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Re-investment Rebound Dynamic in the Cement Industry

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Abstract

The cement industry is a major contributor to global greenhouse gas emissions, making its decarbonization essential for achieving international climate targets. While the industry employs strategies such as improving efficiency, enhancing resource recovery, using low-carbon feedstocks and fuels, and developing lower clinker-to-cement products, environmental assessments increasingly raise concerns about rebound effects. One significant form of rebound is the "re-investment rebound effect", where monetary savings from decarbonization initiatives are reinvested into activities that produce additional emissions, thereby offsetting some of the potential environmental benefits. This study defines the re-investment rebound effect for decarbonization initiatives, using the cement industry as a case study. We quantify the effect using data reported to the CDP (formerly the Carbon Disclosure Project), categorizing the effects by Scope and initiative type, identifying areas most and least susceptible to rebound. The results indicate that equipment modernization and clinker reduction efforts are most vulnerable to re-investment rebound, whereas automation, fuel use reduction, and enhanced process control show the least rebound vulnerability. The study also finds no significant correlation between carbon intensity of firms and the re-investment rebound potential of their decarbonization actions. This work can help inform targeted policies that enhance the effectiveness of industrial decarbonization strategies by equipping production engineers and corporate entities with insights to help address and mitigate unintended emissions rebounds.

Keywords: re-investment rebound, decarbonization, cement, CDP, emission reduction

1. Introduction

Cement is a crucial construction material worldwide, with production rates steadily rising each year [1], [2]. Its material and emissions-intensive manufacturing process has positioned it as a significant contributor to global warming, accounting for 6-8% of global greenhouse gas (GHG) emissions [3], [4], [5]. Emissions from the cement sector have increased by nearly 10% since 2015, and the International Energy Agency (IEA) anticipates numerous conventional plants in the coming years [6]. IEA has forecasted a minimum 20% reduction in cement manufacturing emissions by 2030 is required to remain on track for net-zero emissions by mid-century [6].

Current emissions reduction efforts in the cement industry focus on enhancing material and energy efficiency, implementing resource recovery through recycling and pre-heating of kilns, substituting inputs with alternative low-carbon feedstocks and fuels, and developing innovative products with reduced clinker-to-cement ratios [7], [8]. One of the most challenging aspects of cement decarbonization is addressing this sector's process-related emissions, which play a dominant role in the overall GHG footprint of this industry. In the United States, more than half of cement industry emissions arise from CO_2 directly emitted during the calcination process [9]. Since these emissions are difficult to fully abate, it is likely that carbon capture, utilization, and storage (CCUS) technologies will need to play a key role in a comprehensive decarbonization strategy. The sector is also exploring synergies such as renewable energy integration and collaborations with power plants and waste treatment facilities to achieve varying degrees of CO_2 reduction [7], [8].

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The CDP, formerly the Carbon Disclosure Project, is an international nonprofit organization that supports companies, cities, states, and regions in the collection and public reporting of environmental data. The CDP is frequently used as a credible resource in studies related to the impact of emissions reduction efforts on climate change, as well as associated corporate financial strategy and their carbon management systems [10], [11], [12], [13], [14], [15]. Positive associations between carbon disclosures in CDP reports and long-range carbon performance for the reporting corporate entities have also been demonstrated [16], [17]. Cement producers participating in CDP reporting include Holcim Ltd., Cemex, Ultratech Cement, and Taiheiyo Cement Corporation

A significant yet often overlooked challenge for decarbonization efforts is the rebound effect, whereby planned emissions reductions are partially or fully offset by emissions related to follow-on effects of the intervention [18]. The rebound effect is a rising concern for industrial sustainability concepts such as the circular economy, electrification, and energy transition, where impact-reduction is often paired with operational efficiencies and/or cost-savings[19], [20], [21]. Rebound can occur through a variety of mechanisms; in this study we focus on a mechanism we term re-investment rebound. A re-investment rebound effect occurs when the monetary savings from firm-level initiatives are reinvested in activities that generate additional emissions, thereby offsetting some of the potential environmental benefits. The effect is conceptually similar to the re-spending effect which focuses on consumer behavior, whereas re-investment rebound is an indirect microeconomic effect that occurs on the production side [22]. While numerous studies have documented the rebound effect from re-spending savings at the household or residential level research on the re-investment of savings for the commercial sector remains limited [23] [24], [25], [26]. Understanding this re-investment rebound effect is essential for formulating effective policies and strategies that maximize the intended benefits of decarbonization projects while minimizing unintended negative outcomes.

