American Journal of Environmental Economics (AJEE)

ISSN: 2833-7905 (ONLINE)

VOLUME 5 ISSUE 1 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Environmental Economics (AJEE)

Volume 5 Issue 1, Year 2026
ISSN: 2833-7905 (Online)
DOI: https://doi.org/10.54536/ajee.v5i1.5547
https://journals.e-palli.com/home/index.php/ajee

Institutional Inertia and Path Dependency in the Energy Transition of Taiwan's Cement Industry: A Multi-Level Perspective Analysis

Jia-Ying Lyu[1*]

Article Information

Received: June 18, 2025

Accepted: July 24, 2025

Published: January 10, 2026

Keywords

Carbon Lock-In, Ccus, Energy Transition, Institutional Inertia, Just Transition, Multi-Level Perspective,Policy Mix,Taiwan Cement Industry

ABSTRACT

Taiwan's cement industry accounts for roughly 7 percent of national CO_2 emissions and faces EU CBAM and national net-zero mandates. This study applies the Multi-Level Perspective, carbon lock-in, and policy mix theories to examine decarbonization drivers and barriers in Taiwan's oligopolistic, capital-intensive cement sector. Qualitative content analysis and process tracing reveal that entrenched technological paradigms, fragmented policy regimes, and immature low-carbon niches hinder systemic change. Landscape pressures (border carbon policies, green finance) are intensifying, yet regime inertia limits disruptive innovations (LC3, geopolymer cements, CCUS). Modeling suggests existing best practices can cut emissions by up to 40 percent by 2035, but deeper (> 80 percent) reductions require CCUS deployment. We propose dynamic carbon pricing with revenue recycling, green public procurement, accelerated binder standards, shared CCUS infrastructure, and just transition measures to overcome lock-in and enable deep decarbonization. This integrated framework advances transition theory and informs governance strategies for small open economies.

INTRODUCTION

Since the Paris Agreement entered into force in 2015, global climate governance has entered a new phase of decarbonization planning. The cement industry alone contributes approximately 7 percent of total anthropogenic CO_2 emissions, stemming from both process emissions during limestone calcination and combustion emissions at high temperatures (Habert *et al.*, 2020). With full implementation of the European Union's Carbon Border Adjustment Mechanism (CBAM) scheduled for 2026, export-oriented economies that fail to adopt effective carbon pricing will face additional tariffs and potential market exclusion.

In Taiwan, the cement sector exhibits a concentration ratio (CR_2) of 73 percent, annual clinker output of 15 million tonnes, coal-based heat supply accounting for 85 percent of energy input, and an emission intensity of 670 kg CO_2 per tonne of cement substantially above the EU benchmark of 590 kg CO_2 per tonne (Scrivener *et al.*, 2018). External policy pressures and entrenched high-carbon pathways have therefore grown in tandem, exponentially amplifying the urgency of an energy transition.

From the perspective of carbon lock-in theory, fixed capital investments and institutional arrangements are mutually reinforcing, suppressing the diffusion of disruptive innovations (Seto *et al.*, 2016). The Multi-Level Perspective (MLP) further emphasizes that interactions among landscape pressures, regime structures, and niche innovations shape the trajectory of socio-technical transitions (Geels & Schot, 2007). Given Taiwan's cement industry is simultaneously locked into high-carbon infrastructure and operates within an oligopolistic market, it is imperative to elucidate the mechanisms of institutional inertia and assess the potential for technological innovation.

Accordingly, this study aims first to characterize the structural features of energy use and carbon emissions in Taiwan's cement industry, thereby revealing the origins of institutional inertia and path dependency. Second, it seeks to develop an MLP-based framework for evaluating the drivers and barriers of transition. Finally, it intends to propose specific governance instruments and technology portfolios for governmental and industrial stakeholders. These objectives give rise to the following research questions:

1. How has high-carbon path dependency emerged in Taiwan's cement sector?
2. Within multi-level interactions, what relationships exist among landscape pressures, regime inertia, and niche innovations?
3. Do current policy mixes present gaps across economic incentives, technological push, and market pull dimensions?
4. Which combinations of technologies and governance mechanisms can overcome system lock-in to achieve deep decarbonization?

