FROM INDUSTRY 4.0 TO 6.0: A BUSINESS INTELLIGENCE PARADIGM SHIFT IN THE LATIN AMERICAN AND CARIBBEAN RENEWABLE ENERGY SECTOR

DE LA INDUSTRIA 4.0 LA 6.0: O SCHIMBARE DE PARADIGMĂ ÎN INTELIGENȚA AFACERILOR ÎN SECTORUL ENERGETIC REGENERABIL DIN AMERICA LATINĂ ȘI CARAIBE

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Abstract: *This study examines the transition from Industry 4.0 to 6.0 within the renewable energy sector of Latin America and the Caribbean. Using a cross-sectional, quantitative design with a survey of 60 companies, the research maps 15 items onto four key dimensions. Findings reveal a primary focus on technical capabilities (I4.0) and a recognized yet unevenly implemented human dimension (I5.0). Critically, a significant gap exists in the regenerative vision (I6.0), while systemic barriers in policy and investment are identified as the main constraints to a comprehensive digital and sustainable transformation.*

Keywords: industrial revolutions, renewable energy sector, Latin America and the Caribbean, business intelligence

Rezumat: *Acest studiu examinează tranziția de la Industria 4.0 la 6.0 în sectorul energiei regenerabile din America Latină și Caraibe. Folosind un design transversal, cantitativ și un sondaj aplicat pe 60 de companii,*

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cercetarea mapează 15 itemi pe patru dimensiuni cheie. Constatările relevă un accent primar pe capabilitățile tehnice (I4.0) și o dimensiune umană (I5.0) recunoscută, dar implementată inegal. În mod critic, există un decalaj semnificativ în viziunea regenerativă (I6.0), în timp ce barierele sistemicile în politică și investiții sunt identificate ca principalele constrângeri ale unei transformări digitale și durabile cuprinzătoare.

Cuvinte cheie: revoluțiile industriale, sectorul energiei regenerabile, America Latină și Caraibe, inteligența afacerilor.

1. Introduction

The transition from traditional manufacturing paradigms to contemporary industrial models has evolved through successive stages—namely Industry 4.0, 5.0, and the emerging Industry 6.0. Although these frameworks share conceptual continuity, each presents distinct technological orientations and strategic priorities. Industry 4.0 is primarily defined by the convergence of digital and physical systems through large-scale deployment of cyber-physical systems, the Internet of Things (IoT), big data analytics, and advanced automation, all aimed at optimizing production efficiency and operational reliability [1]. Industry 5.0, in turn, emerges as a complementary yet corrective evolution of this paradigm. While building on the digital infrastructure of I4.0, it shifts focus toward human–machine collaboration, social resilience, and sustainability, emphasizing the integration of ethical and human-centric values within industrial ecosystems [2]. Industry 6.0—still in its formative conceptual stage—envisions a hyperconnected industrial ecosystem characterized by augmented autonomy, contextual intelligence, and explicit objectives of ecological regeneration and inclusive prosperity. Within this framework, virtualization and extreme customization coexist with systemic sustainability criteria [3]. In essence, Industry 4.0 prioritizes digitalization and technical efficiency; Industry 5.0 restores balance by embedding human and societal purpose; and Industry 6.0 projects an advanced synthesis of autonomous intelligence, ecology, and collective well-being.

Within the energy sector, these industrial evolutions have profoundly transformed both infrastructure and operational models. Early instances of digital integration—such as remote metering, supervisory control and data acquisition (SCADA), and automated control systems—enhanced reliability, efficiency, and safety across generation and distribution processes. The widespread adoption of Industry 4.0 technologies, including IoT, digital twins, and machine learning, has further enabled real-time optimization of energy production, integration of renewable sources, and advanced demand-side management, thereby reducing operational costs and systemic losses [4]. Comparative studies indicate that digitalization in the energy sector accelerated significantly between 2017 and 2020, and over the last five years, it has evolved from isolated pilot projects to sector-wide applications that impact production, distribution, and consumption. This trajectory underscores the indispensable role of digital capabilities in addressing challenges associated with renewable integration, regulatory compliance, and emission reduction.