In this study, the authors aim to fill the literature gap related to the re-investment rebound effect resulting from the decarbonization initiatives undertaken by the industrial entities. To achieve this objective, the study proposes a methodology to quantify the underlying re-investment rebound effect using reported CDP data, categorizing the rebound effects according to their respective Scopes, and applying the cement industry as a case study. Additionally, this study seeks to pinpoint those areas of initiatives that are most and least susceptible to re-investment rebounds, thereby assisting policymakers in developing effective policies. The findings can support the production community in optimizing resource use, guide emissions-reducing process design, equip production engineers to consider and address rebound effects, and provide guidelines for monitoring and mitigating rebounds in manufacturing by offering practical examples of rebound mitigation in real-world production contexts.

2. Methodology

2.1. Data orientation

The CDP data used in the study was licensed as part of their academic package and can be accessed by anyone via CDP [27]. The data set includes details of reported decarbonization projects such as investment required (IR) for the project, annual monetary savings (AMS) associated with it, and quantity of annual emission savings (AES) expected. The survey data also reports the associated lifetime of the initiative (LI) as well as the payback period (PB) in the form of categorical data. Monetary values reported in the study were predominantly expressed in the local currencies corresponding to the geographic origin of the respective organizations. The organizations also report their carbon intensity (CI) which was calculated based on their gross or annual carbon emission generated (AEG) and gross or annual revenue generated (ARG) achieved at organization scale within the reporting year.

2.2. Overview of the mathematical framework

Employing the reporting framework of the CDP, a mathematical model was developed to compute the rebound emissions associated with the re-investment of annual monetary savings (AMS) accrued over the lifetime (LI) of decarbonization initiatives. The model operates under the premise that no monetary savings derived from the project remain uninvested, and that companies will continue to generate emissions at the prevailing carbon intensity (CI).

The net present value (NPV) of the total savings acquired over the project's lifetime is calculated by adjusting the AMS for inflation using the discount rate *i*, which accounts for the time value of money and reflects factors such as inflation, opportunity cost, and project risk. Given that the lifetimes of these initiatives (LI) can extend beyond 25 years, the NPV calculation is crucial for assessing long-term benefits. This relationship is expressed mathematically in Equation 1:

$$NPV_{LI} = \left(\frac{AMS}{i}\right)\left(1 - \frac{1}{(1+i)^{LI}}\right) \quad (1)$$

The annual Producer Price Inflation (PPI) for 2023, as published by The World Bank, was used as the inflation rate for each geographic region [28]. Additionally, historical exchange rates to USD were retrieved from the same source [29]. These adjustments ensure that currency volatility and economic differences are accurately reflected in the analysis. The net total profit (NTP), representing the re-investment capacity of the organization, is then estimated by subtracting the investment required (IR) from the NPV of the savings as shown in Equation 2:

$$NTP = NPV_t - IR \quad (2)$$

The Lifetime Emission Reduction (LER) is calculated by multiplying the annual emission savings (AES) by the initiative's lifetime as represented in Equation 3:

$$LER = AES\ x\ LI \quad (3)$$

Rebound emissions (RE) are then determined by multiplying the NTP by the carbon intensity (CI) as shown in Equation 4:

$$RE = NTP \ x \ CI \quad (4)$$

Finally, the rebound percentage (R) is expressed as the ratio of RE to LER, multiplied by 100% illustrated in Equation 5:

$$R\ (\%) = \frac{\sum RE}{\sum LER} \ x \ 100\% \quad (5)$$

An overview of the mathematical framework for the study is presented in Figure 1:

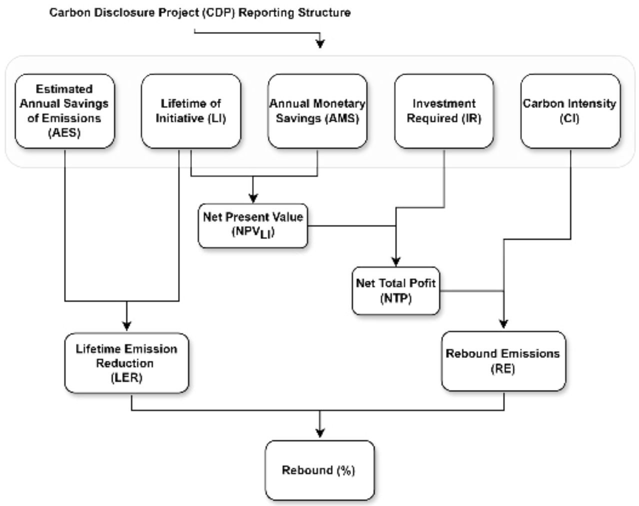

Figure 1: Mathematical framework used for re-investment rebound calculation

All analysis performed on the dataset were done using Python programming language. To make the data suitable as input into our mathematical model, several assumptions were considered -

- Dataset was screened for missing values in key variables including IR, AMS, AES, LI, PB, and CI. Missing values for IR were imputed using the products of AMS and PB, while records with missing data in other variables were excluded from the analysis.
- The dataset was subjected to a rationality check to filter out negative values for IR, AMS, AES, LI, PB, and CI. Projects lacking IR were excluded as they represent non-monetary initiatives outside the study's scope; AMS values were required to be positive to reflect potential re-investment; LI and PB were constrained to non-negative values by definition; and negative CI values were removed due to their lack of relevance to rebound vulnerability. Additionally, cases where AMS and AES savings exceeded 100% of gross revenue and emissions, respectively, were excluded for data quality reasons (savings more than the infeasible)
- Outliers were identified and removed based on values exceeding ±2 standard deviations for AMS, AES, and CI. Monetary values initially reported in local currencies were converted to USD prior to filtering. The outlier removal process was applied simultaneously across all categories to maintain the integrity of the dataset's statistical properties.
- Mean values were used for categorical ranges of LI and PB, with specific values assigned as follows: "<1 year" was set to 1, ">25 years" to 25, ">30 years" to 30, "No payback" to 0, and "Ongoing" to 30.

Before moving to the numerical analysis, the initiatives were further categorized into the targeted source of reduction categories as presented in the study by Khaiyum et al. (2023) based on the project description provided for each initiative to CDP [3]. The relationship between the initiative categories presented on the CDP questionnaire and that with the source reduction strategies implemented by the organizations is shown in Table 1.

3. Results and Discussion

Of the 103 reported decarbonization initiatives for cement manufacturing companies, only 71 remained after the filtering process. The participating organizations of these remaining initiatives reported a total revenue of \$326.8 billion which is 80.44% of the market size of cement industry for 2023 [2] (see Table 2).

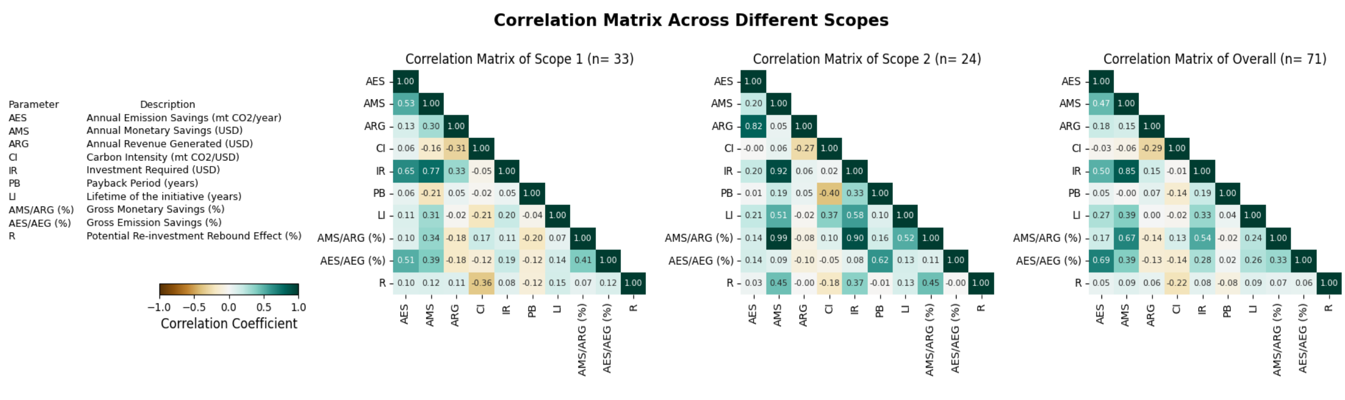

Figure 2: Pearson coefficient correlation matrix of different scopes for all studied metrics reported using the cement sector questionnaire of CDP (n = the count of initiatives)