Methodologically, the study employs parallel qualitative content analysis and process tracing. Data sources include SSCI-indexed journal articles, the International Energy Agency's cement technology roadmap, government carbon inventory reports, and corporate sustainability disclosures. A coding framework is constructed along four dimensions technological inertia, economic lock-in, policy fragmentation, and social narratives to triangulate empirical evidence and theoretical constructs. The

---

[1] School of Finance and Accounting, Fuzhou University of International Studies and Trade, China
[*] Corresponding author's e-mail: m0227118@gmail.com

remainder of the paper is organized as follows: Section 2 reviews theoretical and empirical literature; Section 3 outlines industry evolution and structure; Section 4 examines energy use and emissions; Section 5 analyzes institutional inertia; Section 6 applies the MLP framework to assess transition dynamics; Section 7 proposes technological and policy pathways; and Section 8 presents conclusions and policy recommendations.

Theoretical Foundations and Literature Review

Social–technical transition is understood through the Multi-Level Perspective (MLP), which conceptualizes socio-technical change as arising from interactions among three analytical levels: landscape, regime, and niche (Geels & Schot, 2007). The landscape encompasses long-term external pressures such as scientific consensus on climate change and international carbon policies. The regime consists of dominant technological paradigms, industrial standards, regulatory frameworks, and market strategies. Niches provide protected spaces for experimentation with radical innovations such as low-carbon cement formulations, alternative fuels, and carbon-capture demonstrations that may, once landscape pressure exceeds a threshold and regime structures exhibit fissures, leverage their relative autonomy to disrupt and ultimately reconfigure mainstream technological trajectories (Geels & Schot, 2007).

Contemporary global discourse places increasing emphasis on carbon footprints and emissions reduction, exemplified by the phenomenon of carbon lock-in. Deeply sunk costs and entrenched institutional arrangements render investment in cement kilns alongside their integrated supply chains of quarries, ports, and transport highly path-dependent, thereby foreclosing disruptive alternatives absent prolonged cost-recovery horizons. Concurrently, engineers and managers habituated to legacy processes and quality standards exhibit cognitive lock-in, further inhibiting the uptake of low-carbon technologies (Seto *et al.*, 2016).

Policy mix theory, which recognizes that single instruments cannot address the complexity of deep socio-technical transitions, advocates for coordinated packages combining economic incentives (e.g., carbon pricing), command-and-control regulations (e.g., emissions standards), supportive measures (e.g., R&D subsidies), and market pull (e.g., green public procurement). Such coherent and credible policy bundles are essential to send clear investment signals and steer long-term decarbonization efforts (Rogge & Reichardt, 2016).

Moreover, stakeholder theory underscores that energy transitions are inherently socio-political processes necessitating the inclusion of government, industry, academia, environmental organizations, labor unions, and local communities. Excluding affected quarry communities and displaced workers from fair compensation and participatory mechanisms risks strong policy backlash. The Just Transition framework therefore calls for dedicated transition funds, worker retraining programs, and local economic support to bolster legitimacy and resilience (Avelino & Rotmans, 2009).

The International Energy Agency's 2050 Cement Technology Roadmap and the Global Cement and Concrete Association's net-zero pathways identify a portfolio of mitigation options including energy efficiency improvements, alternative fuel and raw material use, clinker substitution, and carbon capture, utilization, and storage (CCUS). Efficiency gains alone can achieve approximately 20–30 percent emissions reductions; coupling alternative fuels with clinker substitution yields an additional ~10 percent; only CCUS can drive near-zero emissions (Milleret *et al.*, 2021). European demonstration projects have employed amine scrubbing, calcium loop, and oxy-fuel processes, supported by Contracts for Difference to de-risk initial investments and foster low-carbon product markets via Environmental Product Declarations (EPDs) in public procurement (Bataille *et al.*, 2018).

Despite the high mitigation potential of novel binders such as Limestone Calcined Clay Cement (LC3) and geopolymer cement, commercialization is impeded by insufficient standardized data, durability validation, and high costs. While Europe has achieved alternative fuel substitution rates exceeding 40 percent, Taiwan remains at ~10 percent, constrained by waste management regulations and underdeveloped supply-chain coordination (Habert *et al.*, 2020). Existing literature predominantly addresses European contexts, leaving a gap in empirical studies of East Asian oligopolistic markets and cross-border carbon policy impacts.

In sum, this study integrates the MLP's landscape–regime–niche framework with theories of carbon lock-in, policy mixes, and Just Transition. Employing qualitative content analysis and process tracing of the Taiwanese cement sector, it investigates the interplay among cross-border carbon policies, oligopolistic structures, and low-carbon technology portfolios to propose concrete policy and technical pathways, thereby addressing the paucity of research on high-carbon industry transitions in small, open economies.

