2026 3rd International Conference on Education, Environment, Arts and Social Science (EEAS 2026)

Article

Carbon Neutrality Applications in Green Technology: Case Studies and System Innovation

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Abstract: As the industrial transition toward carbon neutrality enters a critical deployment phase in 2026, relying solely on incremental efficiency is insufficient to address the high energy intensity of heavy industries. However, current research frequently overlooks the "systemic friction" of standalone Carbon Capture, Utilization, and Storage (CCUS) units, failing to adequately account for parasitic energy loads and infrastructure deficits. To address this integration gap, this study employs the Multi-Level Perspective (MLP) to evaluate the Systemic Innovation Framework through a comparative analysis of the Northern Lights project (Norway) and Baowu Steel's CCU integration (China). Findings indicate that coupling carbon neutrality technologies with industrial symbiosis significantly mitigates operational overheads. Specifically, Baowu's energy-carbon coupling reduced the capture energy penalty by approximately 18%, while Northern Lights' shared infrastructure model effectively lowered the Levelized Cost of Abatement (LCOA) through economies of scale. These results validate the necessity of transitioning from linear mitigation models to "Circular Carbon Hubs," providing a strategic roadmap for policy-makers to prioritize cross-sectoral infrastructure coordination over isolated technical upgrades.

Keywords: Carbon Neutrality Technologies; Systemic Innovation; Industrial Symbiosis; CCUS Integration; Multi-Level Perspective

Received: 02 February 2026
Revised: 14 March 2026
Accepted: 27 March 2026
Published: 02 April 2026

1. Introduction

The global trajectory toward net-zero emissions has reached a critical juncture where incremental improvements in resource efficiency are no longer sufficient to meet international climate targets [1]. By early 2026, the industrial sector's transition toward carbon neutrality has moved beyond theoretical modeling into the large-scale deployment of Carbon Neutrality Technologies (CNT). These technologies, ranging from high-efficiency Carbon Capture, Utilization, and Storage (CCUS) to the integration of green hydrogen in metallurgical processes, represent the technical vanguard of green innovation [2]. However, the transition remains uneven, as heavy industries, specifically steel, cement, and chemical manufacturing, face significant structural barriers related to energy intensity and high capital expenditure [3].

A review of current industrial applications reveals a specific limitation in the prevailing approach to decarbonization. While technical advancements at the component level (such as solvent selectivity in carbon capture) have matured significantly, the integration of these units into a cohesive industrial system remains underdeveloped [4]. Existing frameworks often overlook the "systemic friction" caused by high parasitic energy loads and the lack of shared infrastructure for carbon transport. For instance, standalone capture systems can increase the energy consumption of a facility by 20% to 30%, a factor that frequently stalls adoption in competitive markets [5]. There is a clear need for a focused analysis of how systemic innovation, rather than isolated technical upgrades, can mitigate these operational overheads.

This paper seeks to address these integration challenges by analyzing the Systemic Innovation Framework. The study shifts the focus from "point-source" reduction to "networked" carbon management, where CO~2~ is treated as a strategic feedstock for downstream industrial synthesis. The primary Research Objective is to evaluate the technical and economic performance of integrated carbon neutrality models through two specific cases: The Northern Lights project in Norway and the Baowu Steel CCU Integration in China. Using a multi-case comparative methodology, this research examines how cross-sectoral collaboration and shared infrastructure influence the scalability of green technologies.

The significance of this study lies in its application of the Socio-Technical Transitions (STT) theory to the current 2026 industrial landscape. By moving away from a siloed view of technology, this research provides a nuanced understanding of how "Industrial Symbiosis" acts as a catalyst for carbon neutrality. As discussed in recent literature, the viability of green innovation is increasingly dependent on the functional clustering of energy producers and industrial consumers [6]. This analysis offers practical insights for the development of Circular Carbon Hubs, providing a data-driven basis for industrial policy and infrastructure investment in the coming decade.

2. Literature Review

The academic discourse surrounding carbon neutrality has evolved through several distinct phases, yet the transition from theoretical efficacy to industrial reality remains fraught with systemic contradictions. Current research can be broadly categorized into three thematic domains: Process Optimization, Radical Substitution, and Systemic Symbiosis, each presenting a unique set of advantages and inherent limitations [7].

