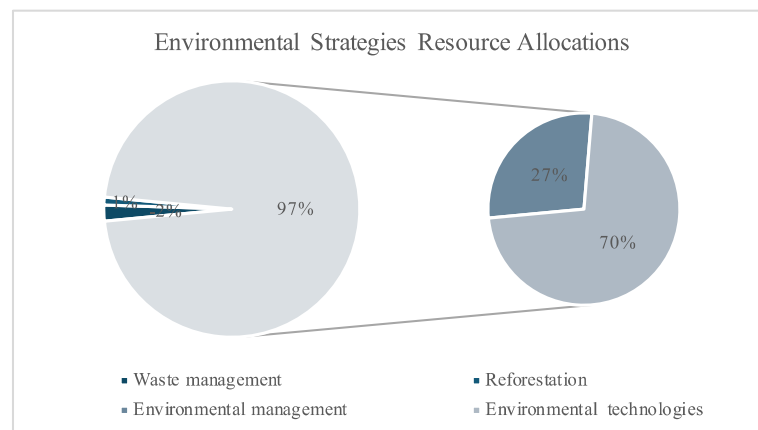


Figure 6. Environmental strategic resource allocation percentages.

- **Renewable Energy (AR):** Plant A has initiated a major solar power project that will help reduce electricity consumption, contributing to a reduction in CO₂ emissions. In addition, the use of renewable energy has risen to 11.4%.

Cement plant B has sourced renewable energy and has its own solar plants to generate renewable electricity. In 2023, they had secured around 12% of the plant's energy demand, mainly from wind energy, and are targeting 100% renewable energy by 2050.

- **CO₂ and heat control (IC) and Innovative technology and integration (II):** Both plants are committed to the COP21 Paris Agreement goals. In 2022, the CO₂ emissions per ton of cement for plant A had reduced to 679 kg/ton of cementitious product. In addition, in 2023, scope 1 emissions had reduced to 648 kg/ton of cementitious product, while scope 2 emissions remained at 0.16 million tons.

For cement plant B, the CO₂ emissions per ton of cement had reached 534 kg/ton of cementitious product in 2023, reducing the specific net emissions by 2%. In addition, the plant's goals for 2030 are to reduce scope 1 and scope 2 CO₂ emissions by around 26% and to reduce NO_x and SO_x emissions by 40%.

- **Change in Raw Material and Product Development (RA, RP, and RC):** Both plants produce advanced low-carbon cement, which is designed to be more environmentally friendly. It also has lower clinker content, which produces lower CO₂ emissions compared with ordinary cement (CEM I). The percentage of low-carbon green products under development in cement plant A reached 13% in 2023, as presented in Figure 7. Cement plant B produces low-carbon cement with 30% lower CO₂ emissions than CEM I, which translates into 30% low-carbon concrete.

Table 10. Model sensitivity analysis of the evaluation of cement plants from the market and operation analysis perspective for CO₂ emission improvement measures.

Abb.	Performance Measure	Evaluation Points						
		Industry Generic Analysis			Plants Comparison to Apply These Measures			
		Technology Maturity and Sensitivity	Economic Viability	Technology Applicability	Site Constraints	Organizational Position	Organizational Readiness and Allocations	CO ₂ Reduction Potential
EEE	Electrical efficiency	5	1	4	3	4	4	3
EET	Thermal efficiency	5	1	4	3	4	4	3
EED	Variable speed drives	3	3	5	3	3	3	3
EPC	Process control systems	3	2	3	4	4	4	4
EPO	Operational efficiency	4	3	4	4	4	3	4
EPR	Recycle and reuse	5	1	4	5	5	5	3
EPP	Pollution control and prevention	5	1	5	5	5	4	4
EKK	Kiln drive improvements	4	4	5	3	3	3	4
EKI	Insulation improvements	3	3	5	5	3	4	3
AF	Alternative Fuels	3	3	5	5	3	4	3
AFB	Biomass							
AFW	Waste materials							
AFN	Non-traditional fuels							
AR	Renewable Energy	3	3	5	5	3	4	4
ARS	Solar energy							
ARW	Wind energy							
ARH	Hydropower							
ARP	Hybrid solar panels (PVT)	3	4	4	5	1	2	4
AH	Waste heat recovery	5	5	5	2	5	5	4
AHH	Heat exchanger							
AHC	Combined heat and power							
RAD	Decarbonated feedstock	3	3	4	3	3	3	4

Table 10. Cont.

Abb.	Performance Measure	Evaluation Points						
		Industry Generic Analysis			Plants Comparison to Apply These Measures			
		Technology Maturity and Sensitivity	Economic Viability	Technology Applicability	Site Constraints	Organizational Position	Organizational Readiness and Allocations	CO ₂ Reduction Potential
RAB	Blending raw materials	5	3	4	3	3	3	3
RAP	Preprocessing of materials	2	3	3	4	2	3	3
RCC	Calcareous oil shale	1	2	3	5	3	1	5
RCS	Supplementary materials	3	3	4	4	4	5	5
RCT	Low-temperature clinker	1	1	1	4	3	1	4
RPI	Blended cement	5	5	5	1	3	4	5
RPN	New product technologies	1	3	3	5	3	4	5
ICS	Carbon capture and storage	1	5	1	1	2	2	4
ICR	Catalytic reduction systems (CSR) and SNCR	4	4	4	3	3	4	5
ICH	Synergistic heating	4	4	4	3	3	4	3
IIT	Advanced process technologies	4	4	4	3	4	4	5
IIR	Developing CO ₂ reduction innovations	3	3	3	3	3	3	5
IIW	Waste treatment integration	4	3	4	3	3	4	4
IIP	Power plant integration	4	4	4	3	3	4	5
IIC	Power plant/cement plant carbonated loop	1	2	2	5	1	1	5
IIS	Syngas co-production	1	3	3	5	1	1	5
O *	Facility operations							

* These are indirect factors and are not included in the industry assessment since they are plant-based; however, they are the foundation of the gross assessment.

