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DIGITAL TRANSFORMATION AND GREEN INNOVATION: EVIDENCE FROM EMERGING MARKETS

Abstract

This study investigates the impact of Green Innovation (GI) on energy efficiency performance across six emerging economies-China, India, Brazil, Turkey, Poland, and South Africa-using a comparative panel econometric approach. These countries represent diverse industrial structures, regulatory environments, and sustainability transitions. Panel data covering the period 2012-2023 are employed. Energy efficiency is measured by energy intensity and renewable energy productivity, while green innovation is proxied by environmental research and development expenditures and green patent activity. Digital readiness indices and GDP per capita are included as moderating and control variables. Fixed-effects and random-effects techniques are applied, with Hausman tests guiding estimator selection. The results show a statistically significant negative relationship between green innovation and energy intensity, implying that higher levels of innovation contribute to improved energy efficiency. Digital readiness further strengthens this relationship across the six-country sample. The findings provide policy-relevant insights for emerging economies seeking energy security and sustainability gains through technological modernization and innovation-led development strategies.

Keywords: Green innovation; Energy efficiency; Digital readiness; Comparative analysis; Emerging markets

Xülasə

Bu tədqiqat müqayisəli panel econometrik yanaşma əsasında altı inkişaf etməkdə olan iqtisadiyyatda - Çin, Hindistan, Braziliya, Türkiyə, Polşa və Cənubi Afrikada - yaşıl innovasiyanın enerji səmərəliliyi göstəricilərinə təsirini araşdırır. Seçilmiş ölkələr müxtəlif sənaye strukturları, tənzimləmə mühitləri və davamlı inkişaf mərhələlərini təmsil edir. Təhlil üçün 2012-2023-cü illəri əhatə edən panel məlumat bazasından istifadə olunmuşdur. Enerji səmərəliliyi enerji intensivliyi və bərpa olunan enerji məhsuldarlığı göstəriciləri ilə ölçülmüş, yaşıl innovasiya isə ekoloji yönümlü elmi-tədqiqat və təcrübi-konstruktor işlərinə qoyulan xərclər və yaşıl patent fəaliyyəti əsasında müəyyən edilmişdir. Rəqəmsal hazırlıq indeksləri və adambaşına düşən ÜDM göstəricisi tənzimləyici və nəzarət dəyişənləri kimi modelə daxil edilmişdir. Təhlildə Fixed Effects və Random Effects econometrik metodlarından istifadə olunmuş, model seçimi üçün Hausman testi tətbiq edilmişdir. Nəticələr yaşıl innovasiya ilə enerji intensivliyi arasında mənfi və statistik əhəmiyyətli əlaqənin mövcudluğunu sübut edir ki, bu da innovasiya səviyyəsinin artmasının enerji səmərəliliyinin yüksəlməsinə səbəb olduğunu göstərir. Rəqəmsal hazırlıq isə bu təsiri daha da gücləndirərək yaşıl innovasiyanın effektivliyini artırır. Əldə olunan nəticələr inkişaf etməkdə olan bazar ölkələrində texnoloji modernləşmə və innovasiya yönümlü inkişaf strategiyaları vasitəsilə enerji təhlükəsizliyinin və davamlılığın təmin olunması baxımından mühüm siyasi və idarəetmə tövsiyələri təqdim edir.

Açar sözlər: Yaşıl innovasiya; Enerji səmərəliliyi; Rəqəmsal hazırlıq; Müqayisəli təhlil; İnkişaf etməkdə olan bazarlar

Introduction

Digital transformation has become a fundamental driver of economic modernization, shaping how firms and countries adapt to global competition, technological disruption, and sustainability pressures. Emerging markets in particular face the dual challenge of maintaining rapid economic growth while reducing their dependency on energy-intensive production structures. At the same time, environmental concerns, climate agreements, and green transition policies have reinforced the need for countries to adopt green innovation strategies, including the development of clean technologies, renewable energy systems, eco-efficient production processes, and environmental R&D investment.

Green innovation is widely recognized as a key mechanism for reducing environmental degradation and improving long-term energy performance. It can lower energy intensity, increase resource efficiency, and support low-carbon industrial development. However, emerging markets often experience constraints such as limited technological infrastructure, financing gaps, weak institutional quality, and regional disparities in innovation capacity. These factors reduce the ability of countries to fully benefit from sustainability-oriented investments.

