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Carbon Emission Control in High-Carbon Industries: Research on Systematic Emission Reduction Pathways for Petroleum Enterprises

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Abstract **Case Studies**

Against the accelerated global carbon neutrality process and increasingly stringent carbon constraint policies, the petroleum industry, as a typical high-carbon sector, generates massive carbon emissions across its entire industrial chain and faces triple pressures including carbon tariffs, ESG investment restrictions and energy structure transformation. Based on the carbon emission characteristics of the full value chain of petroleum enterprises, this paper sorts out core emission sources in upstream, midstream and downstream links, and analyzes practical constraints on systematic carbon reduction in the industry concerning technology, capital and global carbon market mechanisms. Drawing on practical cases of CCUS, green hydrogen substitution, digital carbon management and carbon trading adopted by leading domestic and foreign enterprises such as Equinor and Sinopec, this study constructs a four-dimensional integrated carbon emission control system covering technological innovation, energy structure transition, carbon market operation and full industrial chain collaboration, and verifies the practical effects of various emission reduction tools. Supporting policy suggestions are proposed from the perspectives of carbon pricing, green finance, technological cooperation and multi-stakeholder coordination. This research provides theoretical support and practical schemes for the low-carbon transformation of domestic petroleum enterprises, and offers references for studies on systematic carbon emission control in high-carbon industries.

Keywords: High-carbon industries, Carbon emission control, Petroleum enterprises, Full industrial chain emission reduction, CCUS, Carbon market.

1. Introduction

Global climate change has become a critical public challenge to be addressed in the 21st century. The Paris Agreement drives all countries to fully implement carbon peaking and carbon neutrality targets, while global standards for energy-related carbon emission control keep upgrading. Data from the International Energy Agency (IEA) shows that global energy-related carbon emissions hit 36.8 billion tons in 2022, among which the petroleum industry accounts for about 35%, making it a core source of greenhouse gas emissions. The EU Carbon Border Adjustment Mechanism (CBAM), the U.S. Inflation Reduction Act and China's national carbon emissions trading market have formed multi-layer rigid emission reduction constraints covering the whole chain of oil and gas production, refining and finished oil trade.

Petroleum enterprises shoulder dual missions of energy security and low-carbon transition. The oil and gas industrial chain is lengthy, and emission mechanisms vary greatly across links. Simple energy-saving renovations in single segments cannot achieve overall emission reduction, so a systematic control framework covering the whole industrial chain is urgently required. Existing studies mostly focus on segmented fields such as the economic efficiency of CCUS technologies, carbon market rules and energy-saving transformation of refineries, lacking integrated emission reduction systems that combine technology, energy, market and coordination mechanisms. From the perspective of Management Science and Engineering, this paper combines emission reduction practices of the global oil and gas industry, identifies carbon emission sources and transformation constraints, builds a multi-dimensional systematic emission reduction path and matching policy schemes, fills the fragmentation defects of existing research, and provides decision-making basis for the low-carbon transformation of oil and gas enterprises.

2. Main Carbon Emission Sources of Petroleum Enterprises across the Industrial Chain

Carbon emissions of petroleum enterprises include direct emissions generated throughout production and indirect emissions from purchased electricity and equipment manufacturing. Three core emission segments are divided by industrial chain:

1.**Upstream exploration and production**: Accounting for 40%–50% of total direct emissions, it is the largest emission source. Emissions mainly derive from unorganized methane leakage, associated gas flaring and fuel consumption of production equipment. Methane has an extremely strong greenhouse effect, making upstream links the priority of emission control.

2.**Midstream refining and processing**: Contributing approximately 30% of total emissions. Fuel consumption of heating furnaces, catalytic cracking units and process emissions form concentrated high-concentration CO_2, which is suitable for CCUS renovation. Nevertheless, the transformation of aging equipment brings high costs.

3.**Downstream storage, transportation and sales**: Taking up 20% of total emissions, dominated by scattered unorganized emissions including energy consumption of pipeline transportation, oil volatilization in storage tanks and gas stations. Digital monitoring and oil-gas recovery renovation are core emission reduction measures.

Indirect emissions cannot be ignored. An international oil company recorded 120 million tons of direct carbon emissions in 2021, with another 80 million tons of indirect emissions from purchased electricity and supply chain manufacturing. Systematic carbon control must cover indirect emission accounting across the full value chain.