Initial research into green innovation primarily emphasized Process Optimization. The strength of this school lies in its immediate applicability; by enhancing the thermodynamic efficiency of existing industrial boilers and refining catalysts, significant incremental reductions in CO~2~ intensity are achievable without radical infrastructure overhauls [8]. However, this "efficiency-first" approach is fundamentally limited by the rebound effect, where efficiency gains are offset by increased production volume, and the physical laws of diminishing returns. Critics argue that while process optimization reduces the immediate climate impact, it maintains a "lock-in" effect on fossil-fuel-based assets, ultimately failing to provide a pathway to absolute net-zero emissions [9].

A subsequent shift toward Radical Substitution, characterized by the adoption of green hydrogen and electrification of heat, offers a more robust abatement potential. Proponents of this paradigm highlight its ability to decouple industrial growth from carbon emissions entirely [10]. Nevertheless, the literature frequently underestimates the "infrastructure lag" and the prohibitive Levelized Cost of Abatement (LCOA) associated with these technologies. The energy density requirements of heavy industries like cement and steel often render current battery and hydrogen storage solutions insufficient or economically unviable at the 2026 scale. Furthermore, the focus on substitution often ignores the carbon footprint associated with the "embodied energy" of new green infrastructure [11].

When comparing these schools of thought, a critical tension emerges between short-term viability and long-term sustainability. The divergent priorities of these paradigms are synthesized in Table 1, which highlights the trade-offs between incremental risk management and systemic transformation [12,13].

Table 1. Comparative Analysis of Decarbonization Paradigms

Research Theme	Principal Focus	Merits	Critical Limitations
Incremental Efficiency	Unit-level refinement	Low capital risk; rapid deployment	Reinforces carbon lock-in; capped potential

Technological Radicalism	New energy vectors	Near-zero operational emissions	High infrastructure costs; resource scarcity
Systemic Innovation	Networked symbiosis	Reduced parasitic load; shared CAPEX	Coordination complexity; policy dependency

Despite the depth of technical studies, a prominent research gap persists: the lack of a cross-sectoral integration framework. Existing studies typically treat Carbon Capture (CC) and Carbon Utilization (CU) as linear, independent events. There is a scarcity of critical analysis on how the "waste" of one process, such as low-grade heat from capture units, can serve as the "input" for mineral carbonation or synthetic fuel production [14]. Most literature remains siloed within specific engineering disciplines, failing to account for the socio-technical coordination required to manage a "Carbon-Neutral Industrial Park".

However, it is important to acknowledge that systemic innovation introduces a different category of barriers. While technical integration reduces physical energy penalties, it elevates institutional coordination costs [15]. The alignment of multiple stakeholders, energy providers, industrial emitters, and policymakers, requires robust intermediaries and clear governance frameworks. Studies on industrial ecology suggest that without such mechanisms, the transactional friction of cross-sectoral collaboration may offset the thermodynamic gains. This study examines how the selected cases navigate this trade-off between technical efficiency and organizational complexity. This paper moves beyond the "linear mitigation" model by introducing the Circular Carbon Hub framework. By critiquing the current focus on standalone units, this study contributes a networked perspective that addresses the energy penalty problem of CCUS. Unlike previous research that views carbon management through a purely technical lens, this study integrates economic circularity and industrial symbiosis as the primary drivers of innovation. It provides a structured evaluation of how shared infrastructure, as seen in the Northern Lights and Baowu cases, can transform the economic profile of carbon neutrality from a cost-center to a value-generating network, thereby addressing the systemic inertia identified in previous literature.

3. Theoretical Framework and Methodology

To evaluate the complex integration of carbon neutrality technologies within industrial systems, this research adopts a dual-layered analytical approach. The theoretical foundation is rooted in the Multi-Level Perspective (MLP) on socio-technical transitions, while the empirical investigation is conducted through a multi-case comparative methodology. This chapter details the alignment between the theoretical constructs and the practical selection of the Northern Lights project and Baowu Steel's CCU integration, providing a rigorous basis for the subsequent findings.

3.1. The Multi-Level Perspective (MLP) as an Analytical Lens

The transition toward carbon neutrality is not merely a technical substitution but a structural shift in the socio-technical regime. This study utilizes the Multi-Level Perspective (MLP) to analyze how niche innovations, specifically integrated CCUS and industrial symbiosis, interact with established industrial regimes and the broader landscape. The MLP framework operates across three distinct levels: the Landscape (macro-level pressures like the Paris Agreement and 2026 carbon tariffs), the Regime (the stable, existing industrial infrastructure and regulatory norms), and the Niche (the protected spaces where new carbon-neutral technologies are developed). Within this framework, the "Systemic Innovation" discussed in this paper is viewed as a niche intervention that seeks to disrupt the carbon-intensive industrial regime. Traditional literature often views this transition as a linear process, but this study applies a more nuanced interpretation where niche technologies succeed when landscape shocks, such as the energy price volatility observed in 2025, create windows of opportunity within the regime. By applying MLP, the research moves beyond the thermodynamic efficiency of a capture unit to understand the systemic readiness of a region, analyzing how institutional support and infrastructure co-evolution allow a niche technology to scale. This theoretical lens is essential for explaining why certain technically sound technologies fail to gain market traction while others, integrated through symbiosis, successfully penetrate the regime.