More recently, the pace of transformation has intensified. Updated reviews reveal a growing emphasis on smart grids, demand response, and decentralized energy platforms supported by artificial intelligence, blockchain, and digital twin technologies. These innovations facilitate both large-scale renewable integration and the emergence of more flexible, participatory energy markets [3,5]. Concurrently, the Industry 5.0 paradigm introduces a human-centric agenda, highlighting the importance of developing skilled labor, promoting social equity, and incorporating ethical design in digitalized energy systems. Meanwhile, the nascent vision of Industry 6.0 advances the goal of embedding ecological regeneration and circular economy principles directly into energy system design. Collectively, these advances position the energy sector as a strategic enabler of the transition toward intelligent and sustainable economic models that couple technological progress with environmental and social responsibility.

Finally, the synergistic interplay among Industries 4.0, 5.0, and 6.0 serves as a cornerstone for achieving a smart, sustainable energy economy. The technical foundations of Industry 4.0 provide the infrastructure for data-driven automation and operational optimization. The governance and human-centric principles of Industry 5.0 ensure inclusivity, social acceptance, and resilience. Meanwhile, the systemic perspective of Industry 6.0 aligns innovation with planetary boundaries and long-term regenerative objectives. Together, these industrial paradigms enable the design of enterprise automation roadmaps that enhance efficiency and competitiveness while anchoring energy transformation within measurable environmental and social frameworks—an essential condition for achieving a legitimate, equitable, and durable energy transition in the twenty-first century.

2. Literature Review

Recent research on digitalization and emerging industrial waves in the energy sector demonstrates rapid, albeit uneven, progress between developed and developing countries. In this context, In this context, a systematic review of digitalization in energy production, distribution, and consumption was presented, describing a comprehensive set of technologies—including the Internet of Things (IoT), advanced metering infrastructure (AMI), distributed control systems, and digital twins [4]. The authors emphasize that most mature adoptions are concentrated in advanced economies, where investment and regulatory frameworks enable large-scale implementation of these innovations. While this study provides a robust and methodologically rigorous diagnosis using the PRISMA approach, its main limitation lies in the scarce empirical evidence regarding impacts in contexts with low institutional capacity, which complicates extrapolation to developing countries.

Complementarily, an update on the state-of-the-art on smart grids, artificial intelligence (AI), and demand-response mechanisms, highlighting that advanced data architectures and algorithms enhance operational efficiency and flexibility in networks with high penetration of renewable energy sources, was presented [5]. This research contributes significant technical advantages in forecasting and optimization; however, its applicability relies on the presence of robust communication infrastructures and effective cybersecurity systems—conditions that remain challenging in regions with limited connectivity.

Other studies further explore the use of digital twins for simulation, predictive maintenance, and the management of renewable intermittency [6,7]. These approaches enable reduced downtime and virtual testing of virtual power plants (VPPs) and storage systems. Nevertheless, their main drawbacks include high computational costs and the necessity for precise physical models. In emerging countries, the lack of high-quality data and specialized modeling personnel limits effective implementation. Additionally, although technically rigorous, these studies lack standardized economic frameworks to facilitate comparative cost–benefit evaluations across different regulatory environments.

Moreover, the application of machine learning (ML) in combination with Battery Energy Storage Systems (BESS) to optimize renewable integration has been analyzed [8]. Their scientifically rigorous study demonstrates that this synergy enhances system stability and reduces energy curtailment. However, technical challenges persist, particularly concerning model robustness against noisy data and the limited interpretability of algorithms. Furthermore, the high capital expenditure (CAPEX) for batteries remains a critical barrier to adoption in financially constrained economies.

Regarding developing countries, the adoption of decentralized smart grids—such as solar microgrids and community VPPs—and off-grid models has been addressed [9,10]. These solutions are characterized by modularity, local empowerment, and contributions to energy resilience. Nevertheless, many studies are based on low-replicability pilot cases, without longitudinal evaluations to confirm economic sustainability or institutional governance feasibility. Consequently, literature focusing on the Global South is more applied but less generalizable from a scientific perspective.