3. Necessity of Implementing Systematic Carbon Emission Control for Petroleum Enterprises

3.1 Tightening Global Carbon Supervision and Rising Compliance Costs

Countries have issued mandatory carbon control policies. The EU CBAM imposes carbon tariffs on imported oil, gas and chemical products, while the U.S. guides the application of low-carbon technologies via tax incentives. The domestic petrochemical industry has been gradually incorporated into mandatory emission control scope. Enterprises without complete carbon control systems will face heavy carbon taxes and market access restrictions. Systematic emission reduction serves as a foundation for enterprises to meet diversified global supervision and avoid compliance risks.

3.2 Energy Structure Iteration Forces the Transformation of Business Models

Global energy consumption is continuously shifting towards wind, solar and hydrogen energy, squeezing profit margins of traditional oil and gas businesses. Systematic carbon emission control simultaneously promotes enterprises to layout new energy tracks and cultivate new growth points. Shell plans to allocate 50% of its investment to renewable energy by 2030, hedging the downward risks of fossil fuel businesses through coordinating low-carbon transformation of traditional assets and new energy deployment.

3.3 ESG Investment Reshapes Industrial Competition Landscape

Global ESG investment exceeded 40 trillion US dollars in 2022. Institutional investors regard carbon intensity and low-carbon transformation plans as core evaluation indicators. A sound carbon management system can reduce enterprises' green financing costs. Meanwhile, rising demand for low-carbon consumption enables carbon-neutral service stations and low-carbon oil products to form differentiated market competitiveness.

4. Practical Dilemmas of Systematic Carbon Emission Control for Petroleum Enterprises

4.1 Dual Barriers of Cost and Safety for Low-Carbon Technologies

As the core technology for deep emission reduction of fossil energy, CCUS currently has a capture cost of 50–100 US dollars per ton, with a high investment threshold for large-scale promotion. Underground storage faces geological risks of CO_2 leakage and is difficult to popularize in regions with poor geological conditions. Green hydrogen refining and new-generation biofuels are still in demonstration phases without large-scale commercial application. The procurement cost of digital methane monitoring equipment is high, unaffordable for small and medium-sized regional oil enterprises.

4.2 Huge Transformation Investment and Insufficient Short-Term Economic Benefits

McKinsey estimates that global petroleum enterprises need annual low-carbon investment of 300 billion US dollars to achieve net-zero targets. Emission reduction projects feature high upfront investment and long return cycles. Restricted by short-term performance, corporate management tends to cut low-carbon budgets. In addition, the supply of green credit and special transformation funds is insufficient, narrowing financing channels for small and medium-sized oil enterprises.

4.3 Fragmented Global Carbon Market Pricing and Imbalanced Cross-Border Emission Reduction Strategies

A unified global carbon pricing mechanism has not been formed, resulting in huge regional price gaps: EU carbon prices exceed 80 euros per ton, while China's carbon market price stands at around 60 RMB per ton. Carbon quotas and carbon credits of various countries are mutually unrecognizable. Multinational enterprises cannot uniformly calculate emission reduction benefits, and institutional barriers exist for cross-border trading of carbon assets. Inconsistent carbon accounting standards also easily lead to greenwashing problems.

4.4 Lack of Industrial Chain Coordination Mechanisms and Fragmented Emission Reduction

Most enterprises only focus on self-owned production facilities in carbon management, failing to include upstream suppliers and downstream distributors into control scope. High-carbon raw materials and emissions from end-use oil products are not incorporated into unified accounting. Channels for sharing emission reduction technologies and mature solutions within the industry are inadequate, making it hard to popularize advanced experience from leading enterprises to small and medium-sized ones.

5. Four-Dimensional Implementation Pathways for Systematic Carbon Emission Control of Petroleum Enterprises

Combining global oil enterprise practical cases, this paper constructs an integrated control framework including technology-driven emission reduction, energy structure transition, carbon market operation and full industrial chain collaboration.