Industry Development Context and Structural Characteristics

Historical Evolution and Development Phases

Since the founding of Taiwan Cement Corporation (TCC) in 1946, the Taiwanese cement industry has undergone four principal phases: Post-War Reconstruction, Economic Take-Off, Structural Adjustment, and Globalization and Sustainable Development. In the Post-War Reconstruction Phase (1946–1970), production capacity, centered on single-line dry-process rotary kilns, expanded rapidly from 0.2 million tonnes in the inaugural year to 4 million tonnes, driven by reconstruction demands for roads and buildings.

During the Economic Take-Off Phase (1971–1990), the "Ten Major Construction Projects" and export-oriented economic policies precipitated a surge in infrastructure investment, elevating capacity to over 10 million tonnes and introducing multi-stage preheaters with precalciners, markedly enhancing thermal efficiency. The Structural Adjustment Phase (1991–2000) witnessed a confluence of economic restructuring, a real estate bubble, and stringent environmental regulations, resulting in overcapacity and parallel implementation of rigorous emission standards; firms responded by decommissioning obsolete kilns, engaging in horizontal mergers, and investing in waste-heat recovery power plants as well as desulfurization and dust-removal installations. From 2001 to the present the Globalization and Sustainable Development Phase domestic cement producers have accelerated overseas expansions, notably establishing large-scale plants in China and Southeast Asia, while simultaneously pursuing ISO 14001 environmental management certification, Green Factory recognition, and sustainability reporting to comply with international carbon border adjustment mechanisms and national net-zero mandates (Habert *et al.*, 2020).

As of the end of 2023, the Taiwanese cement market is dominated by two firms TCC and Asia Cement Corporation collectively controlling over 70 percent of market share; Hsing Fu and Universal Cement constitute a secondary tier, while the remaining small and medium-sized enterprises supply only regional niches. Although such concentration fosters economies of scale and capital-intensive technological investment, it may suppress competitive pressure and stifle innovation, since alternative binders or carbon-capture technologies require substantial capital outlays and extended payback periods, posing significant barriers for smaller firms (Geels & Schot, 2007). Furthermore, oligopolistic producers leverage industry associations to participate in government standard-setting processes, thereby reinforcing industry accords and price-stabilization mechanisms and forming a highly integrated industrial consortium.

Resource Geography and Operations Model

From the perspective of resource endowment, Taiwan's limestone deposits are primarily located in Hualien, Taitung, and Nantou. In eastern Taiwan, geological suitability and deep-water port access have attracted multiple large cement plants; the central region, by contrast, relies on plains and high-voltage transmission infrastructure. Producers typically employ a quarry–plant–port triangular operations model, supplying raw material directly from owned quarries, pre-processing on site, and transporting via maritime or rail routes to domestic or export markets thereby minimizing bulk freight costs (Seto *et al.*, 2016). In recent years, in response to sustainability imperatives, certain plants have collaborated with local governments to establish ecological restoration areas and community visitor centers, balancing ecological conservation with corporate image.

The core cement production process comprises limestone crushing and homogenization, raw-meal proportioning and grinding, clinker firing, and cement grinding and packaging. Clinker firing, the most energy-intensive stage, predominantly utilizes coal or refuse-derived fuel (RDF) at temperatures up to 1,450 °C. Domestic mainstream producers have widely adopted five-stage preheaters with precalciners in dry-process kilns achieving thermal efficiencies exceeding 95 percent and installed waste-heat recovery systems to convert kiln exhaust heat into electricity, thereby reducing reliance on external power. Remaining decarbonization potential resides in fuel substitution, raw-meal blending, and intelligent process optimization; however, relying solely on traditional process enhancements is insufficient for deep emissions reductions (Milleret *et al.*, 2021).

Market Demand, Trade Dynamics, and Social–Environmental Tensions

Domestic cement demand is driven by major public infrastructure projects and urban redevelopment schemes; yet, local fiscal constraints and policy interventions can temporarily dampen demand fluctuations. Export-oriented producers target Southeast Asia and the U.S. West Coast, but face value competition from low-cost manufacturers in China and Vietnam. Additionally, the imminent imposition of EU CBAM carbon tariffs will complicate international pricing and cost structures (Rogge & Reichardt, 2016). To command price premiums, some firms have adopted green labeling and Environmental Product Declarations (EPDs) to secure preferential contracts in the EU and Japanese markets.

Concurrently, the industry's concentration in Indigenous territories and ecologically sensitive zones has elicited community concerns regarding habitat destruction, water quality degradation, and health risks. Heightened societal awareness of environmental justice and corporate social responsibility now compels producers to enhance transparency in environmental impact assessments, implement robust community engagement mechanisms, and operationalize ecological compensation and benefit-sharing initiatives to mitigate conflicts and ensure operational stability (Avelino & Rotmans, 2009).

