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GREEN INNOVATION IN HARD-TO-ABATE SECTORS: A CONCEPTUAL MODEL OF GREEN DYNAMIC CAPABILITIES

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Abstract: *Achieving net-zero emissions is a global priority, but hard-to-abate sectors, particularly heavy manufacturing industries, face extreme difficulties in their green transition. Unlike light-asset firms, these sectors suffer from severe physical and cognitive asset lock-ins. High sunk costs in old machinery and rigid management thinking prevent them from adopting green technologies. While existing research often focuses on external pressures like government regulations, this paper shifts the focus to the internal organizational level by using the Dynamic Capability View. To address this gap, this paper builds a conceptual model to explain how these firms can achieve green innovation through green dynamic capabilities. The framework divides these capabilities into three clear stages. First, green sensing allows firms to identify environmental trends and new technologies. Second, green seizing enables management to make concrete green investment decisions. Third, green reconfiguring helps firms physically transform their old production lines. From this logical structure, we develop several theoretical propositions. We argue that these three capabilities are the necessary internal tools to break asset lock-ins and turn external environmental pressures into real green innovation performance. Finally, this paper provides a clear theoretical map for future empirical research.*

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Keywords: *Green innovation; Hard-to-abate sectors; Green dynamic capabilities; Conceptual model*

Introduction

Achieving net-zero emissions is now a shared goal across global industries. However, the pace of this transition varies greatly between different sectors. Light-asset industries, such as information technology, services, or advanced manufacturing, carry fewer physical burdens. As a result, they can adopt green technologies and achieve low-carbon operations with relative ease. In contrast, the green transition is highly difficult for hard-to-abate sectors that rely on heavy machinery and energy-intensive processes, such as basic materials and heavy chemical manufacturing (Bataille et al., 2018; Davis et al., 2018). Recently enacted coercive policies, such as the Carbon Border Adjustment Mechanism (CBAM), further exacerbate the urgency for these heavy manufacturers to adapt (Zhao & Lee, 2025). These sectors are not only major sources of global greenhouse gas emissions but also the areas facing the greatest resistance to change.

When reviewing existing literature on green innovation, most studies tend to look for drivers from an external perspective. Many scholars have examined how government environmental regulations, carbon trading systems, and market demands for green products force firms to upgrade their environmental practices (Berrone et al., 2013). While this 'external pressure' perspective explains why firms need to change, it overlooks the actual execution process within the firm. When facing the exact same environmental regulations, some heavy-asset firms can only passively pay fines or halt production, whereas others successfully develop new low-carbon processes. This difference shows that focusing solely on external environmental pressure is insufficient. It is necessary to open the managerial black box to explore exactly what internal structures and capabilities these firms need to turn external compliance pressure into real green innovation performance (Wang et al., 2024).

To address this theoretical gap, this paper introduces the Dynamic Capability View (DCV). The traditional resource-based view suggests that firms gain a competitive advantage through valuable and rare static resources. However, given the rapid changes in environmental regulations and green technologies today, the massive assets that heavy industries accumulated in the past are no longer an advantage; instead, they have become a burden that hinders innovation. The Dynamic Capability View (Teece et al., 1997) argues that firms must have the ability to constantly update, integrate, and reconfigure their internal resources to adapt to turbulent external environments. In the context of the green transition, this ability is specified as 'green dynamic capabilities' (Chen & Chang, 2013; Garcia et al., 2025).

Therefore, this paper aims to build a conceptual model to explain the role of green dynamic capabilities in the green innovation of hard-to-abate sectors. The main argument is that, given the unique asset lock-in dilemmas of heavy industries, firms cannot rely solely on external policy pressure. Instead, they must develop internal dynamic capabilities across three stages: green sensing, green seizing, and green reconfiguring. This study provides a micro-behavioural perspective on the green transition in heavy-asset sectors and offers a clear theoretical outline for future empirical research.

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Background and the Problem of Asset Lock-ins

Hard-to-abate sectors struggle not necessarily because their management lacks environmental awareness, but because these firms are trapped in deep 'asset lock-ins'. Asset lock-in means that a firm loses the flexibility to change direction when facing new market demands, largely due to its past investment decisions, technological paths, and organisational habits (Unruh, 2000). For heavy industries, this lock-in effect mainly operates on two levels: physical and cognitive (Seto et al., 2016). Together, they form a massive barrier to green innovation.