Recent research highlights that digital transformation can significantly enhance the effectiveness of green innovation. Digital tools-such as smart grids, AI-based energy monitoring, IoT-enabled production systems, and data analytics-enable governments and firms to optimize energy use, detect inefficiencies, track emissions in real time, and reduce operational waste. Thus, energy efficiency improvements increasingly depend on the interaction between green innovation capacity and digital readiness.

Despite growing interest in this topic, cross-country empirical evidence remains limited. Most existing studies focus on single-country cases or developed economies, leaving a knowledge gap regarding how digital transformation influences the relationship between green innovation and energy outcomes in emerging markets. This study contributes by examining six key emerging economies-China, India, Brazil, Turkey, Poland, and South Africa-to understand how digital readiness conditions the impact of green innovation on national energy efficiency.

Research

This study employs an unbalanced country-level panel dataset covering 2012-2023 for China, India, Brazil, Turkey, Poland, and South Africa. These economies represent diverse energy mixes and regulatory structures, providing a suitable framework for comparative analysis. Data are obtained from the World Bank, International Energy Agency, and WIPO databases.

Energy efficiency, the dependent variable, is measured using energy intensity and renewable energy productivity indicators. Lower energy intensity reflects improved energy efficiency performance. Green innovation is proxied by national environmental R&D expenditures as a share of GDP and the number of registered green patents per million population. Digital readiness is captured using ICT infrastructure and digital adoption indices. Control variables include GDP per capita, industrial output share, urbanization rate, and electricity access rates.

The econometric model is defined as:

$$EEit = \alpha + \beta 1GIit + \beta 2DIGit + \beta 3(GIit \times DIGit) + \beta 4GDPpcit + \beta 5Industryit + \varepsilon it$$

Panel regression analysis is conducted using both Fixed Effects (FE) and Random Effects (RE) estimators to control for unobservable country-specific heterogeneity. The Hausman test is applied to determine model consistency, with preference given to the FE specification. Robust standard errors are used to mitigate heteroskedasticity and serial correlation.

Table 1.

Panel Regression Results (Dependent Variable: Energy Intensity)

Variables	OLS	FE	RE
Green Innovation (GI)	-0.028*** (0.007)	-0.025*** (0.006)	-0.026*** (0.006)
Digital Readiness (DIG)	-0.021*** (0.006)	-0.019*** (0.005)	-0.020*** (0.005)
GI × DIG	-	-0.014** (0.006)	-0.013** (0.006)
GDP per capita	-0.016*** (0.005)	-0.015*** (0.004)	-0.015*** (0.004)
Industry Share	0.012* (0.006)	0.011* (0.005)	0.011* (0.005)
Urbanization	-0.009* (0.005)	-0.008* (0.004)	-0.008* (0.004)
Constant	0.082***	0.071***	0.075***
Observations	72	72	72
R^2	0.39	0.43	0.41

Negative coefficients imply improvement in energy efficiency (lower intensity).
*, **, *** denote significance at 10%, 5% and 1% levels.
Hausman test supports the FE estimator.

Results indicate that higher green innovation intensity reduces energy intensity, improving efficiency across the six countries. Digital readiness further strengthens this effect via the significant interaction term, confirming that digitally advanced economies derive greater efficiency gains from green innovation adoption.

Conclusion

The findings provide strong econometric evidence that green innovation significantly improves energy efficiency in emerging markets, particularly when supported by advanced digital infrastructure. Digital readiness acts as a catalytic factor enabling countries to maximize the productivity effects of sustainability investments through real-time energy monitoring, resource optimization, and regulatory compliance management systems.

China and Poland demonstrate the strongest energy efficiency gains relative to innovation inputs, reflecting mature policy frameworks and technological capacity. Brazil's bioenergy model generates moderate efficiency improvements, while Turkey and South Africa illustrate slower transitions constrained by structural energy dependencies. India's efficiency gains remain limited due to rapid industrial expansion despite growing green innovation activity.

From a policy perspective, governments should foster integrated development strategies linking environmental innovation incentives with digital infrastructure expansion programs. Supporting smart-grid technology, eco-R&D financing, and accessible green patent commercialization mechanisms can significantly accelerate national energy productivity.

For businesses and policymakers alike, these results underscore the importance of combining digital modernization with sustainability innovation strategies to achieve long-term economic and environmental objectives.

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