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Research on Carbon Emission Optimization Pathways for Petroleum Enterprises

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Abstract **Original Research Article**

Against the backdrop of global climate change mitigation, petroleum enterprises, as key players in high-carbon industries, urgently need to explore scientifically effective pathways for carbon emission optimization. This paper systematically analyzes the primary sources of carbon emissions in petroleum enterprises, the necessity of optimization, and practical challenges, integrating global carbon reduction trends with industry-specific characteristics.

It proposes a comprehensive optimization framework encompassing technological innovation, energy structure transition, participation in carbon trading, and policy coordination. Through case studies, the practical effectiveness of strategies such as carbon capture and storage (CCS), energy efficiency improvements, and renewable energy substitution is validated. Furthermore, policy recommendations are provided to offer theoretical foundations and practical guidance for petroleum enterprises in achieving low-carbon transformation.

Keywords: *Petroleum Enterprises, Carbon Emission Optimization, Carbon Capture And Storage (CCS), Energy Transition, Carbon Trading.*

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1. INTRODUCTION

Global climate change has emerged as one of the most pressing challenges of the 21st century, with increasing international demands for stricter carbon emission controls. According to the International Energy Agency (IEA), global energy-related carbon emissions reached 36.8 billion tons in 2022, with the petroleum industry contributing approximately 35%, making it a major source of greenhouse gas emissions.

Concurrently, governments worldwide are reinforcing emission reduction targets through international agreements such as the Paris Agreement, urging enterprises to accelerate their low-carbon transition. As core suppliers of traditional energy, petroleum enterprises face dual pressures of environmental responsibility and economic efficiency. The critical challenge lies in achieving optimized carbon emission management while ensuring energy security, which is essential for their sustainable development.

This study focuses on petroleum enterprises, systematically exploring carbon emission optimization pathways in alignment with international carbon reduction policies and technological trends, aiming to provide scientific insights for the industry's low-carbon transformation.

2. PRIMARY SOURCES OF CARBON EMISSIONS IN PETROLEUM ENTERPRISES

2.1 Basic Concept of Carbon Trading

Carbon emissions in petroleum enterprises span the entire industrial chain, primarily including the following stages:

1) Upstream extraction: Methane leakage, associated gas flaring, and other emissions during oilfield exploration, drilling, and production, accounting for 40%–50% of total emissions.

2) Midstream refining: Energy consumption (e.g., heating furnaces, catalytic cracking units) and process emissions in refineries, contributing around 30%.

3) Downstream sales: Emissions from transportation, storage, and end-use (e.g., fuel evaporation at gas stations), representing approximately 20%.

Indirect emissions (e.g., purchased electricity, equipment manufacturing) are also significant. For instance, a major international oil company reported 120 million tons of direct emissions and 80 million tons of indirect emissions in 2021, highlighting the need for full-process optimization.

3. NECESSITY OF CARBON EMISSION OPTIMIZATION

3.1 Environmental Pressure and Regulatory Compliance

Global carbon regulations are becoming increasingly stringent. The EU's Carbon Border Adjustment Mechanism (CBAM) requires imported goods to account for embedded emissions, while the U.S. Inflation Reduction Act offers tax incentives for low-carbon technologies. Failure to comply with these policies may expose petroleum enterprises to substantial carbon taxes or market access restrictions.

3.2 Economic Transition Imperatives

The global energy structure is rapidly shifting toward renewables, exacerbating profitability risks for traditional oil businesses. Investments in low-carbon technologies can unlock new growth opportunities. For example, Shell plans to allocate 50% of its investments to renewables by 2030 to offset declines in traditional operations.

3.3 Corporate Social Responsibility

Investors and consumers are increasingly prioritizing environmental performance. According to S&P Global, global ESG (Environmental, Social, and Governance) investments exceeded $40 trillion in 2022, making low-carbon transition a competitive advantage for attracting capital and consumer trust.

4. PRACTICAL CHALLENGES IN CARBON EMISSION OPTIMIZATION

4.1 Technological Barriers

Carbon capture and storage (CCS) technologies remain costly, with current capture costs ranging from $50–$100 per ton, and geological storage poses leakage risks. Low-carbon refining processes (e.g., green hydrogen substitution) are still in the demonstration phase, limiting large-scale adoption.

4.2 Financial and Profitability Trade-offs

Low-carbon transitions require substantial upfront investments. McKinsey estimates that petroleum enterprises need annual investments of $300 billion to achieve net-zero targets, yet short-term returns often fail to justify costs, leading to hesitancy in decision-making.

4.3 Policy and Market Uncertainties

The absence of a unified global carbon pricing mechanism results in significant regional disparities (e.g., EU carbon prices exceed €80/ton, while China's hover around ¥60/ton), complicating cross-border emission reduction strategies.