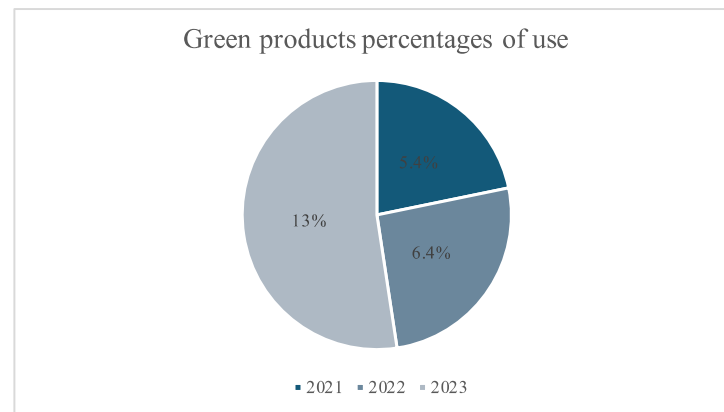


Figure 7. Percentage of plant's green products usage between 2021 and 2023.

In addition, both plants use alternative raw materials such as fly ash, slag, and others. In 2023, cement plant A's usage of alternative raw materials reached approximately 6.4% and raw material usage reached 4.4 Mton. This was compared to 3.6% and 4.1 Mton, respectively, in 2022. Cement plant A's clinker-to-cement ratio reduced to 78.8% in 2023 compared to 82.8% in 2022. In cement plant B, the use of alternative raw materials from by-products or industrial waste increased to around 12% in 2023 compared to around 9% in 2021. These materials are used in clinker production and as cement additives during cement grinding. This results in the use of around 30% less natural materials, which could reduce CO₂ emissions by approximately 40 Mtons per year. The clinker-to-cement ratio decreased to around 70% in 2023 compared to 71.5% in 2022. The plant's goal is to reach a clinker-to-cement ratio of 68% by 2030.

These improvement measures are part of the global sustainability roadmap of the company and reflect the efforts this plant is making to achieve net zero by 2050 in alignment with the European Green Deal, the UN's 2030 Sustainable Development Goals (SDGs), and the Global Cement and Concrete Association (GCCA) [6]. This helps with the reduction of CO₂ emissions. Although these measures are being implemented in the cement plant, there is still room for improvement to further reduce CO₂ emissions associated with cement production. For instance, increasing the use of alternative fuels in the fuel mix, such as biomass, RDFs, and industrial by-products, can significantly reduce reliance on conventional fuels, hence reducing CO₂ emissions. The use of these fuels not only enhances the sustainability of cement production but also encourages the recycling of waste materials instead of contributing to landfills, which aligns with the concept of cleaner production. The production of more low-carbon products like blended cement and green cement using fly ash pozzolans or slag can result in 10% to 30% less CO₂ emissions and achieve a lower clinker-to-cement ratio, which is a major source of CO₂ emissions [40,41]. In addition, the integration of renewable energy, such as wind and solar, can reduce dependence on conventional fossil fuels and reduce emissions [41]. It can be converted to supply cement plants with the energy needed for production. The implementation of advanced energy recovery and emission control systems, such as CCS technologies, can directly impact the sustainability of the plants by capturing CO₂ emissions before they are released [42].

Furthermore, the existing level of implementation of CO₂ emissions reduction measures was evaluated using the assessment model and its software tool through a systematic approach that categorizes the set of measures based on their integration with the sustainability plan of the company and their effectiveness in the cement production process. These improvement measures are evaluated throughout the cement production process and across the stages of inputs and energy efficiency, production optimization, and development of innovative and sustainable output products.

Figure 8 illustrates the various CO₂ emission reduction measures implemented within the simplified cement production model from material and energy streams based on the assessment tool's evaluation and scores. The level of implementation of the improvement measures is color-coded based on a ranking system that is implemented to assess the quality index of the CO₂ emission reduction potential of each measure. This quality index helps evaluate and visually represent the effectiveness of each measure, facilitating the identification of the most impactful and feasible measures for cement plants [27].