Table 1: Categorizing the decarbonization initiatives based on the initiative details reported by the organizations to CDP following [3]

Initiative categories	**Example descriptions of decarbonization initiatives in the cement industry as reported to CDP**
Energy efficiency in buildings	▪ Electricity-related CO_2 emission: replace conventional lighting with more energy-efficient alternatives; enhanced heating and cooling system in buildings
Energy efficiency in production processes	▪ Calcination-related CO_2 emissions: increased kiln efficiency and reduction of calcination ▪ Clinker making in kilns: displacing it with cementitious (pozzolans, calcined clays); usage of decarbonated raw materials and produce low temperature clinker; reduced fuel consumption, hydrogen injection in the kiln; replacing fossil fuel with alternative fuel (tires) improved clinker quality; lowering the clinker to cement ratio (use of calcined clay, 3D printing); enabling autonomous production (reduced manual intervention in production process like grinding operations, optimizing fuel and electricity consumption, enhanced process control) ▪ Combustion-related CO_2 emissions: replacing fossil fuel with alternative fuel (municipal waste, biomass, waste plastics, wood chips, paper waste, fabric scraps) ▪ Electricity-related CO_2 emissions: replacing old machines with modern machines (energy- efficient Medium Voltage Drives (MVD), motors, compressors, new cement mill separator, screw compressors; energy-efficient flat belt systems, implementation of rotary pump, scrubber washer, dust collection system, installing efficient motors and drives, modifying backwashing system, upgrading HTHP machines); process optimization; waste heat recovery system; renewable energy consumption; enabling autonomous production; improved boiler design aimed at improved steam to fuel ratio; better product and service design; replacing fossil fuel with alternative fuel - increase Refuse-Derived Fuel (RDF); ▪ Grinding (Calcareous Material / Finish grinding): enabling autonomous production
Low-carbon energy consumption	▪ Electricity-related CO_2 emissions: purchase of renewable electricity; waste heat recovery system; replacing fossil fuel with alternative fuel (waste and biomass); using solar power system
Low-carbon energy generation	▪ Electricity-related CO_2 emissions: purchase of renewable electricity
Non-energy industrial process emissions reductions	▪ Clinker making in kilns: reduction of the clinker cement ratio (replacing clinker with slags, fly ashes, CKD, artificial pozzolans or calcined clays, limestone, and others); increased production capacity of low-carbon cement; enhanced storage capacity enabling cement production with reduced clinker ratio
Waste reduction and material circularity	▪ Clinker making in kilns: incremental use of fly ash, slag and filler; reduced usage of clinker ▪ Electricity-related CO_2 emissions: replacing fossil fuel with alternative fuel (biomass)
Other, please specify	▪ Electricity-related CO_2 emissions: replace conventional lighting with more energy-efficient alternatives

Table 2 Summary of analysis

Metrics	Results
No. of initiatives	71
Total reported revenue	$ 326.8 bn
Total reported monetary savings	$ 165.07 m
Potential Re-investment Rebound (%)	6.76 %

The Pearson correlation coefficients between all the reporting parameters relevant to the proposed methodology is presented in Figure 2. The number of initiatives considered in the study exclusively for each scoping category is represented by n (Figure 2). Of the 71 reported initiatives, 33 were categorized exclusively under Scope 1, 24 under Scope 2, and one under Scope 3. The remaining 13 initiatives encompassed mixed scopes, representing combinations of Scope 1, 2, and 3. Specifically, eight initiatives were classified as Scope 1 and 2, three as Scope 1 and 3, and two as Scope 1,2 and 3. Due to the limited number of studies within each mixed-scope combination, a comprehensive critical review and statistical analysis of these combinations was not feasible. Consequently, the critical review undertaken in this study focuses primarily on initiatives classified under Scope 1 (n = 33) and Scope 2 (n = 24). However, all 71 initiatives (including the 13 mixed-scope initiatives) were included in the “overall” dataset.

