Industrial Symbiosis and Energy-Technology Integration Pathways for Isolated Cement Plants

Introduction

Cement manufacturing remains one of the most carbon-intensive industrial activities, accounting for between 7 and 8% of global CO_2 emissions. Efforts to decarbonize the sector are complicated by the high thermal demands of clinker production and the process emissions generated during calcination. In the case of isolated cement plants, the lack of external synergies or waste-heat consumers further limits mitigation options, since industrial symbiosis cannot be implemented without integration with other facilities or industries. Nevertheless, even though the traditional concept of industrial symbiosis cannot be directly applied in these plants, it is valuable to explore how new technologies might inspire approaches rooted in industrial symbiosis. By incorporating innovative solutions, these facilities have the opportunity to undergo significant transformation, promoting greater energy diversification and optimizing the use of both internal and external resources. This challenge is reinforced by the fact that cement plants typically rely on a highly unbalanced energy structure, with around 89% of their total consumption coming from thermal energy and only 11% from electricity. Within the thermal fraction, energy use is dominated by petroleum coke (~60%), followed by around 20% coming from a diverse mix of alternative fuels, including meat-and-bone meal, plastics and industrial sludges while the remaining ~10% is supplied by other minor fossil sources.

This study evaluates two contrasting configurations in a representative 2 Mt/year isolated cement plant: (i) a reference scenario reflecting conventional fossil-based operation, and (ii) a technology-integration scenario, inspired in the industrial symbiosis concept, deploying a portfolio of renewable, recovery, storage and carbon-capture technologies. The objective is to quantify improvements in environmental performance, energy autonomy and operational costs arising from system integration.

Methodology

A calculation-driven, technology-agnostic framework was applied using hourly energy-balance computations for a full operational year (2023). The system boundary includes the kiln, clinker-cooler heat streams, electricity demand, fossil-fuel inputs, renewable-generation units, thermal and electrical storage, anaerobic digestion and partial CO_2 capture. Direct emissions were computed from fuel combustion and calcination, whereas indirect emissions reflect the carbon intensity of purchased electricity or, in the technology-integration scenario, credits from renewable-electricity export. Financial modelling accounts for capital expenditures, energy costs, avoided purchases and electricity-export revenues, excluding product-sales revenues to isolate the marginal effects of energy-system integration.

Results

The generated technology-integration scenario incorporates scaled-up technologies, including 91 MW of photovoltaics, a 50 MW Organic Rankine Cycle (ORC) unit, 161 MWh of thermal storage, 113 MWh of battery storage, anaerobic digestion processing 50 kt/year of feedstock, and a carbon-capture system removing 129 Mkg CO_2 annually. The sizing of each technology results from an optimization process aimed at identifying the most efficient and cost-effective integration pathway for the plant. There are marked differences in energy use, emissions and operating costs between the two scenarios. In the reference scenario, the kiln requires approximately 1.5 TWh/year of thermal energy, supplied entirely by fossil fuels, and around 0.12 TWh of electricity is purchased from the grid. No internal energy-conversion or recovery pathways are present in this configuration.

In the technology-integration scenario, photovoltaic generation supplies 0.096 TWh and the ORC delivers 0.067 TWh of electricity, supported by battery storage. Grid-electricity purchases drop to 0.038 TWh, and the plant exports 0.09 TWh of renewable electricity. This transition reshapes the plant from an import-dependent monovector configuration to a diversified multi-vector energy hub.

Direct emissions remain dominated by calcination and fossil-fuel combustion and are effectively constant at 1238 Mkg CO_2/year across both scenarios. However, the integration of a partial-capture unit removes 129 Mkg CO_2/year of process emissions, while indirect emissions fall from +49 Mkg CO_2/year in the reference scenario to -30 Mkg CO_2/year in the technology-integration scenario due to renewable-electricity exports displacing carbon-intensive generation.