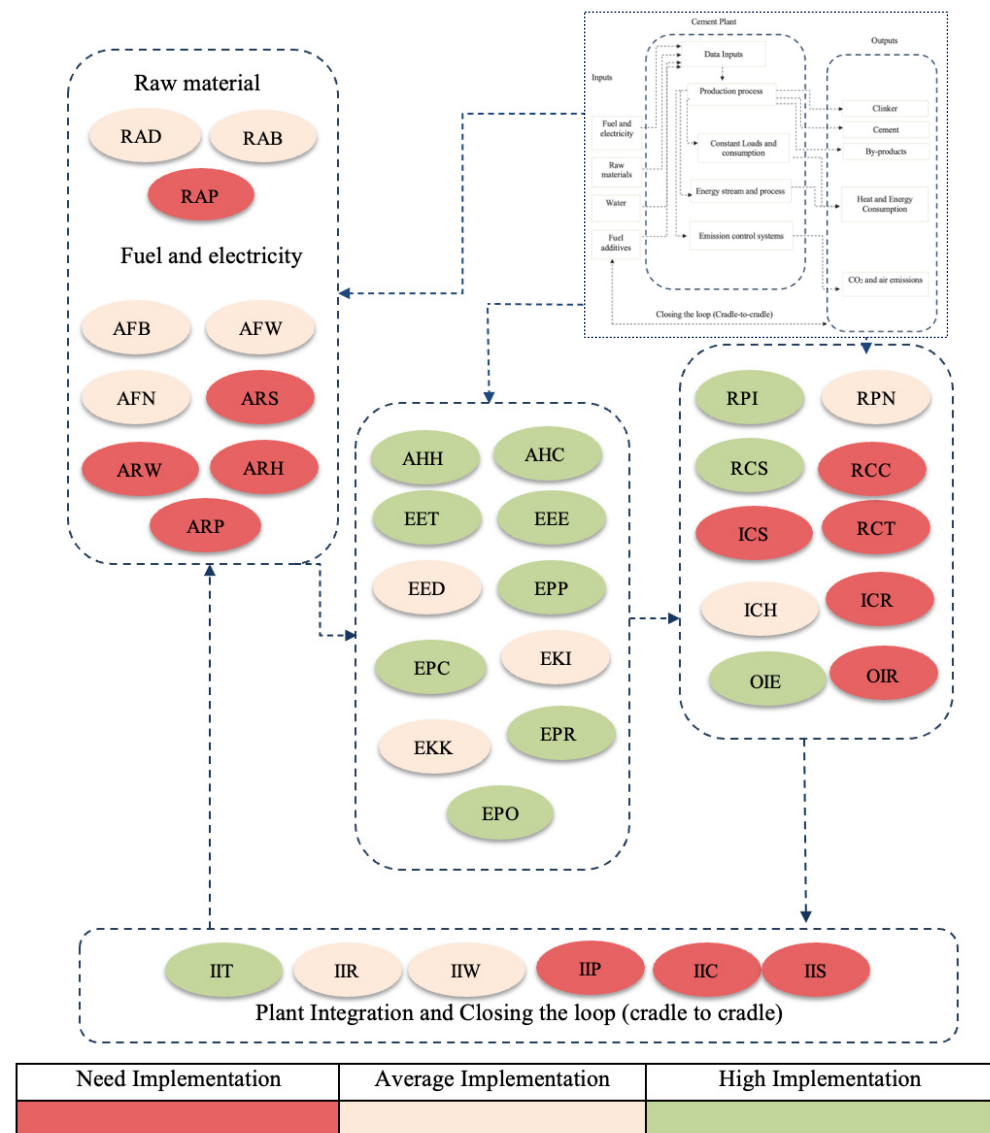


Figure 8. Simplified production model of cement plants and the assessment tool's ranking of each improvement measure based on the model's sensitivity analysis and technology maturity.

The analysis between the reduction measures and their existing level of implementation in the company shows that some measures are more effective at reducing emissions than others; in particular, measures that have low technological maturity and high economic viability have lower scores compared with other measures. Furthermore, some measures that are related to the external measure of industry innovations and technological advancement have low scores due to their initial implementation levels. These improvement measures include waste treatment and power plant integration. Plant A conducts waste treatment integration and has also developed collaborations with co-located firms in different locations. These synergies focus on using high-impact factors, such as alternative

fuels and materials from waste, which are co-processed during the production of cement. For instance, it uses waste-derived fuels such as biomass and industrial by-products as alternative fuels, which help to reduce the need for traditional fuels like coal and oil. Moreover, integrating RDF into its operations is part of its sustainability plan to meet the 2050 goals. It is aligned with cleaner production principles and the goals to reduce CO₂ emissions. It is a means of closing the production loop by using waste as thermal energy in the cement kiln. This not only reduces GHG emissions but also helps with managing waste problems in Egypt by diverting waste from landfills. It is also exploring further synergies with local waste treatment facilities.

In Figure 8, simplified color coding is used to assess each improvement measure and its relation to the sensitivity analysis. Mapping the flow of energy and material through the cement plant shows the improvement measures that are not technologically mature and the ones that are already well implemented and economically viable. This mapping shows that most of the measures are technologically mature, and their sensitivity to market changes is low. Some measures that need industry innovations are in the medium-to-low implementation levels in the cement plant. This is due to the level of technological maturity in the market and the economic viability of each measure that is still in progress. Most of the other elements are either well or medium-implemented.

3.3. Assessment Tool Scores for Both Plants

An assessment software tool was developed to evaluate and score CO₂ emissions improvement measures and overall cement plant performance based on the assessment framework. The tool was run to evaluate the proposed improvement measures for cement plants A and B, and the results are summarized using bar charts for cumulative assessment of the plants. Figures 9 and 10 represent all the improvement measures, main areas, and subareas evaluated and their corresponding scores. These cumulative charts are a valuable tool for visualizing and analyzing performance. They effectively represent the areas that are well implemented and the ones that need further implementation, enabling decision-makers to identify trends, monitor progress, and make faster decisions.