Energy Use Structure and Carbon Emission Characteristics

Global Cement Sector Energy Consumption Profile

The cement sector ranks among the world's most energy-intensive industries, as its production process requires clinker firing at temperatures around 1,450 °C. Studies estimate that cement production accounts for roughly 7 percent of global industrial energy use and contributes an equivalent share to energy-related CO_2 emissions, making it the second-largest industrial emitter after steel (Bataille *et al.*, 2018; Miller *et al.*, 2021). In the clinker production stage, the specific energy intensity including fossil fuel combustion and electricity consumption ranges from 3.2 to 3.6 GJ per tonne of clinker, representing over 80 percent of total process energy. The remaining stages raw meal proportioning and grinding plus cement milling are electricity-intensive and collectively consume about 20 percent of the overall energy input (Miller *et al.*, 2021).

Energy Supply Structure in Taiwan's Cement Industry

Taiwan's cement industry relies heavily on imported fossil fuels. According to the online energy reporting system, coal accounts for 85 percent of the sector's energy mix, electricity comprises 10 percent, and petroleum coke plus other derived fuels account for the remaining 5 percent (Su *et al.*, 2013). Coal, sourced as high- or low-volatile oil shale derivatives, is favored for its lower cost and long-term supply contracts, servicing the kilns' primary heat demand. Electricity is primarily used for raw material crushing and the grinding of raw meal and clinker, with grinding operations alone consuming over 70 percent of the sector's total electricity. A few producers have begun co-firing refuse-derived fuels (RDF) such as waste tires and plastics, but overall RDF substitution remains below 10 percent (Su *et al.*, 2013).

Emission Sources and Characteristics

Cement-related CO_2 emissions derive from two main sources: process emissions and fuel combustion emissions. Process emissions arise from the chemical decomposition of limestone ($CaCO_3$) during clinker firing, representing about 60 percent of total emissions; combustion emissions from fossil fuel use constitute the remaining 40 percent (Ishak, 2014). Taiwan's cement sector mirrors this split, reporting a carbon intensity of approximately 670 kg CO_2 per tonne of cement slightly above the global average of 635 kg CO_2 per tonne primarily due to its high coal share in the fuel mix, which increases combustion emission intensity (Ishak, 2014; Su *et al.*, 2013).

Trends in Energy Intensity and Efficiency

Over the past two decades, Taiwan's cement industry has achieved modest improvements in energy intensity. Data from the 2013 online energy reporting system indicate that compared to 2000 levels, energy intensity per unit of output decreased by about 10 percent electricity intensity fell by approximately 12 percent and fuel intensity by about 8 percent. These gains result principally from the adoption of five-stage preheaters with precalciners and the widespread implementation of waste-heat recovery power systems (Huang *et al.*, 2016). Nevertheless, an estimated 20 percent of additional efficiency potential remains untapped, particularly in areas such as improved raw meal homogenization, smart kiln control, and high-efficiency grinding systems (Huang *et al.*, 2016).

Reductions in Carbon Intensity and Mitigation Potential

Bottom-up modeling studies indicate that, by 2035, Taiwan's cement sector could achieve approximately 25 percent fuel energy savings and a 9 percent reduction through fuel substitution under current best available technologies. On the electricity side, high-efficiency motors and intelligent grinding can reduce power consumption by about 25 percent; clinker substitution through supplementary cementitious materials (e.g., blast-furnace slag, fly ash) can lower the clinker factor by about 15 percent, further cutting process emissions (Huang *et al.*, 2016; Su *et al.*, 2013). However, surpassing 80 percent total emissions reduction demands integration of carbon capture, utilization, and storage (CCUS) to address both process and combustion emissions (Miller *et al.*, 2021).

International Comparison of Emission Intensities

Compared internationally, Taiwan's cement sector records a carbon intensity of about 670 kg CO_2 per tonne of cement slightly below China's approximately 710 kg CO_2 per tonne and India's 700 kg CO_2 per tonne reflecting relative strengths in efficiency and fuel substitution. Nonetheless, Taiwan still exceeds the performance of Europe (approximately 590 kg CO_2 per tonne) and Japan (about 610 kg CO_2 per tonne), attributable to Europe's average alternative fuel share of 44 percent and Japan's near 30 percent, alongside proactive adoption of low-carbon binder technologies by those regions (Bataille *et al.*, 2018).

