

## RENEWABLE ENGINEERING AND SOCIAL TRANSFORMATION: IMPACT OF DIGITALIZATION AND AUTOMATION ON SUSTAINABLE DEVELOPMENT

Kimberlly Tatiana Ascencio Blanco<sup>1</sup>, Omar Eduardo Álvarez Huarca<sup>2</sup>,  
James Boonds Lázaro Osorio<sup>3</sup>, Christian Johnson Velasco Villavicencio<sup>4</sup>

<sup>1</sup>BRB Ingenieros

<sup>2</sup>Pontificia Universidad Católica del Perú

<sup>3</sup>Universidad Internacional de La Rioja (UNIR)

<sup>4</sup>Universidad Estatal de Milagro (UNEMI)

ORCID: <https://orcid.org/0000-0002-1710-168X>

kblanco@brb-ingenieros.com<sup>1</sup>

alvarezhuarca.95@gmail.com<sup>2</sup>

ing.jlazaroo@gmail.com<sup>3</sup>

cvelascov1@unemi.edu.ec<sup>4</sup>

### Summary

This study analyzes the intersection between renewable engineering, digitalization and automation, and how their synergy can promote social transformation towards sustainable development. Through a systematic review of recent literature (2020–2025), the technical mechanisms (smart control, smart grids, predictive analytics), the effects on energy efficiency and demand, as well as the social impacts —positive and risk— associated with technological adoption were identified. Benefits are evident in the integration of variable sources, operational optimization and cost reduction, but also challenges linked to equity, data governance and the energy demand of digital systems. Recommendations for public policies, participatory models and future research agenda focused on digital energy justice are proposed.

**Keywords:** energy digitalization; automation; renewable engineering; just transition; smart grids; energy equity.

### Introduction

Humanity faces an unprecedented challenge in the twenty-first century: to ensure economic and social development without compromising the ecosystems that support life. This challenge, embodied in the United Nations 2030 Agenda, has made **sustainable development** an articulating axis of global scientific and technological policies (United Nations, 2023). In this context, **renewable engineering** – which includes solar, wind, hydroelectric, geothermal, and biomass technologies – emerges as pillars of a low-carbon energy transition, aimed at reducing dependence on fossil fuels and mitigating climate change (Zarrad, Ben Mechichi, Bouattour & Helali, 2025).

However, the transition to sustainable energy systems does not depend only on the availability of renewable resources, but also on the **technological and societal capacity** to integrate them efficiently, equitably and resiliently. In this sense, **digitalisation** and **automation** represent the core of the new industrial and energy revolution. Technologies such as the Internet of Things (IoT), artificial intelligence (AI), *digital twins*, machine learning, data analytics, and automatic control of complex systems are radically transforming the way energy is produced, distributed, and consumed (Mahmood et al., 2024; Khan et al., 2024).

Recent literature highlights that the digitalisation of energy makes it possible to create smart grids, optimise consumption in real time and manage demand more flexibly (Mahmood, Chowdhury, Yeassin, Hasan & Islam, 2024). At the same time, automation—based on sensors, programmable controllers, and predictive algorithms—contributes to improving reliability, reducing losses, and extending the useful life of equipment, generating economic and environmental benefits (Afridi, Ahmad, & Hassan, 2021). These innovations not only increase technical efficiency, but also promote **new business models and energy governance**, in which consumers become "prosumers", actively participating in the generation and management of their own energy (From Digitalization to Renewable Energy, 2025).

Beyond the technical dimension, **energy digitalisation** has profound **social and cultural implications**. The incorporation of smart technologies in the energy sector redefines work, citizen participation and consumption patterns. According to Mondejar et al. (2021), digitalization can be a powerful tool to achieve the Sustainable Development Goals (SDGs), as long as it is approached from an inclusive approach that considers data equity, accessibility, and transparency. However, if it is not accompanied by training and technological justice policies, it can widen the **digital and energy divide**, marginalizing communities with fewer resources or infrastructure (Morrar, Zgheib & Kossai, 2024).

Intelligent **automation** also poses ethical and labor challenges. The replacement of human tasks by automated systems can generate structural unemployment if there are no training and retraining programs (Khan et al., 2024). On the other hand, opportunities are opening up for new jobs in data analysis, digital maintenance and energy cybersecurity. These transformations require coordinated public policies that guarantee a **just transition**, where technological innovation translates into shared well-being and not inequality (IRENA, 2024). On the other hand, the growing **interdependence between digitalization and the energy sector** introduces new vulnerabilities. The expansion of smart grids and connected systems increases exposure to cyberattacks, software failures, or data manipulation. Alsaigh, Mehmood, and Katib (2022) stress the need to incorporate **algorithmic governance** frameworks and transparency into automated decision-making, to ensure the reliability and public acceptance of these technologies.

Likewise, digitalization is not environmentally neutral: data centers, AI model training, and digital infrastructures consume increasing amounts of energy. The International Energy Agency (IEA, 2025) warns that electricity demand from the technology sector could double by 2035, so it is essential to ensure that such growth is supported by renewable sources and energy efficiency strategies.

Finally, the convergence between **renewable engineering, digitalization and automation** is an integral phenomenon that combines science, technology and social transformation. This process not only redefines physical infrastructures, but also social structures, cultural values, and forms of energy governance. Understanding its impact requires an interdisciplinary perspective that articulates engineering with social sciences and public policies, to guide the transition towards a **sustainable, equitable, and technologically responsible development** model (Bamisile, 2025; Wang, 2024).