Cement plant A received a performance score of 3.315, which is a high score based on the assessment tool, which highlights areas of high, medium, and low implementation. The model highlights a high score in two main areas: process and technology efficiency and alternative raw material and clinker production, with scores of 3.47 and 3.62, respectively. In addition, the tool highlighted two other main areas that are above average in their implementation levels: alternative fuels and energy management and emission control and industry innovations, with scores of 2.99 and 2.60, respectively. On the other hand, cement plant B received an overall performance score of 3.68, which is a high on-track score based on the assessment tool's evaluation key. The model highlights that out of the five main areas evaluated, four received high on-track implementation level scores of 3.98, 3.48, 3.60, and 3.03 in process and technology efficiency, alternative fuels and energy management, alternative raw material and clinker production, and emission control and industry innovations, respectively. In addition, the fifth main area, facility operations, received an optimal score of 4.42.

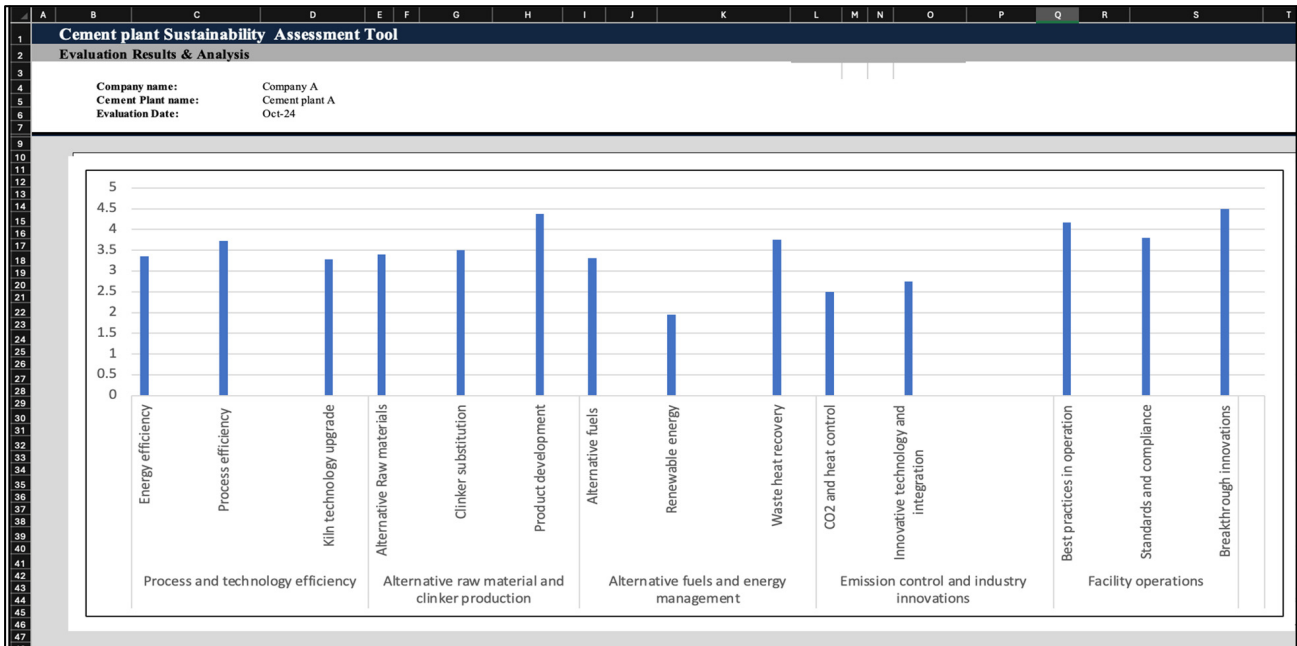


Figure 9. Cumulative chart for the 1st subarea improvement measures, corresponding main areas, and scores for plant A.