Physical Lock-ins

Physical lock-ins stem from the highly rigid production infrastructure and the extremely high sunk costs in heavy-asset sectors. Light-asset firms can quickly update products by upgrading software or changing suppliers. In contrast, the core productivity of hard-to-abate sectors relies on large and expensive physical equipment. For instance, the initial investment for large industrial kilns, high-temperature calcination equipment, or complex fluid transport systems is immense, and these machines are designed to last for thirty to fifty years.

This heavy investment leads to severe technological path dependence. Once a firm invests heavily in an energy-intensive production line based on traditional fossil fuels, it has almost no economic incentive to retire this equipment before the end of its financial lifespan (Erickson et al., 2015). Recent studies confirm that this financial sunk cost paradox is the primary reason heavy manufacturers instinctively resist green overhauls (Smith & Jones, 2024). Forcing these firms to adopt entirely new low-carbon technologies in the short term often means they must completely dismantle their existing core production lines. This would not only turn massive early investments into instant sunk costs but also risk breaking the firm's cash flow.

Consequently, physical lock-ins cause these firms to instinctively delay technological upgrades when facing environmental regulations. They prefer to use minor 'end-of-pipe' treatments rather than make fundamental green process innovations at the source.

Cognitive Lock-ins

Beyond visible machinery, hard-to-abate firms also face invisible barriers in management thinking, known as cognitive lock-ins. Over the past decades of industrial development, the core competitive logic of heavy industries has been based on economies of scale and cost minimisation. Management performance metrics, organisational structures, and daily standard operating procedures (SOPs) are all designed to ensure the continuous operation of production lines and to maximise output.

This long-term focus on efficiency has created highly conservative cognitive inertia within the firm, which can even turn into 'core rigidities' that hinder innovation (Leonard-Barton, 1992; Tripsas & Gavetti, 2000). When facing highly uncertain frontier green technologies, management often develops cognitive biases. They habitually view green investments purely as compliance costs and financial burdens, rather than as strategic investments that could bring long-term competitive advantages (Hahn et al., 2014). Furthermore, because low-carbon technologies are usually in their early stages of development, their payback periods are long. Under the strict assessment of traditional return on investment (ROI) metrics, cognitively locked-in managers often refuse to adopt these technologies, arguing that the timing is not right. This rigid thinking directly blocks the firm from acquiring external green knowledge.

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In summary, the combination of sunk costs from physical assets and the historical inertia of management cognition makes it extremely difficult for hard-to-abate sectors to meet net-zero targets. To break this deadlock, firms cannot achieve the transition using only conventional management methods. Instead, they must build and rely on a higher level of organisational ability: the green dynamic capabilities that this paper will explore next.

Literature Review on Green Innovation in Hard-to-Abate Sectors

External Regulatory Pressures as the Primary Driver

Research on green innovation in heavy industries historically focuses on macro-level environmental regulations. Scholars often use institutional theory to explain how firms respond to external rules. The traditional economic view argued that strict environmental regulations increase production costs and reduce industrial competitiveness. However, Porter and van der Linde (1995) fundamentally challenged this view. They proposed that properly designed environmental standards can trigger innovation that offsets compliance costs. Following this logic, subsequent studies explored how specific policy tools drive heavy industries to innovate. Ambec et al. (2013) reviewed the extensive literature and confirmed that regulatory pressure often acts as the primary trigger for green technology adoption in highly polluting sectors. Berrone et al. (2013) also demonstrated that institutional pressures force firms to invent green technologies primarily to gain social legitimacy. These studies establish that external policy is a necessary condition for starting the green transition.

Market and Stakeholder Demands

Beyond government regulations, a second stream of literature examines the role of market and stakeholder pressures. As global supply chains become more transparent, heavy manufacturers face increasing demands from downstream customers and green investors. Sarkis et al. (2011) conducted a comprehensive review of green supply chain management. They highlighted that heavy industries are no longer isolated entities. These firms must adopt green practices to maintain their positions in global production networks. Similarly, Bocken et al. (2014) pointed out that sustainable business models require heavy industries to move beyond basic pollution control and integrate environmental value into their core operations. Dangelico and Pujari (2010) showed that market demand for low-carbon products pushes traditional manufacturers to rethink their material choices. This body of literature proves that market pull is just as important as regulatory push.