This chapter has elucidated the structural disparities and emission characteristics of global versus Taiwanese cement energy use. Globally, dual emissions from clinker firing and fuel combustion underscore the cement sector's pivotal role in decarbonization agendas. In Taiwan, reliance on imported coal and grid electricity renders the industry acutely sensitive to energy security and carbon mitigation efforts. Although Taiwanese producers have made headway through process optimization and RDF co-firing, further integration of low-carbon binders, smart manufacturing, and CCUS supported by robust policy incentives and market mechanisms is imperative to overcome deep decarbonization bottlenecks.

Institutional Inertia and Structural Dilemmas

Since the advent of the dry-process rotary kiln, cement production technology has been optimized over several decades, resulting in a standardized process centered on Portland clinker. This technological paradigm encompasses firing equipment, waste heat recovery, raw-meal proportioning, and quality control, all of which are reinforced through engineer training, supply-chain networks, and industry standards, thereby establishing a strong path-dependency mechanism. Transitioning to novel low-carbon binders or electrified firing would require major retrofits of existing kilns, with investment payback periods often exceeding fifteen years far beyond the typical corporate threshold of three to five years thus impeding the adoption of disruptive innovations (Seto *et al.*, 2016).

As cement is a bulk commodity of low value density, its unit price is constrained by transportation costs and supply–demand dynamics, yielding profit margins typically between 5 and 10 percent. Such price competition reduces firms' capacity to absorb high upfront investments, particularly for cost-intensive solutions like carbon capture and storage (CCUS). Studies indicate that CCUS investment costs range from USD 50 to 100 per tonne of CO_2 avoided well above prevailing carbon price levels and that the technology's maturity and business models remain unproven (Aghion *et al.*, 2016). Consequently, companies tend to favor short-term energy efficiency improvements and co-firing of alternative fuels to secure relatively stable input–output ratios.

Energy transitions require long-term, stable policy signals; however, in practice, carbon fee targets are frequently adjusted, exemption thresholds are inconsistently applied, and administrative procedures often face delays, making mid- to long-term investment planning difficult. Taiwan's carbon fee, implemented in 2024 at NT$300 per tonne with exemptions for emissions below 25,000 tonnes, has unclear future rate trajectories and lacks mechanisms to recycle revenues, thereby limiting its effectiveness (Rogge & Reichardt, 2016). Moreover, rigid divides and poor communication among energy, environmental, industrial, and local government agencies further highlight failures in policy integration and coordination.

The transformation of the cement industry involves multiple stakeholders government agencies, producers, industry associations, research institutions, community representatives, and environmental organizations whose perceptions of transition objectives and cost–benefit trade-offs often diverge: firms prioritize profitability and competitiveness; government bodies must balance economic growth with emission reduction targets; communities focus on health and ecological impacts. Absent a dialogue and negotiation platform, decision-making barriers and conflicts can intensify. Literature suggests that establishing continuous multi-stakeholder engagement mechanisms and transparent information disclosure processes can effectively narrow perception gaps and enhance policy acceptance (Avelino & Rotmans, 2009).

As a tradable bulk commodity, cement faces intense international market competition. In a unilateral strict carbon-pricing environment, production costs may be passed on to importing countries, prompting relocation of production activity to regions with looser carbon policies a phenomenon known as carbon leakage. The EU's CBAM, implemented from 2026 onwards, will impose charges equivalent to the EU carbon price on imported cement, potentially increasing Taiwan's export costs by 5–15 percent and severely undermining international competitiveness (Bataille *et al.*, 2018). This risk compels both industry and government to consider trade policy linkages and to explore carbon-price mutual recognition or "green" trade agreements with major partners.

The pathway to energy transition requires not only capital and technology but also professional human resources and organizational capabilities. Although large firms have established low-carbon technology teams and collaborate with research institutions on R&D, small and medium-sized enterprises lack the resources and interdisciplinary talent to participate in or lead such projects. Furthermore, mechanisms for knowledge diffusion between academia and industry remain underdeveloped, with no effective platforms for sharing and replicating technical know-how across the value chain (Su *et al.*, 2013).

This chapter has analyzed the multiple institutional barriers confronting Taiwan's cement industry energy transition technological lock-in, high-cost constraints, policy uncertainty, stakeholder conflicts, international carbon policy pressures, and capacity gaps. These structural dilemmas are interwoven, generating systemic resistance that prevents landscape pressures and niche innovations from being rapidly translated into deep decarbonization outcomes. Subsequent chapters will build on this analysis to propose breakthrough pathways in multi-level co-governance and technology portfolios.