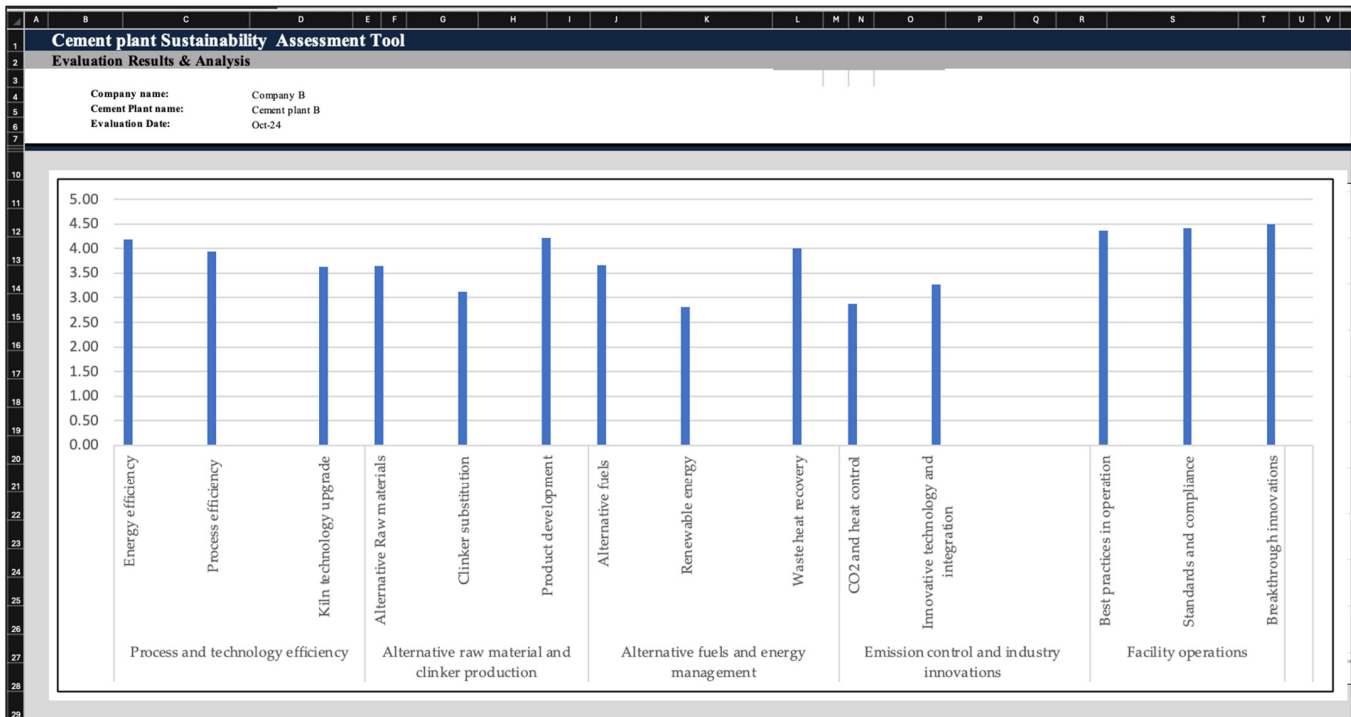


Figure 10. Cumulative chart for the 1st subarea improvement measures, corresponding main areas, and scores for plant B.

The compiled results of the assessment tool for plant A and plant B are summarized and presented in Table 11, providing an evaluation of the plant’s performance scores for the main areas, first subareas, and second subareas.

Table 11. Assessment tool’s summary of improvement measures scores for cement plants A and B.

Main Areas	First Subarea	Score A	Score B	Abb.	Second Subarea	Score A	Score B
Process and technology efficiency	Energy efficiency	3.35	4.18	EEE	Electrical efficiency	3.04	4.13
				EET	Thermal efficiency	3.83	4.45
				EED	Variable speed drives	3	3.75
	Process efficiency	3.72	3.93	EPC	Process control systems	3.5	3.83
				EPO	Operational efficiency	4.06	4.06
				EPR	Recycle and reuse	3.27	3.75
				EPP	Pollution control and prevention	4.13	4.13
	Kiln technology upgrade	3.28	3.63	EKK	Kiln drive improvements	2.81	3.44
				EKI	Insulation improvements	3.85	3.85
Alternative raw material and clinker production	Alternative raw materials	3.40	3.65	RAD	Decarbonated feedstocks	3.3	3.86
				RAB	Blending raw materials	3.33	3.23
				RAP	Preprocessing of materials	3.75	3.75
	Clinker substitution	3.50	3.12	RCC	Calcareous oil shale	1.25	1.25
				RCS	Supplementary materials	3.75	3.06
				RCT	Low-temperature clinkers	3.75	3.75
	Product development	4.37	4.22	RPI	Blended cement	4.53	4.53
				RPN	New product technologies	4.13	3.75
Alternative fuels and energy management	Alternative fuels	3.31	3.66	AFB	Biomass	2.95	3.39
				AFW	Waste materials	2.98	3.37
				AFN	Non-traditional fuels	4.33	4.50
				ARS	Solar energy	1.25	3.75
				ARW	Wind energy	1.88	3.13
Emission control and industry innovations	Renewable energy	1.96	2.81	ARH	Hydropower	3.21	2.50
				ARP	Hybrid solar Panels (PVT)	1.88	1.25
				AHH	Heat exchanger	3.75	3.75
				AHC	Combined heat and power	3.75	4.27
				ICS	Carbon capture and storage	1.25	2.50
	CO ₂ and heat control	2.50	2.88	ICR	Selective non-catalytic reduction systems (SNCR) and CRS	3.75	3.33
				ICH	Synergistic heating	3.75	3.13
				IIT	Advanced process technologies	5	5
	Innovative technology and integration	2.75	3.26	IIR	Developing CO ₂ reduction innovations	3.75	4.20
				IIW	Waste treatment integration	3.75	4.58
				IIP	Power plant integration	1.25	2.03
				IIC	Power plant/cement plant carbonate looping	0.38	0.77
				IIS	Syngas co-production	1.25	1.25

Table 11. Cont.

