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The Dynamic Relationship between Industry 4.0 and Renewable Energy Adoption: A Comparative Analysis of Developed and Developing Countries

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Abstract—**This study examines the dynamic relationship between economic growth, renewable energy (RE), population, CO_2 emissions, and Industry 4.0 (I4.0) adoption across a panel of five developed and five developing countries from 2000 to 2023. Using the Generalized Method of Moments (GMM), the analysis uncovers distinct patterns between the two groups. In developed economies, RE consumption and population growth exert significant short-term negative effects on I4.0 adoption, whereas economic growth has a positive influence. In contrast, I4.0 adoption in developing economies demonstrates strong persistence over time. Notably, a significant positive interaction between CO_2 emissions and RE was identified, suggesting that RE expansion amplifies the impact of industrial activity on I4.0 adoption. These findings highlight the need for integrated, stage-specific policy frameworks that align industrial transformation with sustainable energy and growth objectives.**

Keywords— **Industry 4.0, developed countries, developing countries, renewable energy, economic growth**

I. Introduction

The 21st century is characterized by two major global transitions: the decarbonization of economies through the shift toward renewable energy (RE) sources, and the digital transformation driven by the emergence of Industry 4.0 (I4.0). I4.0 technologies—such as Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data analytics—are designed to enhance industrial efficiency, flexibility, and productivity. However, the environmental implications of I4.0 remain complex. While these technologies have the potential to optimize resource use and reduce emissions, their dependence on energy-intensive digital infrastructures may lead to rebound effects that offset sustainability gains.

Existing studies indicate that the contribution of I4.0 to the green transition varies considerably depending on a country's level of development, regulatory frameworks, and technological readiness. Yet, despite growing attention to the interconnections between digitalization and sustainability, empirical research that simultaneously captures the dynamic interplay among I4.0 adoption, renewable energy use, economic growth, and CO_2 emissions remains scarce.

The present research aims to bridge this gap by empirically examining the determinants of I4.0 adoption within the broader nexus of energy transition and economic performance. It further contrasts these dynamics between developed and developing economies, thereby offering new insights into how technological advancement and environmental sustainability can be jointly fostered across different stages of economic development.

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II. Literature Review

The literature generally supports a positive relationship between Industry 4.0 (I4.0) and economic growth, mainly through productivity gains, technological innovation, and enhanced industrial competitiveness. Digitalization enables automation, reduces transaction costs, and fosters innovation-led expansion, though empirical evidence remains limited by inconsistent I4.0 indicators and measurement heterogeneity across countries.

Regarding environmental outcomes, I4.0 is recognized for its potential to promote sustainability via efficiency gains, smart monitoring, and optimized resource use. However, its overall environmental impact varies by institutional quality, regulatory context, and energy mix. While digitalization can reduce emissions through optimization, increased energy demand from data centers and digital infrastructures may offset these benefits.

The relationship between I4.0 and renewable energy (RE) adoption has gained recent attention. Technologies such as IoT, artificial intelligence, and smart grids enhance RE integration and system reliability but also raise concerns about rising computational energy use. Aligning I4.0 with clean energy transitions is thus essential to achieving Sustainable Development Goals (SDGs).

Finally, demographic dynamics, particularly population growth in developing economies, may hinder I4.0 diffusion by redirecting resources toward basic infrastructure. This contextual heterogeneity underscores the need for comparative empirical analyses examining the interplay among I4.0, RE, economic growth, and environmental factors across development levels.

III. Research Methodology

The analysis employs a balanced panel dataset covering five developed and five developing countries from 2000 to 2023. All data are sourced from the World Bank's World Development Indicators (WDI, 2021).

The dependent variable, Industry 4.0 (I4.0), is measured as a composite index: (ICT goods imports / total imports) + (ICT goods exports / total exports). Independent variables are CO_2 Emissions, Renewable Energy Consumption (RE), Population (POP), and Economic Growth (CE). All variables were log-transformed.

Empirical Strategy:

Panel unit root tests indicated varying integration order.