Multi-Level Perspective Analysis of Transition Drivers and Barriers

Landscape-Level Pressures and Opportunities

The landscape level encompasses long-term external drivers such as the scientific consensus on global climate change, international decarbonization agreements, and border carbon adjustment policies. This scientific consensus intensifies societal pressure on governments to integrate net-zero pathways into industrial development plans. The EU's Carbon Border Adjustment Mechanism (CBAM), which imposes carbon duties on high-carbon goods like cement, forces export-oriented producers to confront cost-pass-through challenges directly. Landscape pressure also prompts financial markets to incorporate green bonds and sustainability-linked loans into cement industry financing frameworks, thereby mobilizing capital for low-carbon solutions. Although landscape pressure is broadly increasing, it must be channeled through regime-level mechanisms to translate into industrial action and avoid becoming merely a policy burden (Geels & Schot, 2007; Geels, 2011).

Regime-Level Stability and Inertia

The regime level refers to the established system of government regulations, industry standards, technological paradigms, and market structures. In cement, the Portland cement process paradigm dominates; sunk costs, entrenched technical know-how, and supply-chain networks collectively generate strong inertia. When governments and industry associations set carbon fees, emission standards, or alternative-fuel regulations, they often opt for incremental adjustments to balance short-term economic interests, failing to provide sufficient incentives for high-cost, constraint-breaking projects. While such stability ensures operational continuity, it impedes rapid diffusion of disruptive innovations such as geopolymer binders or electrified firing (Smith & Raven, 2012; Seto *et al.*, 2016).

Niche-Level Innovation Dynamics and Challenges

The niche level provides protected spaces for emerging low-carbon technologies or business models to experiment. Several Taiwanese universities and research institutes have established pilot kilns for LC3 and geopolymer cements and are collaborating with industry partners on mix design trials; some firms are also testing the co-firing of waste tires and plastics as alternative fuels. However, limited technology readiness, high costs, and undeveloped market demand constrain niche diffusion. Without government demonstration subsidies, standardized certification, and public procurement pull, niche innovations struggle to scale into the regime (Markard *et al.*, 2012; Smith & Raven, 2012).

Multi-Level Interaction Mechanisms and Pathway Typology

The MLP emphasizes that landscape pressure must coincide with regime fissures and niche momentum to trigger systemic change. Transition pathways are typically categorized as transformation (incremental change), reconfiguration (selective recombination), substitution (radical replacement), or de-alignment and re-alignment (system collapse and re-emergence). Taiwan's cement industry currently follows a transformation pathway, focusing on energy-efficiency optimization and partial substitution. Moving toward reconfiguration would require strong regime-level incentives and maturing niche technologies; substitution demands that niche innovations achieve sufficient cost and performance parity. The relative strengths of landscape pressures versus regime resistance determine which pathway is viable (Geels & Schot, 2007; Geels, 2011).

Technological Innovation and Governance Pathways

To reduce combustion emissions, the use of refuse-derived fuel (RDF), biomass fuels, and industrial by-products must be expanded. It is recommended to establish cross-regional waste collection and pre-processing platforms with long-term calorific value contracts to secure stable fuel supply, and to implement joint testing mechanisms to ensure fuel quality consistency (Habert *et al.*, 2020). Simultaneously, alternative raw materials such as steel-making slag, coal-plant fly ash, and construction and demolition waste should be rigorously sorted and fed into clinker kilns to lower the clinker factor and reduce process emissions (Scrivener *et al.*, 2018).

At the equipment level, priority should be given to constructing demonstration plants for Limestone Calcined Clay Cement (LC3) and geopolymer cements, accompanied by long-term durability and environmental exposure testing to generate the data necessary for national standard revisions (Miller, Habert, Myers, & Harvey, 2021). Product Category Rules (PCRs) for LC3 formulations and process parameters should be developed, and Environmental Product Declarations (EPDs) issued by third-party certifiers to build market confidence and traceability in low-carbon binders (Bataille *et al.*, 2018).

To achieve deep decarbonization targets, it is advisable to establish a commercial-scale CCUS demonstration unit in an eastern core plant, utilizing either amine scrubbing or calcium-looping technologies, integrated with nearshore geological storage and carbon utilization pathways such as microalgae cultivation or construction-grade calcium carbonate production (Miller *et al.*, 2021). Concurrently, a CO_2 transport pipeline network and storage sites should be planned under a public-private partnership model to share initial investment risks, with pipeline usage fees offsetting carbon charges to reduce burdens on individual firms (Aghion *et al.*, 2016).