Main Areas	First Subarea	Score A	Score B	Abb.	Second Subarea	Score A	Score B
Facility operations	Best practices in operation	4.17	4.36	OBT	Staff training and public relations	4.17	4.45
				OBM	Maintenance and program enhancing	3.75	3.75
				OBW	Water management	4.64	5
	Standards and compliance	3.80	4.41	OSR	Regulatory compliance	3.75	5
				OSS	Sustainable material standards	4.38	4.37
				OSE	Environmental impact assessment	3.19	3.75
	Breakthrough innovations	4.50	4.50	OIR	Research and CO ₂ reduction innovations	5	5
				OIE	Environmental strategies	3.75	3.75

4. Discussion

This study provides insights into CO₂ reduction and improvement measures in the cement industry. It demonstrates the effectiveness of a structured yet flexible assessment framework, with its input and output, to systematically assess and score several proposed CO₂ improvement measures within the cement value chain. Based on the tools developed in this study, the assessment framework provides a quantitative and qualitative assessment of cement plants using a scoring system based on the implementation level of each improvement measure (proposed in Table 3) to achieve decarbonization and reach NZEs by 2050. The model has milestones, with all the needed data collected from sustainability reports, site visits, and expert interviews. By applying the tool to two cement plants with different production scales and geographical locations, this study highlights the variability in emissions reduction potential and the need for continuously updating mitigation strategies.

Several studies have examined CO₂ reduction plans during cement production, emphasizing the role of alternative fuels, energy efficiency, and clinker substitution in reducing CO₂ emissions by cement plants. For instance, the GCCA is targeting a 20% reduction in emissions by 2030, consistent with the findings of this study [6,43]. However, unlike previous studies, which primarily focused on technological advancements and policy frameworks, this study introduces a structured scoring model that provides a standardized evaluation method for cement plants. By incorporating weighted criteria, this tool enables decision-makers to assess the implementation level of various improvement measures in a systematic manner to identify priority areas for improvement, bridging the gap between high-level decarbonization roadmaps and plant-level implementation. In addition, applying the assessment tool to two cement plants revealed the following insights:

- **Potential variability:** both plants implemented several of the evaluated CO₂ improvement measures, but their overall performance scores differed due to the implementation level of each measure and its impact on the sustainability of the plant and the reduction in CO₂ emissions.
- **Future improvements:** The model provides a cohesive mapping of the level of implementation of CO₂ improvement measures across the cement value chain based on the materials and energy flow. By continuously applying the assessment tool, plants can track their progress over time and adjust strategies and resource allocation. The model revealed that even well-established cement plants have opportunities for improvement and further efficiency.

- **NZE goal alignment:** The model is aligned with the NZEs goal for 2050 and the intermediate milestones for 2030 and 2040, and the tool takes these targets into account during the calculation and evaluation of emissions. The results confirm that achieving NZEs in the cement industry is challenging and requires the integration of technological, operational, and regulatory solutions.

Beyond the cement plants' operations, this study has broader implications for the field of structural engineering and sustainable construction, where sustainable material selection and low-carbon construction practices are becoming essential. By providing a data-driven assessment tool for evaluating cement plant emissions and sustainability, this model enables structural engineers to select environmentally friendly materials, optimize carbon-efficient designs, and align with global net zero targets. Additionally, this study supports the development of industry-wide benchmarks and regulatory policies that drive innovation in green construction materials and techniques, facilitating the transition to a low-carbon built environment.

5. Conclusions

Several studies, roadmaps, and reports have focused on reducing CO₂ emissions in the cement industry for its decarbonization to achieve net zero emissions by 2050. However, a structured, unified, and flexible method is needed to evaluate and rate the implementation of improvement measures within cement plants. This paper presents a comprehensive assessment framework that systematically categorizes, assesses, and rates several proposed CO₂ improvement measures, aiding plant development and decision-making. The assessment framework is inspired by the concept of cleaner production and the 5Cs approach to cement industry decarbonization. The framework integrates both qualitative and quantitative assessments. An assessment tool that evaluates cement plants based on the implementation level of each improvement measure using evaluation questions with an evaluation score from 1 to 5 based on the weighted average approach is developed. The model serves as a diagnostic and mapping tool that can systematically evaluate a cement plant with hundreds of different improvement measures and identify the areas that need enhancements, the most applicable measures, and the most highly implemented measures while integrating strategies to achieve sustainability. It also facilitates decision-making, strategic planning, and resource allocation.

The model is scalable. It was successfully applied to two well-established cement plant case studies with different production scales and geographical locations. Cement plant A achieved a performance score of 3.315, while cement plant B scored 3.68. The results highlight the plants' strong commitment to CO₂ reduction while identifying future optimization opportunities.

This study contributes to the growing body of knowledge on decarbonization in the cement industry and provides a robust framework for evaluating and improving sustainability efforts. However, there are some limitations to this study that should be considered. Variability in real-world conditions, such as regional regulatory differences, plant-specific operational challenges, and variations in raw material availability, may impact the generalizability of these findings. Additionally, the cement industry is evolving, and this can impact the long-term durability of the proposed CO₂ improvement measures, particularly in cement plant operations. The sustainability of these measures may vary over time and operational practices and under different environmental conditions. These should be considered in future updates to the model to adapt to any changes and incorporate the latest real-time data, emerging technologies, policies, and applications, ensuring its continuous effectiveness and maintaining progress toward NZE targets.