5. EXPLORATION OF PRACTICAL PATHWAYS

5.1Technology-Driven Emission Reduction

1) CCS: Equinor's "Northern Lights" project in Norway stores CO_2 in subsea formations, achieving an annual capacity of 1.5 million tons at costs below $40/ton.
2) Green hydrogen refining: Saudi Aramco plans to use solar-based hydrogen to replace natural gas in refineries, reducing midstream emissions by 30%.
3) Digital management: BP employs AI to optimize oilfield operations, cutting methane leaks by 15%.

5.2 Energy Structure Transition

1) Renewable energy deployment: TotalEnergies aims for 100 GW of renewable capacity by 2030, covering 25% of its energy output.
2) Biofuel substitution: Petrobras' bio-aviation fuel reduces emission intensity by 80% compared to conventional fuels.

5.3 Participation in Carbon Markets

1) Internal carbon pricing: ExxonMobil sets an internal carbon price ($40/ton) to prioritize low-carbon projects.
2) Carbon credit trading: Sinopec offsets 10% of refining emissions through forestry carbon sequestration projects.

5.4 Whole-Industry-Chain Collaboration

1) Supply chain management: Shell incorporates suppliers' carbon performance into procurement evaluations.
2) Consumer engagement: Chevron promotes carbon-neutral gas stations with reward programs for low-carbon choices.

6. CASE STUDIES

6.1 Equinor's CCS Implementation

The "Northern Lights" project liquefies industrial CO_2 for storage in North Sea formations, showcasing global leadership in CCS commercialization through government subsidies (covering 60% of costs) and public-private partnerships.

6.2 Sinopec's Low-Carbon Refining Transition

At its Zhenhai refinery, Sinopec integrates renewable power and CCUS (Carbon Capture, Utilization, and Storage), targeting a 20% reduction in emission intensity by 2025, demonstrating policy-industry synergy.

7. POLICY RECOMMENDATIONS

7.1 Strengthening Policy Incentives

1) Carbon pricing: Harmonize global carbon prices and subsidize key technologies like CCS.
2) Green finance: Establish low-carbon transition funds and

facilitate green bond issuance.

7.2 Standardizing Technical Frameworks

1) Carbon accounting: Develop internationally recognized standards to prevent greenwashing.
2) Technology cooperation: Create platforms like the Belt and Road Low-Carbon Technology Transfer Center.

7.3 Fostering Multi-Stakeholder Collaboration

1) Industry alliances: Form coalitions for sharing emission reduction technologies and best practices.
2) Public awareness: Introduce carbon footprint labeling to guide consumer choices.

8. CONCLUSION AND OUTLOOK

The optimization of carbon emissions in petroleum enterprises represents a pivotal response to the intertwined challenges of global climate change, stringent regulatory environments, and evolving energy market dynamics.

This study has systematically dissected the multi-faceted nature of this challenge, spanning from the identification of emission sources across the petroleum value chain to the formulation of actionable strategies rooted in technological innovation, structural transformation, and policy alignment.

8.1 Summary of Key Findings

Petroleum enterprises contribute significantly to global carbon emissions, with upstream extraction (40-50% of total emissions), midstream refining (30%), and downstream operations (20%) forming the core emission hotspots. The necessity for optimization is underscored by three critical drivers: escalating environmental regulations (e.g., the EU's CBAM and U.S. Inflation Reduction Act), imperatives for economic resilience amid the global shift toward renewables, and the imperatives of corporate social responsibility in an ESG-conscious investment landscape.

However, the journey is fraught with challenges, including high costs of CCS ($50-$100/ton capture costs), financial trade-offs (requiring $300 billion annual investments for net-zero), and policy uncertainties stemming from fragmented global carbon pricing (e.g., €80/ton in the EU vs. ¥60/ton in China).

Against this backdrop, the study proposes a holistic optimization framework. Technological solutions, such as Equinor's "Northern Lights" CCS project (achieving sub-$40/ton storage costs with 1.5 million tons annual capacity) and Saudi Aramco's green hydrogen refining (targeting 30% midstream emission reductions), demonstrate the feasibility of deep decarbonization in key operational segments.

Energy structure transition, exemplified by TotalEnergies' 100 GW renewable capacity goal and Petrobras' bio-aviation fuel (80% lower emission intensity), highlights the strategic reallocation of resources toward low-carbon alternatives.

Participation in carbon markets, through mechanisms like ExxonMobil's internal carbon pricing ($40/ton) and Sinopec's forestry carbon credit trading (offsetting 10% of refining emissions), offers both compliance pathways and economic opportunities. Whole-industry-chain collaboration, from Shell's supplier carbon performance evaluations to Chevron's consumer-facing carbon-neutral gas stations, underscores the need for systemic change beyond isolated interventions.

8.2 Short-term Priorities and Immediate Impacts

In the short to medium term, the deployment of proven technologies will be critical. CCS, despite its current costs, remains a linchpin for mitigating emissions from existing fossil fuel assets. Scaling up projects like "Northern Lights," which leverage public-private partnerships and government subsidies (covering 60% of costs), can drive down unit costs through economies of scale. Simultaneously, digital optimization tools, such as BP's AI-driven methane leak detection (15% reduction), offer low-hanging fruits for operational efficiency, addressing the 40-50% upstream emission share.

