

An Analysis of the Impact of Environmental Regulation on Green Technology Innovation in the Oil Industry: Theoretical Mechanisms and Policy Recommendations

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Abstract: Within the context of global carbon neutrality, the oil industry, as a traditional high-carbon sector, plays an undeniable role in the low-carbon transition of the energy system. However, its green technology innovation faces the dual challenges of environmental regulation-driven and internal industry constraints. Based on the Porter hypothesis, this paper reveals the dual mechanism of environmental regulation on green technology innovation in the oil industry, proposing that environmental regulation promotes green innovation through the paths of "cost pressure-market incentives-legitimacy drive." However, it may inhibit long-term R&D investment due to "short-term compliance costs crowding out R&D resources," "technology path lock-in," and "improper design of regulatory tools." Subsequently, in response to the special innovation constraint mechanisms of the oil industry in the three dimensions of technology, organization, and geopolitics, a three-dimensional system of "precise regulation-strategic transformation-international collaboration" is proposed to provide theoretical support for policy formulation and enterprise practice.

Keywords: Environmental regulation; Green technology innovation; Oil industry; Porter hypothesis; Innovation compensation effect.

1. Introduction

Amidst the global imperative for carbon neutrality, the oil industry is undergoing significant strategic realignment. As a core pillar of the traditional high carbon economy, the sector's 2024 CO₂ emissions are projected to constitute 32% of global fossil fuel CO₂ emissions, equating to 11.968 billion tons [1], thereby representing a critical impediment to the low-carbon transition of the energy system. On one hand, the international community has continuously strengthened climate governance through institutional frameworks such as the Paris Agreement [2], and policy instruments like the European Union's Carbon Border Adjustment Mechanism (CBAM) [3] have directly transmitted environmental regulatory pressures across the oil supply chain. On the other hand, Global energy investment is set to exceed USD 3 trillion for the first time in 2024, with USD 2 trillion going to clean energy technologies and infrastructure [4], accelerating the transformation of the energy structure and imposing unprecedented transition pressures on the global oil industry. Against this backdrop, the question of how environmental regulations can drive green technological innovation within the oil sector emerges as a core issue in balancing energy security with climate responsibility.

This paper aims to extend the existing research on the green technology innovation mechanism in the oil industry under environmental regulation. It will conduct an in-depth analysis based on the inherent technical and economic characteristics of the oil industry, and then propose policy recommendations. Theoretically, this study employs the Porter hypothesis to clarify the dynamic mechanism of environmental regulation's impact on green technology innovation in the oil industry, revealing the double-edged sword effect of environmental regulation in the oil industry. Practically, through the analysis of global typical cases, this paper proposes precise regulatory paths adapted to the characteristics of the oil industry and puts

forward policy recommendations, providing a theoretical anchor for the transformation path of the oil industry under the "dual carbon" target.

2. Theoretical Influence Mechanism of Environmental Regulation on Green Technological Innovation in the oil Industry

2.1. Positive Driving Mechanisms

2.1.1. Cost-Pressure effect

Environmental regulations, through instruments such as carbon taxes and emission standards, directly increase the cost of fossil fuel development, thereby compelling firms to pursue technological breakthroughs to mitigate compliance pressures. For instance, the escalating carbon prices in the European Union have incentivized companies like Equinor to invest in projects like "Northern Lights" CCUS, aiming to reduce the lifecycle costs of carbon capture and storage. As carbon costs are progressively transformed into technological assets, this will drive a restructuring of industry competitiveness, thereby validating the innovation compensation effect posited by the Porter hypothesis.

2.1.2. Market Expectation Guidance

Long-term stable policy signals can reshape market expectations and reduce uncertainty in technology investment. Specifically, the government's continuous release of clear policy directions can make enterprises more certain about their future development direction, making them more willing to invest funds in the research and development of new technologies [6].

2.1.3. Legitimacy Acquisition

Environmental regulation triggers the transmission of multiple pressures by reconstructing the boundaries of corporate legitimacy [7]. The government adjusts the

environmental protection standards that enterprises must comply with by formulating rules and constraints. This adjustment makes enterprises face dual supervision pressure from the government and the public, promoting enterprises to improve their environmental protection behavior. In this process, the original legitimate business standards of enterprises are redefined. For example, the originally acceptable pollution emission level may now become illegal due to new regulations. This change forces enterprises to take new environmental protection measures to meet the requirements. At the same time, the government transmits pressure directly to enterprise managers through interviews, penalties, and other means. Ultimately, these multiple pressures form a continuous driving force, prompting enterprises to continuously improve their environmental performance.

2.2. Reverse Inhibition Risks

2.2.1. Short-Term Compliance Costs Crowding Out R&D Resources

In the short term, the capital intensity of heavy-asset industries necessitates substantial investments in environmental protection equipment, thereby crowding out R&D budgets, which highlights the "resource crowding-out effect." Under policy pressure, firms tend to prioritize compliance investments, thereby compressing long-cycle technology R&D budgets, thus forming an "emission reduction crowding out innovation" vicious cycle.