The Theoretical Gap: Internal Organisational Mechanisms

While the external push and pull perspectives provide valuable macro-level insights, they share a common limitation. They often treat the heavy industrial firm as a black box. These macro-level studies assume that heavy-asset firms will automatically generate green innovation once external pressures reach a certain threshold. Delmas and Toffel (2008) strongly criticised this assumption. They argued that researchers must open the organisational black box to understand why different firms adopt completely different environmental strategies under identical external pressures. In hard-to-abate sectors, the physical and cognitive asset lock-ins create massive internal resistance. External pressure alone cannot magically dismantle an obsolete production line or change a conservative management mindset. The existing literature largely lacks a micro-behavioural framework to explain how heavy industrial firms internally digest

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external pressure, reorganise their rigid assets, and execute the transition. This specific research gap highlights the urgent need to introduce a capability-based perspective.

Theoretical Foundation and the Evolution of Green Dynamic Capabilities

The Shift from Static Resources to Dynamic Capabilities

In traditional strategic management, the Resource-Based View assumes that firms gain a competitive advantage by holding valuable, rare, and inimitable resources. However, this static view fails to explain competitive survival in highly volatile environmental landscapes. For heavy manufacturing industries, owning massive physical assets is no longer a unique advantage. In fact, under strict environmental regulations and the pressure of a low-carbon economy, these traditional high-carbon assets easily become liabilities. The Dynamic Capability View represents a necessary evolution from this traditional perspective. It argues that in times of rapid technological change and shifting regulatory mandates, merely owning assets is insufficient. Firms must possess the capacity to integrate, build, and reconfigure their internal and external competencies. This specific capability prevents firms from falling into competence traps, where their past successes in high-volume production stop them from adapting to new ecological demands.

The Theoretical Roots of Green Dynamic Capabilities

The concept of green dynamic capability sits at the intersection of the Dynamic Capability View and the Natural Resource-Based View. While conventional management theories primarily focus on economic efficiency (Abrudan et al,2024; Aftab et al,2023), the Natural Resource-Based View argues that firms must integrate environmental constraints into their core strategic logic to achieve long-term sustainability. In this context, green dynamic capability serves as the active agency for the firm. The Natural Resource-Based View provides the strategic motivation, explaining exactly why firms must value ecological capital. At the same time, the Dynamic Capability View provides the operational mechanism, explaining how firms orchestrate their assets to navigate the green transition. Therefore, green dynamic capability is an environmentally embedded extension of general management capabilities. It reflects a firm's ability to respond proactively to ecological pressures rather than engaging in reactive compliance behaviours, such as short-term pollution control.

Green Sensing as the Cognitive Starting Point

Green sensing forms the first pillar of this dynamic capability. It acts as the sophisticated environmental scanning apparatus of the firm. Through sensing capabilities, an enterprise detects tightening ecological constraints, such as shifting carbon emission quotas, well before actual non-compliance risks materialise. In heavy industries, firms typically focus entirely on internal production efficiency. Green sensing changes this inward focus. It allows the firm to maintain the cognitive awareness needed to detect emerging green technology standards and identify new low-carbon market niches. This capability ensures that the firm moves away from a passive waiting mode and actively shapes its understanding of future environmental demands.

Green Seizing through Strategic Commitment

Once a firm senses a green opportunity, it must seize it through concrete strategic investment and resource commitment. This dimension focuses on structural flexibility and financial mobilisation. In sectors where equipment upgrades require massive capital expenditure, the

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ability to re-allocate human and financial capital is critical. Through seizing capabilities, the firm mobilises administrative resources and makes firm commitments to invest in green technologies rather than maintaining obsolete operational routines. This requires the management team to actively direct funds toward exploratory green projects without jeopardising the stability of existing daily operations. Seizing is the critical step that turns an abstract environmental concept into an approved and funded corporate project.

Green Reconfiguring for Physical Asset Orchestration

The final and most demanding phase of green dynamic capability is reconfiguring. This involves the physical alteration of the core manufacturing infrastructure. Heavy industries suffer from severe path dependency due to the immense costs of their machinery. Through reconfiguring capabilities, the enterprise engages in physical asset orchestration. It changes traditional production lines to incorporate advanced systems, such as alternative fuel injection or carbon capture and storage technologies. This action goes beyond simple administrative changes and touches the very physical foundation of the firm's operations. By physically transforming the heavy asset base, the firm ensures that its green transition is a substantive operational reality rather than a mere rhetorical exercise.