Similarly, the role of IoT and green policies in smart grid sustainability has been investigated [11,12]. Both studies highlight that the combination of IoT with regulatory incentives can significantly accelerate decarbonization processes. However, they caution against risks associated with data privacy and cyberattack exposure, especially when security measures are not integrated from the design phase. Interoperability between legacy systems and new technological platforms also remains a critical technical challenge.

Also, the impact of AI on renewable energy integration, providing evidence of its potential to improve forecasting and operational performance in energy systems, was analized in deep [13]. Despite benefits such as increased reliability and reduced variable costs, these models exhibit weaknesses related to dependence on historical data and lack of explainability, which hinder their integration into dynamic regulatory and commercial frameworks.

Collectively, the literature reveals three major gaps. First, an absence of comparative studies quantifying the socioeconomic benefits of Industry 4.0, 5.0, and 6.0 under different regulatory contexts. Second, the scarcity of methodologies that translate Industry 5.0 principles (human-centric approach) and Industry 6.0 principles (regenerative sustainability) into technical metrics and Key Performance Indicators (KPIs) applicable to the energy sector. Finally, there is limited assessment of cybersecurity and governance in large-scale deployments, particularly in countries with low institutional capacity.

In summary, scientific evidence indicates that Industry 4.0 provides the technical foundation for energy digitalization, Industry 5.0 introduces a human-centered governance framework, and Industry 6.0 offers an integrated vision oriented toward systemic sustainability. Nevertheless, the development of a smart and sustainable economy requires advancing comparative research, socioeconomic impact assessments, and the design of technical protocols tailored to the realities of developing countries, thereby ensuring that the global energy transition is truly inclusive, resilient, and equitable.

3. Method

The study employs an empirical-quantitative, cross-sectional, descriptive-analytical design to evaluate the challenges and opportunities associated with the digitalization of the energy sector in Latin America and the Caribbean (LAC). Conceptually, the investigation is grounded on the three pillars of the Energy Trilemma proposed by the World Energy Council (2023): energy security, equity/accessibility, and environmental sustainability. The sample consisted of 60 energy sector companies, selected through purposive sampling to ensure representation of generators, distributors, retailers, network operators, and renewable energy projects across key countries in the region. Within each organization, a single informant holding a first- or second-level managerial position (e.g., managers, directors, department heads) was contacted due to their operational and strategic knowledge regarding digital transformation.

Data collection was conducted via a structured digital survey administered between January and May 2025. Before deployment, the instrument underwent content validation by an expert panel comprising public sector representatives (regulators and energy agencies) and private sector stakeholders (executives and consultants) in Mexico. Their feedback allowed for refinement of item wording, relevance, and thematic coverage, as well as confirmation of alignment with the Energy Trilemma dimensions. Voluntary participation, informed consent, and response anonymity were ensured to protect organizational confidentiality.

The survey comprised 15 closed-ended items (statements, S) using a 5-point Likert scale (1 = Strongly disagree; 5 = Strongly agree). Organizational sociodemographic variables were also collected, including company type, country, size (number of employees), and self-reported digital maturity. The final response rate was 100% (all 60 contacted companies), facilitated by personalized follow-ups via email and confirmation calls. Descriptive statistics, including means, standard deviations, and percentage agreement, were computed for each dimension. Within a Likert scale framework, the percentage agreement metric represents the proportion of respondents who selected a positive response, typically defined as the combined frequencies of "agree" and "strongly agree" categories.

Complementary qualitative analyses were also incorporated, including optional open-ended survey comments and a validation round of key findings with the expert panel to ensure triangulation and regional contextualization. Recognized limitations include self-report bias, the purposive nature of the sample, and regulatory heterogeneity among countries; nonetheless, the approach provides valuable comparative evidence to inform automation roadmaps that consider security, equity, and sustainability in the region.