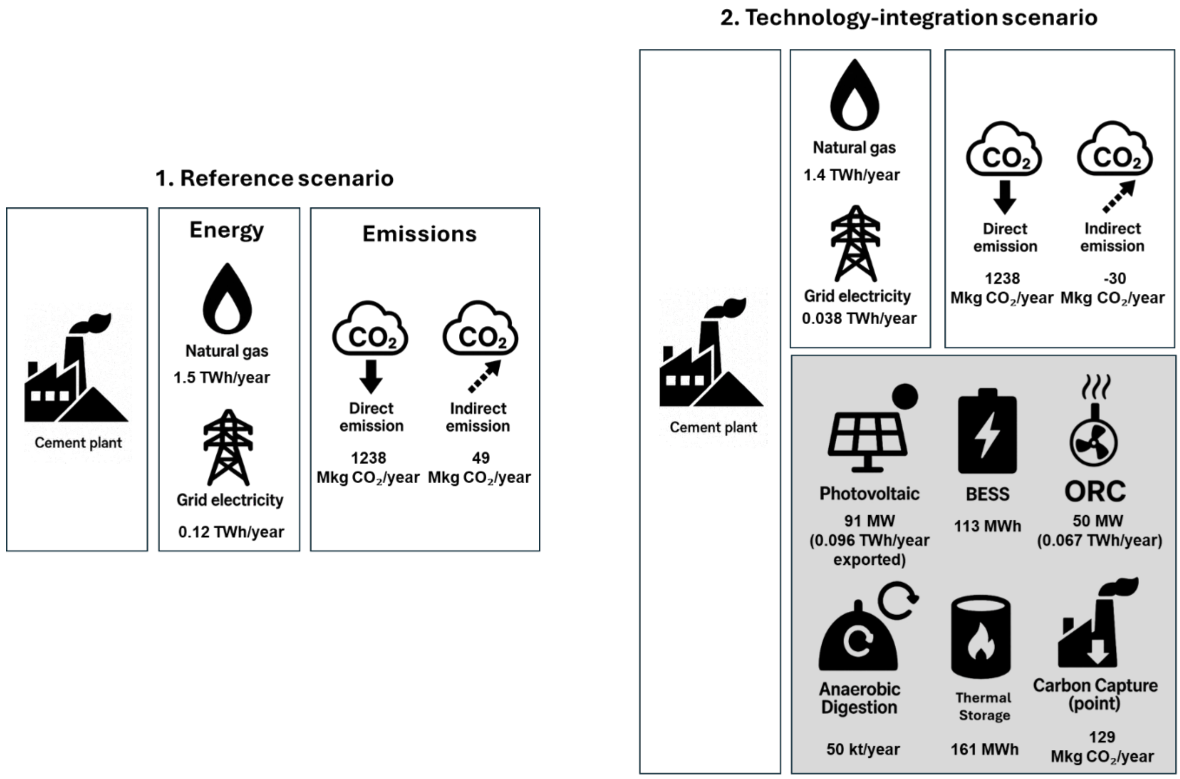

Figure 1 *Annual summary of energy flows and emissions in both the reference and technology-integration scenarios, showing thermal energy demand, electricity supply by source (grid, photovoltaics, and ORC), renewable electricity export, direct process emissions, and indirect emissions associated with electricity consumption.*

Operational costs further reflect the benefits of system integration. The technology-integration scenario achieves an annual cost reduction of ~26 M€, enabled by avoided electricity purchases, reduced fossil-fuel use and revenues derived from renewable-electricity export. Even when accounting for capital expenditures, the integrated configuration outperforms the reference scenario, demonstrating strong techno-economic potential for energy-system integration in isolated cement plants.

These findings align with literature emphasizing that deep decarbonization of cement production requires system-level strategies (Andrew, 2019). While direct process emissions remain largely unchanged unless carbon-capture or clinker-substitution routes are implemented, substantial improvements can be achieved by reducing indirect emissions, recovering waste heat and integrating onsite renewables. This behavior is consistent with prior analyses showing that thermal losses and grid-electricity dependency are major inefficiencies in conventional plants, which can be mitigated through ORC-based heat recovery, renewable-generation hybridization and energy-storage coupling (Madlool et al., 2011; Bataille, 2020). More recently, a systems-approach study within the cement sector demonstrated that combining multiple energy-conversion and storage pathways yields greater decarbonization potential than isolated measures, reinforcing the relevance of multi-vector integration strategies for both environmental and operational performance (Supriya et al., 2023).

Conclusions

The study demonstrates that technology integration-combining renewable generation, waste-heat-to-power conversion, storage systems, anaerobic digestion and partial carbon capture can substantially improve the environmental and economic performance of an isolated cement plant. The transition from full reliance on imported electricity to net renewable-electricity export drives indirect emissions to negative values and enhances regional decarbonization.

Building on the concept of industrial symbiosis, the integrated configuration treats the plant as a coordinated system where technologies and energy flows interact much like resource exchanges in multi-industry clusters. Through thermal-energy valorization, circularity enabled by biogas production and the coupling of multiple energy vectors, the plant evolves into a multi-vector energy hub. This demonstrates that isolated cement plants can still participate meaningfully in broader industrial and power-system net-zero trajectories.

References

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