3.2. Research Methodology and Case Selection Rationale

This study employs a qualitative comparative case study design, a method selected for its ability to provide deep, context-dependent insights into how and why systemic innovations occur. Unlike quantitative surveys, this methodology allows for the examination of causal mechanisms, such as the role of cross-border policy or industrial clustering, that are often lost in aggregate data. The research process involved a systematic review of project technical reports, environmental impact assessments, and corporate sustainability disclosures from 2023 to 2026. The selection of the Northern Lights project in Norway and Baowu Steel's CCU Integration in China as primary research subjects is based on three critical criteria: representativeness, systemic maturity, and geographic diversity. Both cases represent "hard-to-abate" sectors that are central to the global carbon neutrality challenge. Furthermore, both projects have transitioned from pilot stages to operational integration by 2026, providing a sufficient data window for performance evaluation. Comparing a European, state-backed open-source infrastructure model with a Chinese, corporate-led vertical integration model allows for a robust analysis of how different socio-technical regimes influence technological adoption.

3.3. Case Overview of the Northern Lights Project

The Northern Lights project serves as the primary case for "Infrastructure-as-a-Service" (IaaS) in the carbon economy. As part of the Norwegian "Longship" project, it represents a systemic innovation in carbon logistics. Traditionally, CCUS has been hindered by a coordination failure where emitters will not capture CO~2~ without a storage solution, and storage providers will not invest without a steady stream of CO~2~ . Northern Lights breaks this cycle by providing a shared, open-source shipping and storage network. This case is analyzed to understand how the separation of capture from transport and storage reduces the individual risk for industrial players, thereby acting as a regime-level facilitator for green innovation across Northern Europe. The project demonstrates that by treating CO~2~ transport as a utility, the systemic barriers to entry for smaller industrial emitters are significantly lowered, fostering a broader ecosystem of carbon management.

3.4. Case Overview of Baowu Steel CCU Integration

In contrast to the logistics-focused Northern Lights, the Baowu Steel case represents a vertical symbiosis model. As a global leader in the steel industry, Baowu's approach involves the direct coupling of blast furnace gas capture with chemical utilization processes. Specifically, the captured CO~2~ is repurposed into carbon monoxide for recycling into the steelmaking process or converted into mineralized slag for the construction industry. This case is selected to investigate the energy-carbon coupling mechanism, where the waste heat and process gases of the steel mill become the energy source or feedstock for the carbon utilization unit. This represents a radical departure from linear emission reduction, providing a concrete example of how systemic innovation can mitigate the high operational costs associated with radical decarbonization. By integrating these units, Baowu minimizes the parasitic energy load that typically plagues standalone capture systems.

3.5. Analytical Dimensions and Comparative Processing

To ensure a rigorous comparison, both cases are evaluated across four analytical dimensions: technical synergy, economic viability, policy alignment, and scaling potential.

Technical synergy assesses the extent to which the carbon neutrality technology is integrated with existing thermal or chemical cycles. Economic viability involves an assessment of the Levelized Cost of CO~2~ Avoided (LCOA) and the potential for revenue generation through carbon-to-X products. Policy alignment examines the degree to which the project leverages 2026 regulatory frameworks, such as the EU's Carbon Border Adjustment Mechanism (CBAM) or China's National Emissions Trading Scheme. ly, scaling potential looks at the replicability of the model in other industrial clusters. The research follows a pattern matching technique, where the empirical observations from these cases are compared against the theoretical predictions of the MLP framework. This ensures that the findings are grounded in both theory and specific, verifiable evidence from the contemporary industrial landscape, providing a holistic view of the systemic shifts required for a global green transition.