Author Contributions: Conceptualization, E.K. and M.A.; methodology E.K.; software, E.K.; validation, E.K. and M.A.; formal analysis, E.K.; writing—original draft preparation, E.K.; writing—review and editing, E.K.; visualization, E.K.; supervision, M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Harraz, H.Z.; Hamdy, M.M.; Abu El-Ela, A.S.M.; El-Hoseiny, I.M. Assessment of Raw Materials for Cement Industry In El Sukhuna-Zaafrana Area, Eastern Desert, Egypt. *Delta J. Sci.* **2020**, *42*, 108–124. [\[CrossRef\]](#)
2. Hamza, A.S. Assessment of Carbon Dioxide Emission and Its Impact on High-Rise Mixed-Use Buildings in Egypt. Master's Thesis, The American University in Cairo, AUC Knowledge Fountain, Cairo, Egypt, 2021.
3. IEA. *Net Zero by 2050: A Roadmap for the Global Energy Sector*; The International Energy Agency: Paris, France, 2021.
4. CEMBUREAU. *Cementing the European Green Deal: The 5Cs, Reaching Climate Neutrality Along the Cement and Concrete Value Chain By 2050*; The European Cement Association: Brussels, Belgium, 2020.
5. 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 University Press: Cambridge, UK, 2022.
6. GCCA. *Cement Industry Net-Zero Tracker*; World Economy Forum: Geneva, Switzerland, 2023.
7. IPCC. *Climate Change 2022: Mitigation of Climate Change*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2022.
8. UNFCCC. *UNFCCC Secretariat Recognition and Accountability Framework Draft Implementation Plan with Respect to Net-Zero Pledges of Non-State Actors and Integrity Matters*; United Nations Framework Convention on Climate Change: New York, NY, USA, 2023.
9. USGCRP. *The U.S. Global Change Research Program 2022–2031 Strategic Plan*; United States Global Change Research Program: Washington, DC, USA, 2022.
10. Khalil, E.A.; Abouzeid, M.N. Computation of the environmental performance of ready-mix concrete for reducing CO₂ emissions: A case study in Egypt. *J. Elsevier Energy Rep.* **2023**, *9*, 144–148. [\[CrossRef\]](#)
11. Adesina, A. Recent advances in the concrete industry to reduce its carbon dioxide emissions. *J. Elsevier Environ. Chall.* **2020**, *1*, 100004. [\[CrossRef\]](#)
12. Fayomi, G.U.; Mini, S.E.; Fayomi, O.S.I.; Ayoola, A.A. Perspectives on environmental CO₂ emission and energy factor in Cement Industry. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *331*, 012035.
13. USGS. *Cement Production Statistics and Information: Statistics and Information on the Worldwide Supply of, Demand for, and Flow of the Mineral Commodity Cement*; National Minerals Information Center: Denver, CO, USA, 2023.
14. Luo, J.; Hunang, R.; Wang, J.; Zhang, Y. Carbon Sequestration by Preparing Recycled Cement, Recycled Aggregates, and Recycled Concrete from Construction and Demolition (C&D) Wastes. *Materials* **2024**, *17*, 5020. [\[CrossRef\]](#)
15. Mokhtar, A.; Nasooti, M. A decision support tool for cement industry to select energy efficiency measures. *Energy Strategy Rev.* **2020**, *28*, 100458. [\[CrossRef\]](#)
16. Kusuma, R.T.; Hiremath, R.B.; Rajesh, P.; Kumar, B.; Renukappa, S. Sustainable transition towards biomass-based cement industry: A review. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112503. [\[CrossRef\]](#)
17. Fadayini, O.M.; Madu, C.; Oshin, T.T.; Obisanya, A.A.; Ajiboye, G.O.; Ipaye, T.O.; Rabiou, T.O.; Akintola, J.T.; Ajayi, S.J.; Kingsley, N.A. *Energy and Economic Comparison of Different Fuels in Cement Production*; IntechOpen: Rijeka, Croatia, 2021.
18. IEA. *World Energy Outlook 2022*; Report by the International Energy Agency; IEA: Indianapolis, IN, USA, 2022.
19. IEA. *Global Thermal Energy Intensity from Cement Production*; Report by The International Energy Agency; IEA: Indianapolis, IN, USA, 2023.
20. Carbone, C.; Ferrario, D.; Lanzini, A.; Stendardo, S.; Agostini, A. Evaluating the Carbon Footprint of Cement Plants Integrated with the Calcium Looping CO₂ Capture Process. *Front. Sustain.* **2022**, *3*, 809231. [\[CrossRef\]](#)
21. IPCC. *AR6 Synthesis Report: Climate Change 2023*; Dadi, D.K., Zhai, P., Eds.; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2023.
22. Elghamrawi, S. Greening the Cement Industry in Egypt: Exploring Decarbonisation Policies for the Cement Industry. Master's Thesis, The American University in Cairo, AUC Knowledge Fountain, Cairo, Egypt, 2023.
23. Costa, F.N.; Ribeiro, D.V. Reduction in CO₂ emissions during production of cement, with partial replacement of traditional raw materials by civil construction waste (CCW). *J. Clean. Prod.* **2020**, *276*, 123302. [\[CrossRef\]](#)