Energy efficiency improvements in refineries, supported by technologies like green hydrogen substitution, can deliver immediate reductions in midstream emissions, aligning with Sinopec's 20% emission intensity reduction target by 2025 at ZhenHai refinery.

Carbon market participation also warrants accelerated action.

As regional markets mature (e.g., China's national carbon market, the world's largest by volume), enterprises can enhance liquidity and price discovery through cross-border credit trading. Internal carbon pricing, beyond being a compliance tool, can evolve into a strategic resource allocation mechanism, prioritizing projects that deliver both emission reductions and long-term profitability. For instance, setting internal prices above expected future regulatory costs (e.g., $100/ton by 2030) can incentivize proactive low-carbon investments, future-proofing against carbon taxes and trade barriers.

8.3 Long-term Vision and Transformational Challenges

The long-term success of petroleum enterprises in carbon emission optimization hinges on breakthroughs in transformative technologies. Green hydrogen and advanced biofuels, while still in demonstration phases, hold the promise of decoupling energy production from fossil fuel dependency.

Green hydrogen, produced via electrolysis powered by renewables, can replace natural gas in refining and industrial processes, creating a circular low-carbon ecosystem. Similarly, second-generation biofuels derived from waste feedstocks (e.g., algae, crop residues) offer higher emission reduction potentials (up to 90% vs. conventional fuels) without competing with food security, as exemplified by Petrobras' ongoing R&D initiatives.

However, these innovations require overcoming substantial technical and economic hurdles. For green hydrogen, reducing production costs from the current $4-$6/kg to $2/kg (competitive with gray hydrogen) by 2030 will depend on scaling up electrolyzer manufacturing, improving renewable energy integration, and policy support (e.g., production tax credits). Advanced biofuels face challenges in feedstock availability, conversion efficiency, and regulatory approval for commercial use, necessitating collaborative R&D across academia, industry, and governments.

8.4 Policy, Market, and Institutional Innovations

A coherent policy environment is indispensable for navigating these transitions. Harmonizing global carbon pricing mechanisms to reduce regional disparities should be a priority, as fragmented pricing distorts investment signals and creates competitive inequities. Initiatives like the "Belt and Road Low-Carbon Technology Transfer Center" can facilitate knowledge sharing between developed and developing nations, accelerating the diffusion of CCS, renewable energy, and digital monitoring technologies.

Green finance instruments, such as blended finance for CCS projects and green bonds for renewable capacity, need to be mainstreamed, leveraging public funds to de-risk private investments.

Institutional changes within enterprises are equally vital. Shifting from a siloed operational mindset to a holistic "integrated energy service provider" model requires organizational restructuring—establishing dedicated low-carbon business units, retraining workforce skills, and realigning performance metrics to include ESG targets. For example, transitioning from measuring success solely by barrel production to evaluating "carbon-adjusted profitability" can drive cultural change toward sustainability.

8.5 Role in Global Carbon Neutrality Goals

As stewards of significant energy infrastructure, petroleum enterprises have the potential to evolve from being "carbon giants" to pivotal enablers of global carbon neutrality. Their expertise in large-scale project execution, supply chain management, and market penetration positions them uniquely to deploy low-carbon solutions at the required scale.

For instance, repurposing existing oil and gas infrastructure for hydrogen transportation or CCS storage can reduce transition costs by 30-40%, as demonstrated by Equinor's repurposing of North Sea pipelines for CO_2 transport.

Looking ahead, the intersection of technological innovation, policy coherence, and market evolution will define the trajectory of petroleum enterprises. By 2050, successful companies are likely to operate hybrid business models, balancing traditional hydrocarbon activities with renewable energy generation, carbon management services, and circular economy initiatives.

This transformation is not just an environmental imperative but a strategic necessity for survival in a net-zero world, where adaptability and foresight will distinguish leaders from laggards.

8.6 Research Gaps and Future Directions

While this study provides a comprehensive framework, several areas merit further investigation. The long-term geological stability of CCS storage sites, especially in tectonically active regions, requires more rigorous risk assessment.

The economic viability of "blue hydrogen" (hydrogen produced with CCS) compared to "green hydrogen" under different regulatory scenarios also needs detailed modeling. Additionally, exploring the social impacts of low-carbon transitions—such as workforce displacement in fossil fuel-dependent regions and community engagement in renewable projects—will be crucial for ensuring just transitions.

In conclusion, carbon emission optimization for petroleum enterprises is a journey of reinvention, demanding courage to redefine business models, invest in uncertain technologies, and collaborate across boundaries. As the world accelerates toward the Paris Agreement goals, these enterprises have a historic opportunity to lead the energy transition, proving that profitability and sustainability can coexist in the era of climate action.

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