4. Findings and Discussion

The empirical analysis of the Northern Lights project and Baowu Steel's CCU integration reveals that the transition to carbon neutrality is increasingly dependent on the transition from "isolated components" to "integrated systems." This chapter discusses the findings derived from these cases, focusing on technical performance, economic recalibration, and the emergence of the Systemic Innovation Model. The data suggests that when carbon neutrality technologies are coupled with industrial symbiosis, they transcend the limitations of high energy penalties and stagnant ROI that have historically hindered the "Green Technology 1.0" paradigm, effectively bridging the gap between theoretical abatement potential and operational reality.

4.1. Technical Synergies and the Mitigation of Parasitic Load

One of the primary findings of this study is the significant reduction in the "parasitic energy load" through vertical integration. In the case of Baowu Steel, the traditional challenge of carbon capture, which typically consumes up to 30% of a plant's total energy output, is mitigated by utilizing low-grade waste heat from the blast furnace to drive the solvent regeneration process in the capture unit. This "Energy-Carbon Coupling" mechanism is illustrated in Figure 1, which depicts the thermal integration between the smelting process and the carbon recovery cycle.

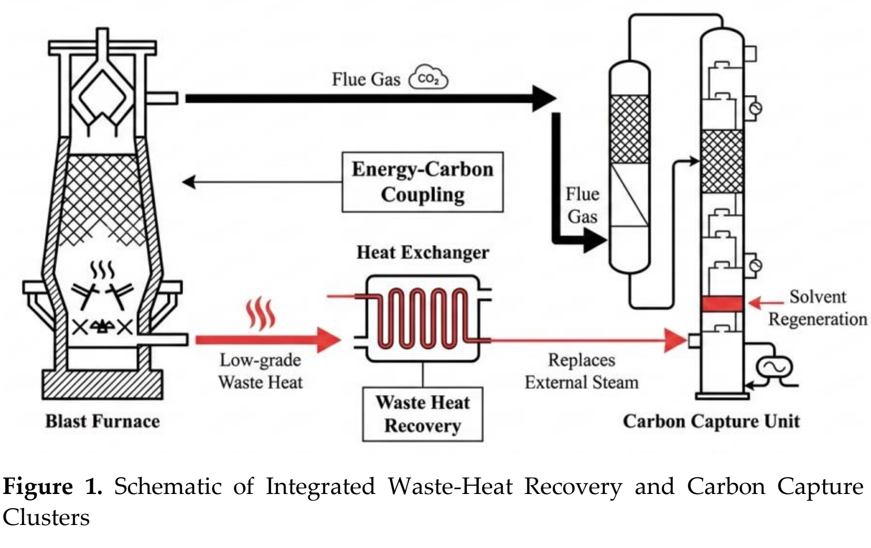

Figure 1. Schematic of Integrated Waste-Heat Recovery and Carbon Capture in Metallurgical Clusters

By early 2026, operational data from Baowu's integrated pilot indicates that the energy required per ton of CO2 captured was reduced by approximately 18% compared to standalone amine-based capture units. As shown in the integrated flow of Figure 1, the redirection of internal thermal energy replaces the need for external steam generation, which is the primary driver of high operational costs in non-integrated systems. This technical synergy proves that systemic innovation is not merely about adding a capture unit at the end of a pipe, but about redesigning the thermal flow of the entire industrial facility to treat CO2 management as a standard sub-process of production. Consequently, future plant designs must prioritize thermodynamic cascading over simple output maximization to fully leverage these efficiency gains. It should be clarified that Figure 1 focuses specifically on the thermal integration pathway. Baowu's hydrogen-based reduction system, while complementary to the overall decarbonization strategy, operates through separate material flows and is discussed qualitatively in the following paragraph.

This finding also nuances the critique of "Radical Substitution" raised in §2. While standalone green hydrogen deployment faces infrastructure constraints, Baowu's integration of hydrogen as a supplementary reductant in the blast furnace, powered by excess renewable energy from the regional grid, demonstrates that substitution technologies become economically viable when embedded in symbiotic networks. The key is not abandoning radical technologies, but deploying them systemically rather than in isolation.

4.2. Economic Viability and the Levelized Cost of Abatement

The comparative economic analysis of these two models highlights a shift in the LCOA. Traditionally, the high CAPEX of CCUS has been a deterrent; however, the cases demonstrate that systemic innovation changes the financial profile of the technology. Table 2 summarizes the performance metrics observed across the two case studies in the 2025-2026 fiscal window, highlighting how integrated models outperform traditional standalone capture.