Alternatively, intelligent kiln control systems and predictive maintenance platforms should be deployed, leveraging big data and machine learning to optimize combustion parameters, raw-meal proportioning, and firing profiles thereby minimizing energy fluctuations and maximizing thermal efficiency (Huang *et al.*, 2016). An integrated plant-wide Energy Management System (EMS) can monitor energy use and emissions in real time across all production stages, with multi-plant networked coordination to smooth power demand peaks and enhance renewable energy integration (Ishak, 2014).

It is recommended that the government lead by example, mandating low-carbon cement and concrete procurement in major public projects, with phased minimum purchase ratios; requiring bidders to submit EPDs and carbon-footprint reports; and incorporating low-carbon certification as an evaluation criterion to generate quantifiable market pull (Rogge & Reichardt, 2016). Furthermore, low-carbon certificates or Contracts for Difference could be introduced to financially reward firms that exceed emission-reduction targets, effectively converting carbon savings into economic returns.

To ensure a just transition, a "Cement Industry Just Transition Committee" should be established, including representatives from government, industry, labor organizations, community and Indigenous groups, and environmental NGOs. This committee would define and oversee the allocation of a transition fund, prioritizing mine-site ecological restoration, community livelihood compensation, and worker retraining, with regular public reporting to strengthen social trust and legitimacy (Avelino & Rotmans, 2009).

Finally, a "Cement Industry Net-Zero Transition Task Force" should be formed under the Ministry of Economic Affairs, the Environmental Protection Administration, local governments, and industry associations to drive policy coherence. This task force would integrate energy, environmental, and industrial support policies; develop a phased roadmap with clear timelines and targets for each emission-reduction technology; and establish a cross-agency coordination mechanism to ensure policy consistency and timely adjustments creating a closed-loop governance model from landscape pressures through regime reform to niche innovation (Geels & Schot, 2007).

Policy Recommendations

Main Findings

This study combines the Multi-Level Perspective

(MLP) with carbon lock-in and policy mix theories to systematically analyze the drivers and barriers of Taiwan's cement industry energy transition. First, the industry's history and structure were reviewed to confirm that oligopolistic competition and sunk costs have engendered strong technological lock-in, inhibiting the diffusion of disruptive low-carbon technologies (Seto *et al.*, 2016). Second, quantification of energy and carbon characteristics revealed high energy intensity during clinker firing and low alternative fuel utilization, resulting in carbon intensities above international benchmarks (Miller *et al.*, 2021). Institutional analysis showed policy fragmentation and cost–benefit constraints that lead firms to favor incremental efficiency improvements over deep transformation (Rogge & Reichardt, 2016), while the MLP framework demonstrates that landscape pressures and niche innovations require regime-level fissures to serve as catalysts for systemic reconfiguration (Geels & Schot, 2007).

Theoretical Contributions

This research integrates carbon lock-in with the MLP framework to reveal how technological, economic, policy, and social locking mechanisms reinforce one another in carbon-intensive, capital-intensive industries, addressing gaps in the literature on deep decarbonization in heavy industries. By applying policy mix theory, we show that incremental carbon pricing and green procurement must be coordinated to achieve synergistic transition effects, thus enriching the "market pull" dimension of the MLP. By introducing the Just Transition perspective, we emphasize stakeholder power dynamics and benefit distribution, proposing a transition fund mechanism that adds an equity dimension to socio-technical transitions (Avelino & Rotmans, 2009).

Policy Implications and Specific Recommendations

(1) Dynamic Carbon Pricing with Revenue Reinvestment: From 2025, increase the carbon fee by USD 10 annually to reach USD 60 per tonne by 2030, and allocate 30 percent of revenues to a "Cement Low-Carbon Transition Fund" dedicated to supporting alternative fuels, low-carbon binder demonstrations, and just transition projects in mining regions (Rogge & Reichardt, 2016).

(2) Green Public Procurement Leadership: Mandate that national major public works use at least 30 percent low-carbon cement by 2027 and 50 percent by 2032, requiring Environmental Product Declarations (EPDs) for relevant construction materials to create early market demand (Bataille *et al.*, 2018).

(3) Standards and Certification Updates: Expedite the development and certification procedures for Limestone Calcined Clay Cement (LC3) and geopolymer cements under national standards, and incorporate durability assessment outcomes into building codes to reduce application barriers (Scrivener *et al.*, 2018).

(4) Regional CCUS Infrastructure: Government to plan and develop eastern storage sites and CO_2 transport pipelines under public–private partnerships, sharing investment risk, and align with offshore wind–powered green hydrogen projects to enhance demonstration efficacy (Miller *et al.*, 2021).