1. Developed Countries (DCs): Given the panel's small size, the stationarity of all variables at levels (Fisher-PP $p < 0.05$ for all), and the rejection of the Random Effects model by the Hausman test (chi^2 = 71.15; $p < 0.001$), the Fixed Effects (FE) Model with cluster-robust standard errors was used to capture short-term effects and unobserved heterogeneity.
2. Developing Countries (LDCs): Since the dependent variable (I4.0) was non-stationary at levels ($p=0.0903$) while regressors were stationary, and due to the high persistence of I4.0 adoption, a Dynamic Panel Model estimated via the Generalized Method of Moments (GMM) was employed. This approach provides robust estimates by addressing endogeneity and the correlation between the lagged dependent variable and the error term.

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IV. Empirical Results and Discussion

A. Determinants of I4.0 Adoption in Developed Countries (Fixed Effects Model)

TABLE I: FIXED EFFECTS ESTIMATION WITH CLUSTER-ROBUST STANDARD ERRORS FOR DEVELOPED COUNTRIES

Variable	**Coefficient**	**p-value**	**Significance**
logENR	-0.309	0.003	***
logPOP	-2.147	0.028	**
logCE	0.033	0.025	**
logCO_2	0.118	0.312	-
R^2 within	0.733		

- Renewable Energy (logENR): The significant negative relationship (Coef = -0.309) suggests a short-term trade-off. This is potentially explained by a temporal misalignment where financial and political resources are primarily allocated to the demanding energy transition, temporarily diverting investments away from industrial digitalization. Furthermore, the intermittency of RE sources may pose technical barriers to I4.0 technologies requiring stable power supply.
- Population (logPOP): A significant negative effect (Coef.= -2.147) indicates that in developed nations, greater population size, and associated institutional inertia, can slow I4.0 diffusion. Conversely, less populous developed countries may adopt automation faster due to acute labor constraints.
- Economic Growth (logCE): A positive association (Coef. = 0.033) confirms I4.0's role as a driver of productivity gains and competitiveness in developed economies, enabling new models like servitization and mass customization.
- CO_2 Emissions (logCO_2): The variable is not statistically significant. This is likely due to high collinearity and the fact that, in developed countries, strong environmental policies often lead to the decoupling of industrial growth from carbon emissions.

B. Determinants of I4.0 Adoption in Developing Countries (Dynamic GMM Model)

The GMM dynamic estimation confirmed strong path-dependence in I4.0 adoption, with the lagged I4.0 variable (L.I40) being highly significant (Coef. = 0.688; $p < 0.001$). The key findings focus on the direct and interaction effects (Table II):

Direct Effects: The direct effects of RE and CO_2 emissions are not individually significant.

Interaction Effect (CO_2#ENR): The interaction term is positive and significant (Coef. = 0.011; $p = 0.039$). This crucial finding implies that the marginal impact of industrial activity on I4.0 adoption increases in tandem with higher renewable energy penetration. RE deployment thus facilitates industrial growth compatible with digital transition by mitigating the environmental constraints typically associated with rapid industrialization. This underscores the essential role of the energy mix in supporting technological modernization in LDCs.

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TABLE II : GMM AND FIXED EFFECTS MODEL WITH INTERACTION TERM - ESTIMATION RESULTS

Variable	**Dynamic Model (GMM) Coeff. (p-value)**	**Interaction Model (Fixed Effects) Coeff. (p-value)**
L.I40	0.688***(0.000)	-
ENR	-0.0022 (0.855)	-0.0290 (0.249)
c.CO_2#c.ENR	-	0.0110** (0.039)

V. V. CONCLUSION AND POLICY IMPLICATIONS

These findings highlight the need for tailored and integrated policy strategies. Developed countries should manage short-term trade-offs to reinforce long-term synergies between Industry 4.0 and the energy transition. Developing countries ought to prioritize technological adoption and align digital industrialization with renewable energy deployment to support sustainable digital growth. Policies must combine investments in digital infrastructure with context-specific sustainable development measures, positioning Industry 4.0 as a key driver of economic growth aligned with global decarbonization objectives. Future research should employ larger panels and more direct indicators of digital transformation.

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