Figure-2 indicates that the payback period (PB) of decarbonization projects, a commonly used metric for assessing the profitability of these initiatives, shows no correlation (r = - 0.08) with the potential re-investment rebound **[30]**. Amjadi et al. (2018) studied fuel and electricity rebound effect of heavy industries (pulp and paper, basic iron and steel, chemical, and mining) in Sweden and found CO2 intensity to be a useful indicator for identifying rebound effect within the sector **[31]**. Contrary to the findings of Amjadi et al. (2018), this study finds no significant correlation between carbon intensity (CI) and rebound, as indicated by r = - 0.22 in the analyzed data presented in Figure 2 **[31]**. Figure 2 also reveals that the correlation between re-investment rebound and annual monetary savings (AMS) is 0.12 for Scope 1 initiatives but increases to 0.45 for Scope 2 initiatives. This suggests a small correlation between them for Scope 2 initiatives, highlighting an area for further research on this relationship.

Figure 3 presents the potential re-investment rebound effect (in percentage) for each initiative category across different scoping categories. To interpret the results, the potential re-investment rebound effects (%) of the initiatives were classified according to the approach outlined by Saunders (2008) and utilized by Amjadi et al. (2022) [32], [33]. Brief summaries of the five rebound classification categories as adopted from the literatures is presented below [32], [33]:

1. **Backfire Effect (RE > 1):** This occurs when emission reduction improvements lead to an increase in overall emission generation rather than a decrease, as the economic gains from efficiency spur more emission than is saved.
2. **Full Rebound (RE = 1):** In this scenario, all emission savings from efficiency improvements are offset by increased emission generation elsewhere, resulting in no net reduction in emission.
3. **Partial Rebound (0 < RE < 1):** This represents a situation where some, but not all, of the emission savings from efficiency gains are offset by increased emission generation, leading to a net reduction, albeit smaller than expected.
4. **Zero Rebound (RE = 0):** In this case, emission reduction improvements do not lead to any offsetting increase in emission generation, meaning all the savings translate into actual reductions in emission.
5. **Super Conservation (RE < 0):** This rare scenario occurs when emission reduction gains lead to a greater reduction in emission than anticipated, often due to behavioral or economic responses that further minimize emission generation.

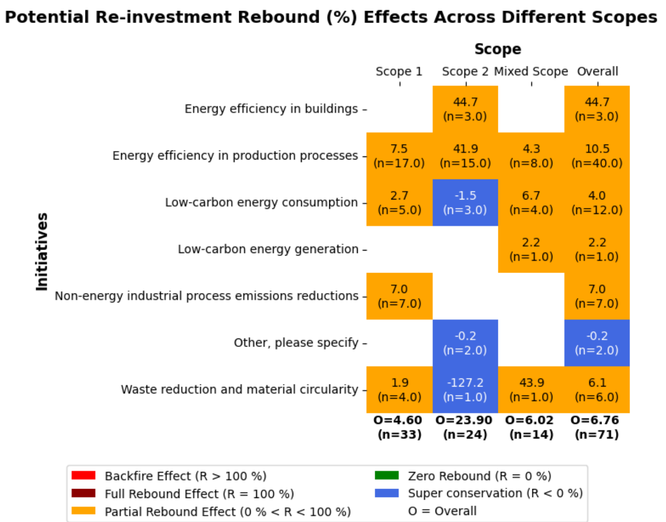

Figure 3: Potential re-investment rebound (%) using aggregated emission across different scopes (n = the number of initiatives) for each category using equation (5)