(5) Just Transition and Capacity Building: Prioritize transition fund allocations for mining-site ecological restoration, community compensation, worker retraining, and employment transition support; establish community participation platforms to ensure policy legitimacy and societal backing (Avelino & Rotmans, 2009).

Research Limitations and Future Directions

This study primarily employs qualitative content analysis and process tracing, which provide in-depth insights into institutional inertia and driving mechanisms but lack quantitative economic assessments of transition pathways. Additionally, focusing on a single case in Taiwan limits external generalizability, which future cross-country comparative research could address. Subsequent work could integrate input–output analysis and life-cycle assessment models, extending the framework to other high-carbon, capital-intensive sectors to evaluate policy mix effectiveness and practical feasibility.

Closing Remarks

The energy transition of Taiwan's cement industry represents a complex socio-technical system reconfiguration requiring aligned efforts in policy, technology, market, and social spheres. Only by overcoming technological lock-in, strengthening carbon pricing signals, creating robust market pull, and institutionalizing just transition mechanisms can the industry shift from "incremental transformation" toward "reconfiguration" or "technological substitution" for deep decarbonization. Policymakers and industry stakeholders must collaborate through a systemic lens to drive low-carbon transformation, ensuring both industrial competitiveness and climate objectives are met.

CONCLUSION

This study combines the Multi-Level Perspective (MLP) with carbon lock-in and policy mix theories to systematically analyze the drivers and barriers of Taiwan's cement industry energy transition. First, the industry's history and structure were reviewed to confirm that oligopolistic competition and sunk costs have engendered strong technological lock-in, inhibiting the diffusion of disruptive low-carbon technologies (Seto *et al.*, 2016). Second, quantification of energy and carbon characteristics revealed high energy intensity during clinker firing and low alternative fuel utilization, resulting in carbon intensities above international benchmarks (Miller *et al.*, 2021). Institutional analysis showed policy fragmentation and cost–benefit constraints that lead firms to favor incremental efficiency improvements over deep transformation (Rogge & Reichardt, 2016), while the MLP framework demonstrates that landscape pressures and niche innovations require regime-level fissures to serve as catalysts for systemic reconfiguration (Geels & Schot, 2007).

REFERENCES

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency and directed technical change: Evidence from the auto industry. *Journal of International Economics, 99*, 192–213. https://doi.org/10.1016/j.jinteco.2015.12.005

Avelino, F., & Rotmans, J. (2009). Power in transition: An interdisciplinary framework to study power in relation to structural change. *European Journal of Social Theory, 12*(4), 543–569. https://doi.org/10.1177/1368431009349830

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., … Zhou, P. (2018). A review of technology and policy deep decarbonization pathway options for the industrial sector. *Journal of Cleaner Production, 206,* 1187–1196. https://doi.org/10.1016/j.jclepro.2018.09.044

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Habert, G., Miller, S. A., John, V. M., Antoni, M., & Scrivener, K. L. (2020). Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nature Reviews Earth & Environment, 1*(11), 559–573. https://doi.org/10.1038/s43017-020-0093-3

Huang, Y.-H., Chang, Y.-L., & Fleiter, T. (2016). A critical analysis of energy efficiency improvement potentials in Taiwan's cement industry. *Energy Policy, 96,* 14–26. https://doi.org/10.1016/j.enpol.2016.05.025

Ishak, M. (2014). Low carbon measures for cement plant A review. *Journal of Cleaner Production, 103,* 260–275. https://doi.org/10.1016/j.jclepro.2014.11.003

Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy, 41*(6), 955–967. https://doi.org/10.1016/j.respol.2012.02.013

Miller, S. A., Habert, G., Myers, R. J., & Harvey, J. T. (2021). Achieving net-zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. *One Earth, 4*(10), 1398–1411. https://doi.org/10.1016/j.oneear.2021.09.011

Rogge, K. S., & Reichardt, K. (2016). Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Research Policy, 45*(8), 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004

Scrivener, K. L., John, V. M., & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry. *Cement and Concrete Research, 114*, 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources, 41,* 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Research Policy, 41*(6), 1025–1036. https://doi.org/10.1016/j.respol.2012.02.013

Su, T.-L., Chan, D. Y.-L., Hung, C.-Y., & Hong, G.-B. (2013). The status of energy conservation in Taiwan's cement industry. *Energy Policy, 60*, 481–486. https://doi.org/10.1016/j.enpol.2013.04.002