2.2.2. Technological Path Dependence and Lock-in Effects

In the long term, technological path dependence and infrastructure lock-in effects are significant [8]. Existing refining and chemical installations exhibit poor compatibility with green hydrogen feedstocks, and the pressure ratings of oil pipelines are inadequate for hydrogen transport requirements. The sunk costs of full-process retrofits are exceedingly high, incentivizing firms to opt for marginal improvements rather than disruptive innovation.

2.2.3. Distortionary Effects of Inappropriate Regulatory Tool Design

At the policy level, the application of "one-size-fits-all" management approaches exacerbates the problem. Uniform carbon emission reduction targets are unreasonable; for instance, the emission reduction costs of high-water-content oil fields and heavy oil fields differ by more than a factor of three. When carbon emission reduction targets are identical, this leads firms to shift towards "data-driven emission reduction" rather than substantive technological investment, which reduces data reliability while simultaneously restricting firms' innovation space.

3. Special Constraints on Green Technology Innovation in the Oil Industry

Green technology innovation in the oil industry is not only driven by external environmental regulations but is also profoundly constrained by its inherent technical and economic characteristics. This section reveals the innovation constraint mechanisms that distinguish the oil industry from other energy sectors, focusing on three dimensions: technology, organization, and geography.

3.1. Technological Dimension: Long Cycles and Asset Specificity Lock-in

The oil industry is characterized by long technology development cycles, creating a sharp contradiction with the urgency of policy goals, which places firms in a dilemma of "technology not yet mature, policy already in place." At the same time, its asset-intensive nature leads to high sunk costs in the retrofitting of existing facilities. Traditional refining units, oil pipelines, and other infrastructure are often incompatible with new technological standards such as green hydrogen production and carbon dioxide transportation, and the initial investment for the entire process transformation typically requires a large amount of capital. Traditional refining capacity still faces severe pressure for energy-saving retrofits.

3.2. Organizational Dimension: Supply Chain Coordination Challenges

The oil industry follows a vertically integrated model of "exploration-extraction-transportation-refining-sales" and green technology innovation faces challenges in adapting across the entire chain. For example, when shale oil companies adopt enhanced oil recovery (EOR) technology using carbon dioxide, they need to solve not only the problem of carbon source capture but also to build supporting cross-regional transportation pipelines and storage facilities; delays in any of these links will lead to the failure of technology application. Horizontally, cross-industry technology integration faces the reality of fragmented standards. With the rapid development of the hydrogen energy industry, the technical requirements for hydrogen pipelines have significantly increased, while existing oil and gas pipelines have obvious compatibility defects in terms of design pressure and material performance [9]. The intertwining of vertical dependence and horizontal conflict makes the oil industry's technological innovation present complex systemic risks.

3.3. Geopolitical Dimension: The Politicization of Technology

As a strategic resource, technological innovation in the oil sector is often constrained by the principle of national energy autonomy. U.S. exports of finished oil products increased steadily since the onset of the shale oil revolution in 2005, and in 2008 the U.S. became a net exporter of refined products [10]. While technological breakthroughs have reduced reliance on oil and gas imports, the surge in production has led to a decline in global oil prices, thereby stimulating fossil fuel consumption, creating a "rebound effect" paradox. Furthermore, the competition for green technology advantages has evolved into a tool for great power competition. The EU's politicization measures, such as carbon tariffs and green certification systems, further fragment the global technological cooperation ecosystem by reinforcing its rule-making dominance.

4. Policy Recommendations

To facilitate green technology innovation within the oil industry, a paradigm shift is required, moving beyond sole reliance on environmental regulations. A collaborative framework involving governmental bodies, private enterprises, and international entities is essential. This approach addresses both technological and cost barriers while

simultaneously fostering intrinsic innovation incentives.

At the governmental level, the establishment of a more nuanced, long-term, and unified regulatory framework and policy regime is imperative. Given the oil sector's high carbon emissions and the slow pace of technological advancements, a uniform policy approach is inadequate; differentiated governance is necessary. Initially, carbon quotas can be allocated based on the carbon emission intensity of oil fields, rewarding low-carbon operations with innovation incentives while mandating technological upgrades for high-carbon facilities. Furthermore, allowing firms to offset a portion of their green technology R&D expenditures against their carbon quota deficits can establish a virtuous cycle between pollution reduction and technological innovation. To mitigate the risks associated with the lengthy R&D cycles, the establishment of a national oil industry low-carbon transition fund is recommended to support long-term technology development. This fund should be capitalized through carbon market auction revenues, special oil revenues, and social investments, with a priority on technologies with a Technology Readiness Level (TRL) of 6 or higher. Key areas of focus should include electrocatalytic refining, geothermal enhanced oil recovery, and infrastructure development such as carbon dioxide transport pipelines. Additionally, a risk-sharing mechanism involving government, corporations, and insurance providers should be implemented to provide graduated compensation for unsuccessful technology projects, thereby alleviating corporate innovation concerns. Moreover, the formulation of comprehensive carbon management standards covering the entire lifecycle—from exploration to refining, storage, and transportation—is crucial. This should include mandatory public disclosure of emission data across all operational stages and the establishment of cross-industry collaboration platforms to address the standardization of technologies such as hydrogen transport and carbon material applications.