Survey Instrument (15 closed-ended items — Likert scale 1–5)
Instruction: Please indicate your level of agreement with each statement (1 = Strongly disagree; 5 = Strongly agree).

S1. Our company has a formal digital strategy aligned with sustainability objectives.
S2. Technological advancements (IoT, digital twins, AI) have improved the operational security of our facilities.
S3. The adoption of digitalized technologies has reduced operational costs over the past three years.
S4. The integration of renewable energy is facilitated by our data-driven prediction and management capabilities.
S5. We possess the communication infrastructure necessary to deploy Industry 4.0 solutions at scale.
S6. Cybersecurity represents a significant barrier to accelerating digitalization in our organization.
S7. Our organization incorporates equity and accessibility criteria into digitalization projects (e.g., social impact, tariffs).
S8. Human-machine collaboration (Industry 5.0) has improved productivity and employee well-being in our company.
S9. We have internal talent with the analytical and modeling capabilities required for digital twins and machine learning.
S10. Investment costs (CAPEX) in storage and digitalization limit the implementation of large-scale solutions.
S11. Regulatory or public policy incentives in our country favor sustainable digitalization.

S12. Our company systematically evaluates the environmental impact of its digital projects.
S13. The digital solutions we implement are interoperable with legacy infrastructure.
S14. We participate in regional initiatives or public-private collaborations to accelerate the transition to a smart and sustainable economy.
S15. I consider the Industry 6.0 vision (regenerative approach) relevant and applicable to our business model over the next decade.

The 15 survey items were mapped onto four distinct dimensions, defined as follows:

- Technical_I4.0: Pertains to digital infrastructure and strategy—including IoT, AI, and digital twins—aimed at enhancing security, operational efficiency, and cost reduction.
- Human_I5.0: Focuses on human-machine collaboration that prioritizes employee well-being, productivity, equity, and the development of in-house talent.
- Regenerative_I6.0: Reflects a corporate vision that systematically evaluates and prioritizes environmental impact and regenerative principles within digital projects
- Barriers_Policy: Encompasses challenges such as cybersecurity risks, high capital investment, and regulatory frameworks that hinder the large-scale implementation of digital solutions.

4. Results and discussions

The allocation of companies across the selected countries reflects prevailing market realities and their World Energy Council Trilemma rankings. Brazil, owing to its market size and energy diversity, constitutes the largest subset of the sample (10 companies). In contrast, nations with more limited market capacity, such as Nicaragua and Honduras, are represented by a single company each. Countries with high Trilemma performance and stable regulatory ecosystems, namely Chile and Uruguay, exhibit a relatively significant presence (6 and 3 companies, respectively), thereby enabling the capture of more representative perceptions on digitalization and sustainability.

This sample distribution facilitates a comparative analysis between mature and emerging markets, allowing for statistical contrasts. A limitation, however, exists for countries with a small sample size ($n \leq 2$), where statistical inference will be constrained.

In terms of sampling design, a balance between representativeness and feasibility was prioritized. This approach resulted in greater representation from strategic markets (e.g., Brazil, Chile, Argentina, Colombia, Peru), while maintaining a minimal coverage in smaller economies. This strategy preserves regional heterogeneity without allowing any single market to dominate the sample. This allocation pattern is consistent with the disparities in financial capacity, infrastructure, and regulatory frameworks documented by the World Energy Council (WEC).

Table 1. **Number of companies per country**

Country	Number of companies	Country	Number of companies
Uruguay	3	Paraguay	2
Chile	6	El Salvador	2
Argentina	5	Bolivia	2
Costa Rica	3	Guatemala	3
Brazil	10	Dominican Republic	3
Ecuador	4	Jamaica	2
Panama	3	Nicaragua	1
Peru	5	Honduras	1
Colombia	5		

All survey items/statements were systematically mapped onto four dimensions corresponding to the most relevant aspects of the different industrial revolutions. The classification of each item is detailed in Table 2. It should be noted that, due to their inherent nature, certain items are associated with multiple dimensions. This multi-dimensional assignment was, in fact, a final recommendation following the instrument validation process.