5.1 Technology-Driven Emission Reduction: Cutting Direct Emissions from Production Sides

1.Large-scale CCUS deployment: Equinor's Northern Lights subsea storage project in Norway achieves an annual CO_2 storage capacity of 1.5 million tons, with the government covering 60% of construction costs and unit storage costs below 40 US dollars per ton. Retrofitting existing oil and gas pipelines for CO_2 transportation drastically reduces infrastructure investment and delivers replicable promotion value.

2.Green hydrogen substitution for refining heat sources: Saudi Aramco plans to adopt photovoltaic electrolytic green hydrogen to replace natural gas in refineries, which is expected to cut midstream carbon emissions by 30% and reduce stationary combustion emissions from the source of production processes.

3.Digital intelligent control: BP builds an AI oilfield monitoring system to accurately locate methane leakage points, cutting unorganized emissions by 15%. With low renovation costs and quick effects, this technology is suitable for priority short-term implementation.

5.2 Energy Structure Transition: Optimizing Energy Consumption via Renewable Energy

1.Self-built wind and solar new energy bases: TotalEnergies sets a target of 100 GW renewable energy installed capacity by 2030, whose power generation covers 25% of corporate energy demand and reduces indirect emissions from purchased thermal power. Domestic oil enterprises can build distributed photovoltaics on idle land of factory areas to realize self-generation and self-consumption.

2.Biofuel substitution for traditional oil products: Petrobras develops second-generation bio-aviation kerosene with agricultural and forestry waste and algae as raw materials, whose carbon emission intensity is 80% lower than conventional aviation fuel without competing for food resources, expanding the track of downstream low-carbon products.

5.3 Carbon Market Operation: Balancing Emission Reduction Costs through Market-Oriented Tools

1.Internal carbon pricing mechanism: ExxonMobil sets an internal carbon price of 40 US dollars per ton. All new projects are mandatory to calculate carbon costs, with low-carbon projects prioritized for approval to control new emissions from the source of investment. Enterprises can moderately raise internal carbon prices to hedge future risks of carbon tariff and quota price hikes in advance.

2.Carbon sink offset for compliance: Sinopec Zhenhai Refinery offsets 10% of refining emissions through forestry carbon sink projects, completing mandatory compliance with compliant carbon credits and alleviating capital pressure of short-term equipment transformation. The enterprise simultaneously participates in national carbon market trading to revitalize carbon assets.

5.4 Full Industrial Chain Collaborative Control: Integrated Carbon Management across Value Chains

1.Carbon access for supply chains: Shell incorporates suppliers' carbon emission intensity into procurement assessment and phases out suppliers providing high-carbon raw materials. A unified supply chain carbon footprint accounting standard is established to realize traceable and controllable upstream indirect emissions.

2.Guidance on low-carbon terminal consumption: Chevron builds carbon-neutral gas stations with incentive policies for low-carbon consumption, and popularizes oil-gas recovery equipment to cut unorganized emissions from oil volatilization at gas stations.

6. Case Verification: Systematic Emission Reduction Practices of Domestic and Foreign Petroleum Enterprises

6.1 Equinor's Northern Lights CCUS Project

As a global benchmark for commercial subsea carbon storage, this project adopts a government-enterprise joint operation model. Retrofitting original North Sea oil and gas pipelines for CO_2 transportation reduces infrastructure costs by 30%–40%. The enterprise matches AI methane monitoring and factory photovoltaic power stations, forming a combined model of core emission reduction via CCUS, leakage control via digitalization and substitution via new energy, providing a mature model for systematic carbon control of large overseas oil and gas enterprises.

6.2 Low-Carbon Transformation Project of Sinopec Zhenhai Refinery

Zhenhai Refinery integrates distributed photovoltaics, CCUS capture facilities and green hydrogen pilot projects, setting a target of 20% reduction in carbon emission intensity by 2025. The enterprise establishes a full-process carbon accounting ledger covering procurement, production, storage and transportation, eases capital pressure via green bonds and policy subsidies, and completes compliance through forestry carbon sinks. It offers practical references for localized carbon control of state-owned domestic refineries.

7. Supporting Policy Suggestions for Improving Systematic Carbon Emission Control of Petroleum Enterprises

7.1 Coordinate Global Carbon Pricing Mechanisms and Enrich Green Financial Instruments

Promote the unification of global carbon prices and carbon credit recognition standards, and build cross-border mutual recognition and trading platforms for carbon assets. Set up special subsidies for core emission reduction technologies such as CCUS and green hydrogen. Expand the green financial system, establish special funds for energy low-carbon transition, simplify the issuance procedures of green bonds, and provide low-interest credit for emission reduction projects to relieve corporate capital constraints.