Table 1: Conceptual Delineation and Operational Examples of Green Dynamic Capabilities

Dimension	Theoretical Definition	Key Managerial Focus in Hard-to-Abate Sectors	Concrete Operational Examples
Green Sensing	The capability to actively scan, identify, and interpret environmental regulatory shifts and emerging low-carbon technologies in the external market.	Overcoming selective blindness and conservative routines; breaking the cognitive lock-ins of management teams regarding environmental trends.	Monitoring changes in carbon emission quotas; tracking the technical maturity of carbon capture blueprints.
Green Seizing	The capability to mobilise internal administrative and financial resources to make firm strategic commitments and investments in green technologies.	Breaking the sunk cost fallacy; adjusting rigid return-on-investment metrics to approve high-risk, long-term environmental budgets.	Directing capital expenditures toward low-carbon research; approving budgets for alternative material testing.
Green Reconfiguring	The capability to physically alter, orchestrate, and transform core manufacturing infrastructure, assets, and operational routines to implement green practices.	Overcoming heavy physical asset lock-ins and high asset specificity; executing the structural transformation of traditional production lines.	Retrofitting traditional rotary kilns for alternative fuel injection; installing carbon capture systems; dismantling machinery.

Source: Authors' compilation

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Conceptual Model and Theoretical Logic

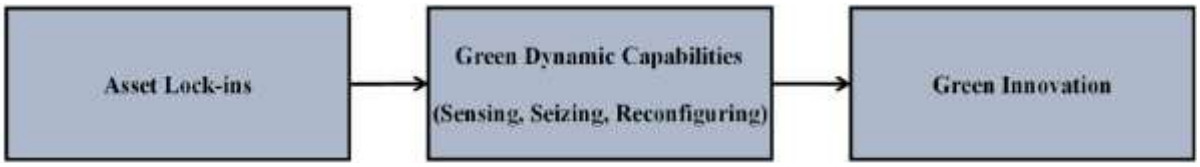

Figure 1: The Conceptual Framework of Green Dynamic Capabilities in Breaking Asset Lock-ins
Source: Authors' compilation

Based on the previous analysis of the asset lock-in dilemma and the breakdown of green dynamic capabilities, this paper builds a conceptual model to explain the green innovation mechanism in hard-to-abate sectors. This model shows a clear logical chain. The physical and cognitive lock-ins specific to heavy industries form the initial barrier preventing innovation.

The Suppressive Effect of Asset Lock-ins on Sensing and Seizing Capabilities

In heavy industries like cement manufacturing, the "sunk cost" problem creates a massive barrier. Companies spend millions of dollars on heavy machines, such as large rotary kilns. These machines are designed to run continuously for 30 to 40 years. Because the company has not made its money back yet, the top managers develop a narrow focus. They only want to see information that helps the current machines run faster or cheaper. If engineers present a new idea about low-carbon technology, managers often ignore it. They might say the new green fuel is too expensive or too risky for the daily work. In this situation, the firm naturally rejects outside knowledge. They do not want to hear about upcoming carbon taxes or strict environmental rules. Therefore, having too many expensive, old assets stops the firm from sensing green trends. It acts like a blindfold. This severe lock-in effect makes it incredibly hard for the firm to take the next step and seize any green opportunities.

Green Seizing as a Critical Hub to Overcome Cognitive Rigidities

To overcome this blindfold, the firm must take real action from the top down. Even if a heavy industrial firm has a good team that collects environmental information, it might still fail to change. This usually happens because the green information stays at the bottom level of the company. For example, technical staff might discover a great low-carbon production method. However, they send the report to the top executives, and nothing happens. Why? Because the top executives are judged by short-term profits and high production volumes. This is where "green seizing" becomes the most critical step. Green seizing means the top managers actually listen to the information and decide to take a financial risk. They must be willing to change their traditional budget rules. They need to approve the money for green projects, even if those projects do not make a quick profit. Without this seizing capability, the environmental reports are just useless paper. The firm must move the information from a simple idea into an approved and funded corporate project.