Table 2. **Alignment of assessment criteria with sustainability and digitalization dimensions**

Dimension	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Technical_I4.0		☑	☑	☑	☑				☑				☑		
Human_I5.0	☑						☑	☑				☑		☑	
Regenerative_I6.0	☑										☑				☑
Barriers_Policy					☑	☑				☑			☑		

Table 3 presents the statistical results for all countries, disaggregated by dimension. The ranking indicates that the technical dimension (I4.0) achieved the highest mean score. This finding is consistent with the operational prioritization observed in energy companies, where investments in IoT, predictive analytics, and automation are typically among the first to be implemented. The human-centric dimension (I5.0) ranks second, suggesting that organizations acknowledge the importance of human factors and governance in their digital initiatives, albeit at a slightly lower priority than technical capabilities.

The regenerative dimension (I6.0) exhibits moderate scores, indicating that a systemic and regenerative vision has not yet been fully translated into concrete actions across the region. This is likely attributable to regulatory limitations and resource constraints. Finally, the policy and barriers dimension recorded the lowest mean score, which aligns with the recognition that obstacles such as cybersecurity, CAPEX, and interoperability are perceived as significant impediments to progress.

In summary, while companies prioritize the development of technical capabilities and value the human component, they face regulatory and financial limitations that hinder the transition towards regenerative business models.

Table 3. **Descriptive statistics of digitalization and sustainability dimensions**

Dimension	**Mean**	**Standard deviation**	**Number of items/ statements**
Technical_I4.0	3.92	0.28	6
Human_I5.0	3.83	0.31	5
Regenerative_I6.0	3.62	0.24	3
Barriers Policy	3.45	0.19	4

The statistical results for each country, corresponding to the dimensions assessed by the data collection instrument, are presented in Tables 4 through 7. In particular, countries with the highest positioning in the Trilemma (Chile, Uruguay, Costa Rica) exhibit elevated mean scores in the technical dimension (≥4.0) and high agreement percentages (≥0.67–1.00), suggesting a convergence between regulatory capacity, investment, and organizational perceptions of I4.0. In contrast, lower-performing nations (Nicaragua, Honduras, Paraguay) demonstrate lower technical means (≈2.5–3.0) and markedly low agreement proportions, reflecting constraints in infrastructure and financing. The humanistic dimension (I5.0) is relatively homogeneous across intermediate and advanced countries, indicating that concerns for governance and human capital are prevalent across different contexts; however, their practical implementation varies. The regenerative dimension (I6.0) achieves moderate averages in mature markets, implying that while the vision is present, it has not yet been uniformly translated into concrete actions. Finally, the metrics on barriers reveal that issues such as cybersecurity and CAPEX are universally perceived as limiting factors, albeit with greater intensity in economies with a lower Trilemma ranking. These findings suggest that targeted public policies and directed financing could mitigate the regional gap.

Table 4. **Descriptive statistics of the Technical_I4.0 dimension**

Country	n	Technical_I4.0_mean	Technical_I4.0_std	Technical_I4.0_%_agree
Uruguay	3	4.17	0.27	0.67
Chile	6	4.36	0.18	1
Argentina	5	3.5	0.26	0
Costa Rica	3	3.83	0.14	0.33
Brazil	10	3.87	0.35	0.5
Ecuador	4	3.71	0.07	0
Panama	3	3.78	0.16	0.33
Peru	5	3.67	0.15	0
Colombia	5	3.73	0.34	0.4
Paraguay	2	2.67	0	0
El Salvador	2	3.08	0.25	0
Bolivia	2	3	0.17	0
Guatemala	3	3.22	0.52	0
Dominican Republic	3	3.56	0.21	0
Jamaica	2	2.92	0.08	0
Nicaragua	1	3	0	0
Honduras	1	2.17	0	0

