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Impact of the Digital Economy on the Performance of China's Petroleum Enterprises

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Abstract: The rapid development of the digital economy profoundly impacts global industries, presenting both opportunities and challenges for traditional sectors like petroleum. This study investigates the impact of the digital economy on the performance of Chinese petroleum enterprises, focusing on the mediating role of total factor productivity (TFP). Utilizing panel data from Chinese petroleum firms (2018–2023), we construct a macro digital economy development index (using the entropy method) and a micro-level enterprise digital transformation index. Empirical analysis employs panel data models and mediation effect models. Findings reveal that regional digital economy development significantly positively affects firms' Tobin's Q (coefficient = 0.516). Enterprise digital transformation significantly enhances Return on Equity (ROE) (coefficient = 27.456). Mediation tests confirm that TFP partially mediates the relationship between digital transformation and firm performance. Heterogeneity analysis shows differences based on ownership: regional digital economy development has a slightly stronger effect on state-owned enterprises' (SOEs) market value, while its effect is statistically more significant for private enterprises. Conversely, digital transformation boosts ROE more significantly in private firms. The study concludes with policy recommendations, including promoting digital governance reform in SOEs, increasing support for private firms' digitalization, building a digital technology innovation ecosystem to enhance TFP, and optimizing digital investment structures for better capital market recognition.

Keywords: Digital economy; Enterprise performance; Total factor productivity; Petroleum industry; China

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1. Background

The global economy is rapidly transitioning into a digital era. The digital economy, driven by technologies like big data, artificial intelligence, and blockchain, has become a new engine for economic growth, significantly altering industrial landscapes and competitive environments. Traditional industries, including the energy sector represented by petroleum enterprises, face an urgent need for digital transformation to adapt and thrive [1–12].

China's digital economy has experienced substantial growth, reaching CNY 53.9 trillion in 2023. National strategies like the "Digital China" initiative underscore the importance of digitalization. Petroleum enterprises,

being capital-intensive, technologically complex, and strategically vital, are under pressure from volatile global oil prices, geopolitical tensions, and the energy transition. Digital transformation offers avenues for these firms to enhance supply chain agility, production process intelligence, customer relationship management, and overall operational efficiency, ultimately aiming for high-quality development [13].

While existing research explores the general relationship between the digital economy and firm performance in various sectors, studies specifically targeting the petroleum industry, particularly in China, are limited. Furthermore, the mediating mechanism through which digitalization affects performance, especially via total factor productivity (TFP), remains underexplored. This research gap is critical given the potential of digital technologies to optimize resource allocation and improve efficiency in this traditional sector [14–20].

2. Research purpose

This study aims to empirically analyze the impact mechanism of the digital economy on the performance of Chinese petroleum enterprises. Specifically, it seeks to:

(1) Examine the direct impact of regional (macro) digital economy development on petroleum firms' market value (measured by Tobin's Q).

(2) Investigate the direct impact of enterprise-level (micro) digital transformation on profitability (measured by return on equity, ROE).

(3) Test the mediating role of TFP in the relationship between digital transformation and firm performance.

(4) Explore heterogeneity in these effects based on enterprise ownership (state-owned vs. private).

(5) Provide evidence-based policy recommendations to support the digital transformation and performance enhancement of Chinese petroleum enterprises.

3. Methodology

This research employs a mixed-methods approach, combining theoretical analysis with empirical testing.

3.1. Data sources and sample

The study uses panel data from Chinese A-listed companies in the petroleum and natural gas extraction and processing industries from 2018 to 2023. Data primarily comes from the CSMAR database (firm-level financial and governance data) and the National Bureau of Statistics of China (macroeconomic indicators for constructing the digital economy index). Samples marked ST or ST and those with severe missing data were excluded [20–35].

3.2. Variable construction and measurement

Dependent variables:

Tobin's Q (Tobin_Q): Market value divided by asset replacement cost, reflecting market valuation and future expectations. Used for analyzing macro-level effects [35].

Return on equity (ROE): Net income divided by shareholders' equity, measuring profitability and efficiency in using shareholder capital. Used for analyzing micro-level effects.

Core independent variables:

Macro digital economy development index (lnDigital): Constructed using the entropy method. This comprehensive index incorporates 19 indicators across three dimensions: information infrastructure (e.g., fiber

optic cable length), internet development level (e.g., internet penetration rate, mobile users), and digital transaction development level (e.g., number of e-commerce enterprises, e-commerce sales). Data was standardized and weighted objectively using entropy values.

Enterprise digital transformation index (DigitalTrans): Measured by the proportion of digital technology-related intangible assets (identified by keywords like "software," "network," "client," "management system," "smart platform," and related patents) to total intangible assets for the year [10].

Mediating variable:

Total factor productivity (TFP): Calculated using both OLS and fixed effects (FE) methods, following the approach of Xiaodong Lu (2012), to measure output efficiency not attributable to standard inputs (capital, labor) [36–38].

Control variables: Include leverage (LEV), current ratio (CR), capital intensity (AI, log of total assets per employee), company growth (growth, revenue growth rate), and company age (lnAge, log of years since establishment) [35].