7.2 Unify Industrial Carbon Accounting Standards and Build International Technology Cooperation Platforms

Formulate unified full-industrial-chain carbon footprint accounting specifications for the petroleum industry, clarify statistical calibers of direct and indirect emissions, and curb greenwashing behaviors. Rely on the Belt and Road Low-Carbon Technology Transfer Center to promote cross-border sharing of CCUS, digital monitoring technologies and reduce repeated R&D costs of enterprises worldwide.

7.3 Construct Multi-Stakeholder Collaborative Governance System

Set up low-carbon alliances for the petroleum industry to share emission reduction technologies and operation experience and jointly carry out R&D of low-carbon processes. Implement carbon labeling systems for finished oil products to mark carbon emission intensity and guide consumers to choose low-carbon products, forming a multi-party emission reduction pattern involving governments, enterprises, industries and the public.

8. Conclusion and Prospect

8.1 Core Research Conclusions

Carbon emissions of petroleum enterprises are distributed hierarchically along the industrial chain: upstream production accounts for 40%–50%, midstream refining 30%, and downstream storage, transportation and sales 20%, while indirect emissions cannot be overlooked. Three driving forces including stringent global carbon supervision, energy structure transformation and ESG capital competition force the industry to build a systematic carbon emission control system. Current core transformation obstacles focus on four aspects: high costs of low-carbon technologies, heavy capital investment pressure, fragmented global carbon markets and fragmented emission reduction across industrial chains.

The four-dimensional integrated control framework constructed in this paper has been verified feasible by practices of leading domestic and foreign oil enterprises: CCUS and digital control rapidly cut direct production emissions; wind, solar and biofuels optimize corporate energy consumption structures; internal carbon pricing and carbon sink trading balance emission reduction costs via market mechanisms; collaborative control of upstream and downstream links realizes deep carbon control across the full value chain. Combined implementation of multiple pathways can balance short-term emission reduction effects and long-term low-carbon business model transformation.

8.2 Short-Term and Medium-Long-Term Implementation Priorities

In the short term (1–5 years), prioritize low-cost mature solutions: popularize AI methane monitoring, waste heat and oil-gas recovery renovation in refineries; implement internal carbon pricing and participate in domestic carbon market trading; deploy distributed photovoltaics in factory areas and strive for government low-carbon subsidies to launch CCUS projects. In the medium and long term (5–20 years), focus on industrialization of disruptive low-carbon technologies: promote large-scale substitution of refining fuels via photovoltaic green hydrogen; develop second-generation biofuels made from agricultural and forestry waste; transform existing oil and gas infrastructure for CO_2 storage and hydrogen transportation. Enterprises will transform from single oil and gas producers to comprehensive energy service providers operating three business lines: fossil energy, renewable energy and carbon management services.

8.3 Research Limitations and Future Expansion Directions

This paper focuses on constructing emission reduction path frameworks and case analysis, with remaining limitations: it fails to quantitatively evaluate long-term geological risks of CCUS storage sites in tectonically active regions; lacks economic comparison models of blue hydrogen and green hydrogen under differentiated carbon price scenarios; does not measure the social impacts of low-carbon transformation on employment and local economies in oil and gas producing areas. Follow-up research can be deepened from three dimensions: establish quantitative models for geological risk assessment of CCUS storage sites; conduct multi-scenario simulation on investment returns of low-carbon technologies under varying carbon prices; carry out research on fairness of energy transition and design transition schemes balancing emission reduction and regional people’s livelihood.

8.4 Summary

Carbon emission control of high-carbon industries is a key link of global climate governance. Systematic emission reduction of petroleum enterprises represents an all-round reconstruction of business models covering technology, energy, market and industrial chains. Supported by multi-dimensional collaborative emission reduction pathways as well as matching policy, financial and technical support, petroleum enterprises can transform from high-carbon emission entities to promoters of carbon neutrality. On the premise of guaranteeing energy security, they can balance operating benefits and low-carbon responsibilities, facilitating the realization of global carbon neutrality goals proposed by the Paris Agreement.

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