Table 5. **Descriptive statistics of the Human_I5.0 dimension**

Country	n	Human_I5.0_mean	Human_I5.0_std	Human_I5.0_%_agree
Uruguay	3	4.07	0.34	0.67
Chile	6	4.4	0.28	1
Argentina	5	3.8	0.33	0.6
Costa Rica	3	4.2	0.28	0.67
Brazil	10	3.64	0.32	0.2
Ecuador	4	3.7	0.3	0.25
Panama	3	3.8	0.43	0.67
Peru	5	3.56	0.23	0
Colombia	5	3.72	0.2	0.2
Paraguay	2	3	0.4	0
El Salvador	2	3.1	0.3	0

Bolivia	2	3.4	0	0
Guatemala	3	2.8	0.16	0
Dominican Republic	3	3.2	0.43	0
Jamaica	2	3.1	0.3	0
Nicaragua	1	2.6	0	0
Honduras	1	2.8	0	0

Table 6. **Descriptive statistics of the Regenerative_I6.0 dimension**

Country	n	Regenerative_I6.0_mean	Regenerative_I6.0_std	Regenerative_I6.0_%_agree
Uruguay	3	4.22	0.31	1
Chile	6	4.56	0.25	1
Argentina	5	3.6	0.13	0
Costa Rica	3	4	0	1
Brazil	10	3.77	0.47	0.4
Ecuador	4	3.33	0.24	0
Panama	3	4	0.47	0.67
Peru	5	4	0.42	0.8
Colombia	5	3.8	0.27	0.6
Paraguay	2	3.17	0.17	0
El Salvador	2	3.5	0.5	0.5
Bolivia	2	3.5	0.5	0.5
Guatemala	3	3	0.27	0
Dominican Republic	3	3.11	0.57	0
Jamaica	2	3	0.33	0
Nicaragua	1	3	0	0
Honduras	1	3	0	0

Table 7. **Descriptive statistics of the Barriers_Policy dimension**

Country	n	Barriers_Policy_mean	Barriers_Policy_std	Barriers_Policy_%_agree
Uruguay	3	4	0	1
Chile	6	4.33	0.24	1
Argentina	5	3.45	0.19	0
Costa Rica	3	3.83	0.31	0.33
Brazil	10	3.92	0.28	0.5
Ecuador	4	3.62	0.22	0
Panama	3	3.92	0.47	0.67
Peru	5	3.5	0.42	0.2
Colombia	5	3.85	0.2	0.2
Paraguay	2	2.88	0.12	0
El Salvador	2	3.12	0.38	0

Bolivia	2	3.62	0.12	0
Guatemala	3	3.25	0.35	0
Dominican Republic	3	3.5	0.2	0
Jamaica	2	3	0	0
Nicaragua	1	3	0	0
Honduras	1	2.5	0	0

Research findings

Operational efficiency is the primary focus. The technical dimension (Industry 4.0) received the highest mean score (3.92), indicating that firms prioritize investments in digital infrastructure. This suggests a tactical emphasis on achieving immediate gains in operational efficiency and security, potentially at the expense of longer-term strategic sustainability goals associated with more advanced industrial paradigms.

A gap exists in the regenerative vision. The Industry 6.0 dimension recorded the lowest average score (3.62). This result indicates that the principles of a regenerative approach and systematic environmental assessment have not yet been effectively translated into concrete corporate practices, revealing a significant conceptual and practical barrier to establishing truly sustainable business models in the region.

Trilemma performance correlates with technological adoption. Countries with higher Energy Trilemma rankings, such as Chile and Uruguay, demonstrated superior scores in the technical dimension (≥4.0). This correlation underscores that robust regulatory frameworks and institutional stability are critical enablers for the successful adoption and positive perception of digitalization initiatives.

Systemic barriers are a universal constraint. The Barriers and Policy dimension was ranked the lowest overall (3.45). Pervasive challenges, including cybersecurity risks, high CAPEX, and inadequate regulatory frameworks, are perceived as critical impediments. These barriers collectively hinder the large-scale digital transition and perpetuate regional heterogeneity in technological capabilities.

The human dimension is recognized but inconsistently implemented. While the human-centric dimension (Industry 5.0) achieved the second-highest score (3.83), signaling an awareness of the importance of human-machine collaboration, its implementation is uneven across the region. More mature markets show stronger adoption, revealing persistent challenges in operationalizing human-centric governance and developing the necessary internal talent pipeline.