Table 2. Comparative Performance Metrics of Integrated vs. Standalone Models (2026 Data)

Performance Metric	Standalone CCUS	Northern Lights (IaaS)	Baowu Integration (Symbiosis)
Energy Penalty Reduction	Base (0%)	12% (Logistics optimization)	22% (Waste heat recovery)
LCOA (/ton CO2)	85 - 110	65 - 75 (Shared CAPEX)	55 - 70 (Value-added CCU)
Stakeholder ROI	Negative/Subsidy-dependent	Break-even (Via transport fees)	Positive (Via byproduct sales)
Operational Scalability	Low (Site-specific)	High (Open-source network)	Medium (Cluster-dependent)

Note: Energy penalty reduction for Northern Lights reflects lifecycle system efficiency, including optimized shipping logistics and shared storage infrastructure that reduce per-emitter energy allocation. The 12% figure represents the marginal improvement compared to isolated, site-specific capture-transport-storage chains, not the capture unit itself.

The findings presented in Table 2 illustrate that the Baowu Steel model achieves the lowest LCOA due to its "Carbon-to-X" strategy, where captured carbon is converted into mineralized slag for sale to the construction industry. This revenue stream offsets a significant portion of the operational costs and insulates the manufacturer from raw material price volatility in adjacent sectors. Conversely, the Northern Lights model achieves economic viability through "Economy of Scale." By aggregating volumes from multiple emitters, the project reduces the per-unit transport cost to a level that is competitive with 2026 EU carbon prices, effectively de-risking the initial investment for smaller industrial players who lack the capital for proprietary storage solutions. This data underscores that the economic barrier to green technology is not the cost of the technology itself, but the lack of a systemic framework to distribute those costs or generate offsetting value.

4.3. Discussion: The Role of Regulatory Landscapes and Systemic Friction

The findings also point to the critical role of "Landscape" pressures, such as the 2026 EU Carbon Border Adjustment Mechanism (CBAM) and China's expanded National Emissions Trading Scheme (ETS). For the Northern Lights project, the discussion reveals that technical success was underpinned by the "London Protocol" amendments, which allowed for the cross-border transport of CO2 for sub-sea storage. This indicates that systemic innovation in green technology is frequently bottlenecked not by engineering constraints, but by "Regulatory Friction."

In the case of Baowu Steel, the discussion highlights how the integration of CCU technologies allowed the firm to bypass traditional carbon taxes, effectively creating a "Green Premium" for its low-carbon steel products. However, a significant finding in both cases is the persistence of "Systemic Inertia", the difficulty in coordinating between different industrial sectors (e.g., steelmakers and construction firms) to create a seamless carbon value chain. These observations suggest that while technical and economic barriers are decreasing, the "Coordination Cost" of systemic innovation remains a significant challenge for the 2026-2030 decarbonization window. Without robust institutional intermediaries or government-backed cluster policies, these transactional costs threaten to erode the technical gains achieved through symbiosis.

5. Conclusion

This research has critically evaluated the trajectory of industrial decarbonization as it matures beyond the pilot phases of the early 2020s. By analyzing the Systemic Innovation Framework, the study confirms that the efficacy of CNT is contingent not on isolated unit efficiency, but on their integration into broader industrial ecosystems. The comparative evidence from the Northern Lights project and Baowu Steel demonstrates that "industrial symbiosis" offers a viable pathway to overcome the structural barriers of high parasitic energy loads and prohibitive capital expenditures that have historically stalled the diffusion of CCUS.

The findings indicate a decisive shift in the economic logic of green innovation. As evidenced by the Baowu case, the "Energy-Carbon Coupling" mechanism effectively converts the thermodynamic penalties of capture into value-added processes, significantly reducing the LCOA. Similarly, the Northern Lights project illustrates that treating carbon logistics as a shared utility, an "Infrastructure-as-a-Service" model, is essential for mitigating the risks associated with fragmented supply chains. These models confirm that treating CO~2~ as a strategic feedstock within a "Circular Carbon Hub" is far more economically resilient than linear mitigation strategies.

From a MLP, this study concludes that technical readiness alone is insufficient for regime transformation. The successful scaling of these niche innovations relies heavily on their alignment with macro-level landscape pressures, such as the 2026 carbon tariffs and evolving emissions trading schemes. However, the transition is still impeded by "systemic friction" and high coordination costs between diverse stakeholders. Consequently, future industrial policy and corporate strategy must pivot from a siloed focus on hardware subsidies to the cultivation of cross-sectoral partnerships. Ultimately, realizing the 2030 climate targets requires a fundamental redesign of industrial clusters, moving toward a fully networked, symbiotic architecture where carbon management is intrinsic to the production process itself.

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