A comprehensive restructuring is essential at the corporate level. In the short term, technological advancements should prioritize the enhancement of existing technologies, leveraging digital management and energy-efficient retrofits to curtail emissions. Long-term strategies should focus on the development of alternative fuels, such as bio-aviation fuels and green ammonia. Management practices can draw from the experiences of international oil companies undergoing transitions, segregating conventional and renewable energy operations to grant the latter independent decision-making and budgetary authority. Furthermore, the integration of a "virtual carbon cost" into project approvals, such as a \$100 per ton CO₂ assessment, will incentivize departments to adopt low-carbon solutions. On the financial front, the securitization of assets like carbon capture and storage (CCS) projects and renewable energy power plants into green bonds can attract environmentally conscious investors. Simultaneously, divesting high-emission assets and reinvesting the proceeds into low-carbon technology research will establish a virtuous cycle of capital allocation.

At the international level, establishing collaborative networks is crucial. In the realm of technology cooperation, the "Belt and Road" initiative can serve as a platform for a global green technology hub, utilizing mechanisms like patent royalties and emission reduction sharing to disseminate critical carbon capture technologies, including CCS, to resource-rich nations. Moreover, the formation of an international oil and gas zero-carbon alliance can facilitate

joint research on pivotal technologies, such as deep-sea carbon sequestration. Standardization efforts should focus on promoting mutual recognition of carbon emission accounting standards between China and the European Union, thereby reducing compliance costs for multinational oil companies. Simultaneously, exploring linkages between Chinese and Middle Eastern carbon markets can pave the way for the recognition of cross-border green certificates. Financial cooperation can be advanced through the establishment of an OPEC+ transition fund, providing carbon tax compensation to affected oil-producing nations like Nigeria and allowing heavily indebted countries to offset their debt through environmental investments. This approach enables debt reduction to be coupled with environmental action, addressing both financial and ecological challenges.

These measures are anticipated to transform environmental regulatory pressures into a sustained impetus for green technology innovation within the oil industry, thereby balancing energy security with climate responsibility and reshaping industry competitiveness. This reform not only facilitates the transformation of the oil sector but also offers a precedent for addressing carbon emissions challenges in other high-polluting industries.

5. Conclusion

Green technological innovation in the oil industry represents a critical approach to resolving the conflict between energy security and climate change mitigation. Research indicates that environmental regulations stimulate green technology innovation through a "cost-push market incentive-legitimacy-driven" mechanism. However, these effects are constrained by three industry-specific characteristics: the increase in asset specificity and sunk costs, the mismatch between long technology lifecycles and policy windows, and the fragmentation of technology cooperation ecosystems due to geopolitical competition. To facilitate green technology innovation in the oil sector, a "precise regulation-strategic transformation-international collaboration" framework is required. Governments should implement differentiated carbon quota allocation and risk-sharing funds. Simultaneously, firms must undertake comprehensive reforms in technology, management, and finance. At the international level, reducing transition friction necessitates mutual recognition of standards and innovative financial instruments. Promoting the green and low-carbon transformation of oil enterprises through these methods will advance the global carbon neutrality process.

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References

- [1] Friedlingstein P, O'Sullivan M, Jones M W, et al. Global carbon budget 2024 [J]. *Earth System Science Data Discussions*, 2024, 2024: 1-133.
- [2] Lirong D O U, Longde S U N, Weifeng L Y U, et al. Trend of global carbon dioxide capture, utilization and storage industry and challenges and countermeasures in China [J]. *oil Exploration and Development*, 2023, 50(5): 1246-1260.
- [3] Böhringer C, Carbone J C, Rutherford T F. Embodied carbon tariffs [J]. *The Scandinavian Journal of Economics*, 2018, 120(1): 183-210.

- [4] IEA (2024), World Energy Investment 2024, IEA, Paris <https://www.iea.org/reports/world-energy-investment-2024>, Licence: CC BY 4.0
- [5] Dinica V. Sustained diffusion of renewable energy [J]. 2003.
- [6] Suchman M C. Managing legitimacy: Strategic and institutional approaches [J]. Academy of management review, 1995, 20(3): 571-610.
- [7] Markard J. Transformation of infrastructures: sector characteristics and implications for fundamental change [J]. Journal of Infrastructure Systems, 2011, 17(3): 107-117.
- [8] Wang H, Tong Z, Zhou G, et al. Research and demonstration on hydrogen compatibility of pipelines: a review of current status and challenges [J]. International journal of hydrogen energy, 2022, 47(66): 28585-28604.
- [9] Ruble I. The US crude oil refining industry: Recent developments, upcoming challenges and prospects for exports [J]. The Journal of Economic Asymmetries, 2019, 20: e00132.