5. Implications and limitations

Research implications

The findings carry significant implications across technical, economic, social, and environmental domains, providing a roadmap for stakeholders.

Technical implications: The results underscore the necessity of developing technological architectures that are not only efficient but also interoperable and cyber-resilient. The high perception of technical barriers suggests that modular, "plug-and-play" solutions capable of integrating with legacy infrastructure are essential for scalable adoption. Furthermore, the relative weakness of the I6.0 dimension indicates a lack of standardized tools for measuring and managing the environmental impact of digital projects, highlighting a critical area for the development of specialized software and life-cycle assessment protocols.

Economic implications: The identification of high CAPEX and insufficient policy incentives as primary constraints calls for a re-evaluation of financing models. This involves promoting risk-sharing investment mechanisms, patient capital funds for green enabling technologies, and blended finance schemes. For firms, the results justify strategic investments in digitalization by quantifying its association with operational cost reduction, while for governments, they highlight the significant economic cost of regulatory inaction.

Social implications: The acknowledged yet uneven implementation of the human dimension (I5.0) implies an urgent need for targeted upskilling and reskilling programs in digital and analytical competencies. Closing the talent gap is crucial to preventing labor exclusion and ensuring an equitable digital transition. Moreover, integrating equity and accessibility criteria into digital projects, though nascent, is vital to prevent the exacerbation of energy poverty and to ensure the benefits of the transition reach all societal segments.

Environmental implications: The identified gap in the regenerative vision has profound consequences. It suggests the LAC energy sector may be missing the opportunity to leverage digitalization to move beyond efficiency and toward the active regeneration of natural systems. This demands that firms formally integrate environmental impact assessments and circular economy principles into the life cycle of their digital projects, and that regulators develop frameworks that reward not only clean energy but also the sustainable management of digital resources and infrastructure.

Study limitations

This study is subject to several methodological constraints. First, the purposive, non-probabilistic sampling design, while strategic for capturing diverse sector actors, limits the statistical generalizability of the findings to the entire population of energy firms in LAC. The overrepresentation of larger markets like Brazil and minimal presence in smaller economies may skew aggregate means, potentially underestimating the severity of challenges in more vulnerable contexts. Second, reliance on self-reported data from a single informant per firm introduces risks of social desirability bias and a potentially optimistic or centralized view of digital maturity that may not reflect operational realities across the organization. The significant regulatory and market heterogeneity across the 17 included countries further complicates the establishment of direct causal relationships, as the results aggregate perceptions from environments with profoundly different incentives and barriers. Finally, the cross-sectional nature of the research provides a snapshot in time, precluding analysis of the temporal evolution of perceptions and digital maturity, which is crucial for understanding a dynamic transition such as the digital-energy nexus.

6. Conclusions

This research provides a critical assessment of the digital paradigm shift in the LAC renewable energy sector, revealing a strategic imbalance. While the sector demonstrates maturity in adopting Industry 4.0 technologies for operational efficiency, it lags in integrating the human-centric principles of Industry 5.0 and, most notably, the regenerative vision of Industry 6.0. The universal perception of systemic barriers—cybersecurity, high CAPEX, and inadequate policy—highlights a fragile foundation for a truly smart and sustainable energy economy. The correlation between national Energy Trilemma performance and technological adoption scores underscores that institutional strength is a prerequisite for successful digitalization.

To address these gaps, future work must focus on three fronts. First, developing integrated policy frameworks that simultaneously incentivize technological investment, human capital development, and regenerative outcomes. Second, creating standardized metrics and Key Performance Indicators (KPIs) to quantify the socio-environmental impact of digital projects, thereby translating the I5.0 and I6.0 visions into actionable corporate strategies. Finally, longitudinal and comparative studies are essential to track the evolution of these dimensions and to design context-specific roadmaps that account for the region's significant heterogeneity. Advancing on these fronts is imperative to ensure the region's energy transition is not only digital but also inclusive, resilient, and genuinely sustainable.