3.3. Empirical models

Panel data models (fixed effects): To assess the direct impact of the macro and micro digital economy variables on firm performance, controlling for firm and time-invariant characteristics [39].

Model for macro effect:

`Tobin_Q_it = α + β1 lnDigital_t + β2 Controls_it + λ_i + γ_t + ε_it`

Model for Micro Effect:

`ROE_it = α + β1 DigitalTrans_it + β2 Controls_it + λ_i + γ_t + ε_it`

Mediation effect model: Based on the stepwise approach by Zhonglin Wen (2014) to test whether TFP mediates the link between digital transformation (DigitalTrans) and performance (ROE) [38,39].

1. ROE_it = α + c DigitalTrans_it + β Controls_it + λ_i + γ_t + ε_it` (Test total effect c)
2. TFP_it = α + a DigitalTrans_it + β Controls_it + λ_i + γ_t + ε_it` (Test effect of IV on mediator a)
3. ROE_it = α + c' DigitalTrans_it + b TFP_it + β Controls_it + λ_i + γ_t + ε_it` (Test direct effect c' and effect of mediator on DV b)

Mediation is supported if a and b are significant. If c' is insignificant, full mediation; if c' is significant but reduced, partial mediation.

4. Results

4.1. Descriptive statistics and correlation

Descriptive statistics showed variation in all key variables. Correlation analysis indicated significant relationships among some control variables but no severe multicollinearity (all VIFs < 2 for macro analysis, < 1.5 for micro analysis), ensuring reliable regression estimates.

4.2. Impact of regional digital economy (macro)

Regression analysis controlling for firm and year effects showed that the development of the regional digital economy (lnDigital) had a significant positive impact on petroleum enterprises' Tobin's Q value.

Coefficient for lnDigital: 0.516 (significant at the 10% level, t = 1.807).

This suggests that improved regional digital infrastructure and environment enhance investor confidence and market valuation of petroleum firms [3].

4.3. Impact of enterprise digital transformation (micro)

Enterprise-level digital transformation (DigitalTrans) significantly positively affected profitability.

Coefficient for DigitalTrans: 27.456 (significant at the 5% level, t = 2.101).

This indicates that investments in digital technologies directly improve the operational efficiency and profitability of petroleum enterprises [17,23].

4.4. Mediating role of total factor productivity

The mediation analysis confirmed the hypothesized role of TFP.

Digital transformation → TFP: Coefficient a = 42.135 (significant at 1% level).

TFP → ROE: Coefficient b = 0.126 (significant at 1% level).

When including both DigitalTrans and TFP in the model predicting ROE, the direct effect of DigitalTrans became smaller and statistically insignificant (c'), while the effect of TFP remained significant.

This result indicates that TFP fully mediates the relationship between digital transformation and ROE. Digital transformation enhances performance primarily by improving overall productive efficiency [14,38].

4.5. Heterogeneity analysis: Ownership matters

The effects varied between state-owned enterprises (SOEs) and private enterprises.

Regional digital economy (lnDigital) on Tobin's Q:

SOEs: Coefficient = 0.755 (significant at 10% level). Stronger effect size.

Private: Coefficient = 0.687 (significant at 5% level). Higher statistical significance.

Enterprise digital transformation (DigitalTrans) on ROE:

SOEs: Coefficient = 24.218 (not statistically significant).

Private: Coefficient = 34.842 (significant at 10% level).

This suggests that while the regional digital environment boosts market value slightly more for SOEs, private enterprises are statistically more responsive to it and are significantly more effective at translating their own digital investments into improved profitability (ROE). This might be due to more flexible decision-making and market orientation in private firms [18].

5. Conclusion

This study demonstrates that the digital economy significantly influences the performance of Chinese petroleum enterprises through both macro-environmental and micro-enterprise level channels. Regional digital development enhances market valuation (Tobin's Q), while firm-specific digital transformation directly improves profitability (ROE). Crucially, the mechanism involves digital transformation boosting total factor productivity (TFP), which in turn drives better financial performance. The impact is heterogeneous: state-owned enterprises see a slightly stronger market value benefit from the regional digital environment, but private enterprises demonstrate a greater ability to convert their own digital investments into higher profitability.

6. Policy recommendations

Based on the findings, the following policy recommendations are proposed:

(1) Promote digital governance reform in SOEs: SOEs should establish dedicated digital transformation

committees, optimize resource allocation for digital projects, and enhance data asset management to improve TFP and overcome market skepticism about their transformation efficiency.

(2) Increase digital support for private enterprises: Provide targeted financial and tax incentives (e.g., accelerated depreciation, R&D deductions), facilitate access to specialized loans, and establish public service platforms to lower the barriers and costs of digital transformation for private petroleum firms [18,40].

(3) Build a digital technology innovation ecosystem: Foster industry-academia-research collaboration to develop key technologies relevant to petroleum (e.g., digital twins, smart monitoring). Adjust educational curricula to cultivate talent with dual expertise in digital tech and petroleum engineering, sustaining TFP growth [14,40–52].

(4) Optimize digital investment structure: Encourage firms to balance investments in tangible assets and intangible digital assets. Improve disclosure of digital strategy and outcomes to enhance capital market understanding and valuation of digital transformation efforts.

Disclosure statement

The authors declare no conflict of interest.

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