Here, "Mixed Scope" includes all the initiatives that were not exclusively reported as Scope 1 or Scope 2 initiative. This includes all initiatives targeting Scope 3 emissions reductions, as well as initiatives designed to address emissions across multiple Scopes. As shown in Figure 3, the "overall" column (including all 71 projects) indicates that the highest number of decarbonization initiatives (n=40) for the cement industry were categorized under "Energy efficiency in production processes." Breakdown of these initiatives into Scope categories shows a relatively balanced distribution between Scope 1 and Scope 2. However, Scope 2 initiatives at R= 41.9% are potentially much more vulnerable than Scope 1 initiatives. Initiatives like replacing old machines with new machines (Energy-efficient Medium Voltage Drives (MVD), motors, compressors, etc.) are the topmost contributors for Scope 2 rebound emissions under this category. These improvements in electricity usage will induce a substitution effect where energy services will substitute for other inputs (such as capital or labor) due to the increased productivity of energy (reduced cost of per unit usage) **[34]**. Use of calcinated clay, 3D printing, and other clinker reduction efforts also contribute significantly for Scope 2 emissions as part of this segment. However, the individual project with the highest measured conservation potential was autonomous production at -99.1%.

Out of all the categories, the three initiatives of "Energy efficiency in buildings" listed under Scope 2 depict most rebound potential (R=44.7%). Activities listed under this initiative include replacing conventional lighting with more energy-efficient alternatives and enhancing heating and cooling systems. According to Nadel (1993), building lighting programs have take-back effects of at least 30% **[35]**. These results resonate with previously studied energy related rebound effects where technological progress in power sector has seen to result in rebound **[36], [37]**.

The one initiative in mixed Scope with R= 43.9% offers a solution to save CO_2 primarily from clinker substitution in the value chain as well as from landfilling avoidance. It is a proprietary technology that utilizes the beneficiated fly ash for use in concrete. However, the potential most re-investment rebound (187.3%) vulnerable project is a waste heat recovery project at the manufacturing site that will generate electricity replacing the previous coal-based power plant. It was reported under "Low-carbon energy consumption".

For Scope 1 initiatives, one of the projects under "Non-energy industrial process emissions reductions" holds a potential re-investment rebound of 77.6% and is project that aims at increasing the production capacity of low-carbon cement aimed at producing large quantity of environmentally friendly cement. Second to that is a waste heat recovery system (R = 69.1%) expected to operationalize during the first quarter of 2023-24.

4. Limitation of the study

The accuracy of this study largely depends on the integrity, expertise, reporting capabilities, and adherence to protocols of the reporting entities. Additionally, the anticipated reduction in carbon intensity from successful implementation of initiatives will directly impact the rebound emission estimates produced by the model. The analysis presumes that the re-investment of savings will occur at a business-as-usual level and remain consistent throughout the lifetime of each initiative. However, the validity of this assumption depends on the level of independent structural changes that may occur in the production system over the lifetime of the decarbonization initiative, which separately impact production intensity and emissions [38]. Fluctuating changes in supply and demand for cement-based products, shifts in supply chains and distribution networks, international relations and policies, can all affect outcomes. While the study does not currently include statistical analyses on the significance of the results, these aspects, along with other considerations highlighted in this section, are intended to be addressed in future research, strengthening the overall robustness of the findings.

5. Conclusion

This study addresses a critical gap in the literature on re-investment rebound effects in the context of decarbonization initiatives, using the global cement industry as a case study. By proposing a methodology that quantifies re-investment rebounds using reported CDP data, this research categorizes the effects according to their respective Scopes and identifies specific areas within the cement industry that are most and least vulnerable to such rebounds. The results reveal that initiatives focusing on energy efficiency in production processes, particularly through equipment modernization and clinker reduction efforts, show the highest susceptibility to re-investment rebound. In contrast, initiatives aimed at enabling autonomous production (refer to Table 1) demonstrate the lowest rebound potential, highlighting priority areas where policy interventions could yield the greatest impact. Additionally, the analysis found no significant correlation between carbon intensity (CI) and re-investment rebound emissions, suggesting that companies are susceptible to rebound regardless of their progress in overall decarbonization. These findings underscore the need to consider rebound effects in policy interventions, ensuring that decarbonization efforts deliver their intended environmental benefits. By identifying which initiatives are prone to generating additional emissions through re-investment, this study provides valuable insights that can guide policymakers in developing more robust and effective strategies. Future work will focus on statistical validation and further refinement of the model, enhancing its application to broader contexts and strengthening the foundation for sustainable decarbonization policies in high-emission industries.

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