R E F E R E N C E S

[1] *N. Bhagwan, M. Evans,* "A review of Industry 4.0 technologies used in the production of energy in China, Germany, and South Africa," Renewable and Sustainable Energy Reviews, 173, Article 113075, 2023. https://doi.org/10.1016/j.rser.2022.113075

[2] *M. Ghobakhloo, M. Iranmanesh, M.-L. Tseng, A. Grybauskas, A. Stefanini, A. Amran,* "Behind the definition of Industry 5.0: A systematic review of technologies, principles, components, and values," Journal of Industrial and Production Engineering, Vol. 40, no. 6, pag. 432–447, 2023.

[3] *A. S. Duggal, P. K. Malik, A. Gehlot, R. Singh, G. S. Gaba, M. Masud,* "A sequential roadmap to Industry 6.0: Exploring future manufacturing trends," IET Communications, Vol. 16, no. 5, pag. 521–531, 2022. https://doi.org/10.1049/cmu2.12284

[4] *C.-P. Simion, C.-A. Verdeș, A.-A. Mironescu, F.-G. Anghel*, "Digitalization in energy production, distribution, and consumption: A systematic literature review," Energies, Vol. 16, no. 4, pag. 1960, 2023. https://doi.org/10.3390/en16041960

[5] *M. Mahmood, P. Chowdhury, R. Yeassin, M. Hasan, T. Ahmad, N.-U.-R. Chowdhury,* "Impacts of digitalization on smart grids, renewable energy, and demand response: An updated review of current applications," Energy Conversion and Management: X, Vol. 24, 2024. https://doi.org/10.1016/j.ecmx.2024.100790

[6] *J. V. S. do Amaral, C. H. dos Santos, J.A.B Montevechi, A.R. de Queiroz*, "Energy digital twin applications: A review," Renewable and Sustainable Energy Reviews, Vol. 188, 2023. https://doi.org/10.1016/j.rser.2023.113891

[7] A. Aghazadeh Ardebili, M. Zappatore, A.I.H. Attia Ramadan, A. Longo, A. Ficarella, "Digital twins of smart energy systems: A systematic literature review," Energy Informatics, Vol. 7m no. 1, pag. 1–62, 2024. https://doi.org/10.1186/s42162-024-00385-5

[8] *M. Kiasari, M. Ghaffari, H.H. Aly,* "A Comprehensive Review of the Current Status of Smart Grid Technologies for Renewable Energies Integration and Future Trends: The Role of Machine Learning and Energy Storage Systems," Energies, Vol. 17, no. 16, pag. 4128, 2024. https://doi.org/10.3390/en17164128

[9] *M. J. B. Kabeyi, O.A. Olanrewaju,* "Smart grid technologies and application in the sustainable energy transition: a review," International Journal of Sustainable Energy, Vol. 42, no. 1, pag. 685–758, 2023.

[10] *C. P. Ohanu, S.A. Rufai, U.C. Oluchi,* "A comprehensive review of recent developments in smart grid through renewable energy resources integration," Heliyon, Vol. 10, no. 3, 2024. https://doi.org/10.1016/j.heliyon.2024.e25705

[11] *C. S. Ball*, "IoT implementation for energy system sustainability," Utilities Policy, Vol. 90, 2024. https://doi.org/10.1016/j.jup.2024.101769

[12] *P. Campana, C. Riccardo, R. Ruggieri, C. Amendola,* "Smart Grids and Sustainability: The Impact of Digital Technologies on the Energy Transition," Energies, Vol. 18, no. 9, pag. 2149, 2025. https://doi.org/10.3390/en18092149

[13] *S. Algburi, S.S.A. Al Kareem, I.B. Sapaev, O. Mukhitdinov, Q. Hassan, D.H. Khalaf, F.I. Jabbar,* "The role of artificial intelligence in accelerating renewable energy integration: A review," Unconventional Resources, Vol. 8, 2025. https://doi.org/10.1016/j.uncres.2025.100229

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