24. Khalil, E.A.; Abouzeid, M.N. Environmental Impact of Cement Plants in Egypt: A Comprehensive Study on Carbon Dioxide Mitigation Measures and Evaluation. In Proceedings of the Canadian Society for Civil Engineering (CSCE), Niagara Falls, ON, Canada, 5–8 June 2024.
25. WBCSD. *Vision 2050: Time to Transform*; World Business Council for Sustainable Development: Geneva, Switzerland, 2021. Available online: <https://archive.wbcsd.org/Overview/About-us/Vision-2050-Time-to-Transform/Resources/Time-to-Transform> (accessed on 4 February 2025).
26. Sayad, T.; Moursy, F.I.; El-Tantawi, A.M.; Saad, M.; Morsy, M. Assessment the impact of different fuels used in cement industry on pollutant emissions and ambient air quality: A case study in Egypt. *J. Environ. Health Sci. Eng.* **2023**, *21*, 107–121. [\[CrossRef\]](#)
27. Vasileiadou, A.; Zoras, S.; Iordanidis, A. Fuel Quality Index and Fuel Quality Label: Two versatile tools for the objective evaluation of biomass/wastes with application in sustainable energy practices. *Environ. Technol. Innov.* **2021**, *23*, 101739. [\[CrossRef\]](#)
28. Rocha, S.; Candia, O.; Valdebenito, F.; Flavio Espinoza-Monje, J.; Azócar, L. Biomass quality index: Searching for suitable biomass as an energy source in Chile. *Fuel* **2020**, *264*, 116820. [\[CrossRef\]](#)
29. Khalil, E.A. A Global Assessment Tool for Reduction of CO₂ Emissions Associated with Portland Cement and Relevant Sectors. Ph.D. Thesis, The American University in Cairo, AUC Knowledge Fountain, Cairo, Egypt, 2025.
30. CEMBUREAU. Cementing the European Green Deal: Reaching Climate Neutrality Along the Cement and Concrete Value Chain by 2050. 2020. Available online: <https://www.scribd.com/document/478753604/2020-Cementing-the-European-Green-Deal> (accessed on 17 November 2024).
31. El Haggag, S.M. Rural and Developing Country Solutions. In *Environmental Solutions*, 13th ed.; Elsevier: Amsterdam, The Netherlands, 2005; Volume 13, pp. 313–400.
32. Yesilyurt, M.; Kocadagistan, B. Carbon Footprint Evaluation of a Ready-Mixed Concrete Plant. *Nanoera* **2023**, *3*, 8–15. [\[CrossRef\]](#)
33. Breathe. *ESG in the Cement and Concrete Industry*; Breathe Foundation: St. Louis, MO, USA, 2023.
34. IPCC. Guidelines for National Greenhouse Gas Inventories. Agriculture, Forestry, and Other Land Use. The Intergovernmental Panel on Climate Change. Available online: <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/> (accessed on 20 November 2024).
35. Nie, S.; Zhou, J.; Yang, F.; Lan, M.; Li, J.; Chen, Z.; Xu, M.; Li, H. Analysis of theoretical carbon dioxide emissions from cement production: Methodology and application. *J. Clean. Prod.* **2022**, *334*, 130270. [\[CrossRef\]](#)
36. IPCC. Updates Methodology for National Greenhouse Gas Inventories. The Intergovernmental Panel on Climate Change. Available online: <https://www.ipcc.ch/2019/05/13/ipcc-2019-refinement/> (accessed on 25 January 2025).
37. Gibbs, M.; Soyka, P.; Conneely, D. CO₂ Emissions from Cement Production. The Intergovernmental Panel on Climate Change. Available online: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_1_Cement_Production (accessed on 14 October 2024).
38. Vasileiadou, A. Reduction of CO₂ emissions through the co-combustion of lignite with biomass residues: Renewable and non-renewable CO₂ per produced megajoule and fuel characterization. *Therm. Sci. Eng. Prog.* **2024**, *50*, 102566. [\[CrossRef\]](#)
39. ISO. International Organization for Standards in Energy Management. International Organization for Standards. Available online: <https://www.iso.org/iso-50001-energy-management.html> (accessed on 11 February 2025).
40. Variny, M.; Varga, A.; Rimár, M.; Janošovský, J.; Kizek, J.; Lukáč, L.; Jablonský, G.; Mierka, O. Advances in biomass co-combustion with fossil fuels in the European context: A review. *Processes* **2021**, *9*, 100. [\[CrossRef\]](#)
41. Saradar, A.; Rexakhani, Y.; Rahmati, K.; Majd, F.; Moein, M.; Karakouzian, M. Investigating the properties and microstructure of high-performance cement composites with nano-silica, silica fume, and ultra-fine TiO₂. *J. Innov. Infrastruct. Solut.* **2024**, *9*, 84. [\[CrossRef\]](#)
42. Plaza, M.G.; Martínez, S.; Rubiera, F. CO₂ capture, use, and storage in the cement industry: State of the art and expectations. *Energies* **2020**, *13*, 5692. [\[CrossRef\]](#)
43. Tkachenko, N.; Tang, K.; McCarten, M.; Reece, S.; Kampmann, D.; Hickey, C.; Bayarara, M.; Foster, P.; Layman, C.; Rossi, C.; et al. Global database of cement production assets and upstream suppliers. *Sci. Data* **2023**, *10*, 696. [\[CrossRef\]](#) [\[PubMed\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.