Green Reconfiguring as the Boundary of Substantive Green Innovation

The final and most important goal of this model is to achieve real, physical green innovation. When governments create strict environmental rules, many heavy-asset firms try to find an easy way out. They might spend money on beautiful sustainability reports, or they might buy carbon credits to look good. However, they refuse to change the way their factories actually

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work. In academic research, this fake action is called "greenwashing." This paper strongly argues that "green reconfiguring" is the only true test of green innovation. To stop greenwashing, a firm must do the hard work of changing its physical assets. The early steps of collecting information and approving budgets mean nothing if the machines stay the same. Real innovation happens when a cement plant stops its production line to install a carbon capture system. It happens when they physically take apart old pipes and replace them with alternative fuel systems. This physical change is very painful and expensive, but it is the only way to create real ecological value and finish the green transition.

Proposed Methodological Approach and Operationalisation

While this paper primarily serves to construct a conceptual framework, its academic utility relies on its empirical testability. To provide a robust methodological blueprint for future researchers, we propose the following operationalisation strategy. Future empirical studies should quantitatively measure "Green Dynamic Capabilities" by adapting recently validated Likert-scale instruments specific to environmental management (Li et al., 2025). The population should consist of traditional hard-to-abate sectors (cement and steel). Given the difficulty of accessing top executives in these traditional sectors, researchers should deploy targeted purposive and snowball sampling strategies. Furthermore, to effectively measure the transition from 'Sensing' to 'Reconfiguring', researchers should employ Structural Equation Modelling (SEM) to test the causal pathways. Finally, to mitigate Common Method Bias (CMB), future research designs must employ psychological separation in survey design and triangulate subjective survey responses with objective secondary data, such as verified corporate carbon emission reductions (Podsakoff et al., 2003).

Conclusion and Future Research

This paper explores the core barriers and transition paths for hard-to-abate sectors in achieving net-zero emissions. Past research often placed too much emphasis on government regulations and external market pressures. However, this paper argues that external pressure alone cannot achieve a real green transition for heavy-asset firms facing severe physical sunk costs and rigid executive thinking. Firms must look inward and build green dynamic capabilities to break both physical and cognitive asset lock-ins. This capability is not an abstract concept. It is a system made up of three progressive action stages: green sensing, green seizing, and green reconfiguring. Only by completing all three stages can a firm avoid the greenwashing trap and turn external environmental pressure into substantial green innovation performance.

Based on this theoretical logic, this paper offers practical strategic advice for heavy industry managers. First, the executive team must watch out for the sunk cost fallacy and abandon the traditional output-first mindset. Firms should not view environmental protection purely as a compliance burden. Instead, they should actively build cross-departmental information collection networks to break organisational blind spots by developing green sensing capabilities first. Second, a green transition does not mean forcing firms to blindly and immediately destroy all old production lines. Firms should conduct scientific budget planning during the seizing stage. While ensuring stable cash flow from their core business, they should gradually and firmly advance the substantial reconfiguring of their energy-intensive machinery.

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Future Empirical Research

To turn this conceptual model into a practical tool, future researchers should focus on four specific areas.

First, researchers need to develop a measurement scale for "green dynamic capabilities" in heavy industries. Currently, there is no standard survey to measure this. Future studies should create a list of clear questions that measure sensing, seizing, and reconfiguring. They should interview factory managers and engineers to make sure the survey questions match the reality of heavy manufacturing.

Second, future studies should test this model using large-sample surveys. Researchers can collect data from hundreds of companies in the cement, steel, and chemical sectors. By using statistical tools like Structural Equation Modelling (SEM), they can prove if these three capabilities actually lead to better green innovation. Comparing different heavy industries will also show if the "lock-in" effect is stronger in steel plants than in cement plants.

Third, researchers should introduce moderating variables into the model. Other factors can make the green transition easier or harder. For example, does strong government financial support (subsidies) make "green seizing" easier for top managers? Does a CEO with strong personal environmental beliefs break the "cognitive lock-in" faster? Adding these variables will make the conceptual model much richer and more realistic.

Finally, researchers should conduct long-term case studies. A survey only shows a snapshot of a company. However, physically changing a heavy factory takes many years. Researchers should follow one or two traditional cement companies over three to five years. They can record exactly how the management team fights over green budgets and how the engineers physically take apart the old machines. These detailed stories will provide deep evidence that numbers alone cannot show.

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