For all of the above, this article aims to critically and systematically analyze the effects of digitalization and automation on renewable engineering, evaluating its potential to promote sustainability and social transformation. Through a recent scientific literature review (2020–

2025), it seeks to identify the most relevant technological advances, emerging social impacts, and strategies that can favor a **just, resilient, and sustainable** digital energy transition.

**Theoretical framework**

The theoretical framework of this article articulates the conceptual and empirical foundations to understand the confluence between digitalization, automation and renewable engineering, as well as its social implications. It is organized into six subblocks:

1. Energy digitalisation and renewable energies
2. Automation, AI and intelligent control
3. Industry 4.0 applied to the energy sector
4. Data governance, explainability, and security
5. Energy justice, digital divide and social transformation
6. Emerging challenges and tensions

**1. Energy digitalisation and renewable energies**

Digitalization in the energy sector refers to the use of digital technologies (IoT sensors, advanced metering, data platforms, connectivity, analytics) to optimize the operation, maintenance, control, and coordination of energy systems. Its critical function in the context of renewables is to absorb the variability inherent in sources such as solar and wind, and to enable adjusted decisions in real time (Energy digitalization: Main categories, applications, merits, and challenges, 2023) (see table 1).

A recent study by *Energies* documents that digitalization supports the diffusion of renewable energies through mechanisms such as monitoring, prediction, control, and optimization, but also points to barriers such as costs and security risks (Digitalization in the Renewable Energy Sector, 2024). Other econometric work in the European context confirms that the use of digitalisation reduces emissions and that the expansion of renewables accentuates these effects (Zarrad, Ben Mechichi, Bouattour & Helali, 2025).

In addition, a recent article in *ScienceDirect* on digital technologies for a net-zero future argues that these technologies can accelerate renewable integration, improve energy efficiency and facilitate new energy market models (Digital technologies for a net-zero energy future: A comprehensive review, 2024).

In short, digitalisation – correctly applied and governed – is an essential enabler for increasing the penetration of renewables, buffering variability and energising new distributed energy architectures.

**Table 1. Main digital applications in renewable energy systems**

<i>Digital Application</i>	<i>Function in renewable systems</i>	<i>Main benefit</i>	<i>Risks/barriers</i>
<i>IoT Sensors &amp; Advanced Metering</i>	Collect real-time data on generation, system status, environmental conditions	Improved operational visibility, early detection of failures	Cost of deployment, interoperability
<i>Analytics and big data platforms</i>	Processing large volumes of historical and real-time data	More accurate predictive models and behavioral analysis	Privacy, scalability
<i>Digital twins</i>	Virtual replication of the real system for	Scenario testing, optimization without real risk	Modeling complexity,

	simulations and planning		continuous updating
<i>Digital Control / Automation</i>	Adaptive control of inverters, dispatch	Quick response, operational flexibility	Robustness, latency, cybersecurity failures
<i>Blockchain / mercados P2P</i>	Distributed and decentralized record of energy transactions	Trust, decentralization, empowerment of prosumers	Scalability, market regulation

(Authors' elaboration based on synthesis of recent literature, e.g. Mahmood et al., 2024; *Digitalization in the Renewable Energy Sector, 2024*)

## 2. Automation, AI and intelligent control

Automation refers to the use of automatic systems—hardware, software, algorithms—to execute functions that were traditionally operated by humans. In the renewable energy context, automation manifests itself in adaptive control of generators, storage, grid switches, predictive maintenance, and adjustments in demand.

Recent research (Automation and Its Influence on Sustainable Development, 2025) quantifies the double dimension of automation: on the one hand, it increases productivity, improves energy efficiency, supports environmental innovation; on the other, it can exacerbate inequalities by eliminating low-skilled positions (Almusharraf, 2025). In the energy sector, the International Society of Automation (ISA) has published that automation "is critical to achieving global energy goals", as it allows for the optimization of production, transmission, demand control, and dynamic response (ISA Reinforces Critical Nature of Automation, 2024).

The intersection between AI and energy systems is particularly promising: deep learning models are employed for generation and demand forecasting, anomaly detection, dispatch planning, and operational optimization. A recent survey (Present and Future of AI in Renewable Energy Domain, 2024) lists nine AI strategies applied in renewables, from advanced regression to deep neural networks and hybrid algorithms (Rashid, Biswas, Gupta, et al., 2024).

Another relevant source is a paper on AI governance in energy: the lack of explainability and accountability mechanisms is a barrier to institutional acceptance of these intelligent systems (AI Explainability and Governance in Smart Energy Systems, 2022) (Alsaigh, Mehmood & Katib, 2022).

## 3. Industry 4.0 applied to the energy sector

The fourth industrial revolution (Industry 4.0) integrates technologies such as industrial IoT, cyber-physical systems, robotization, cloud analytics and advanced automation. In the energy sector, its application extends from plant operation to smart grids and maintenance.

A recent review by *Discover Sustainability* identified that Industry 4.0 technologies have enhancement effects on environmental sustainability across multiple industries, including the energy sector, but warns of risks if externalities such as system energy consumption or inequalities are not controlled (Shabur et al., 2024). Similarly, an article on integrating Industry 4.0 and sustainability highlights that, without proper planning, automated adoption

could exacerbate social gaps or produce counterproductive effects (Integrating industry 4.0 for enhanced sustainability: Pathways and governance, 2024).

In the specific energy sector, a recent article on energy digitalization points out how Industry 4.0 technologies apply to the deployment of renewables, grid control, and distributed operation (Digitalization of the energy sector, 2024).

#### **4. Data governance, explainability, and security**

Digitized energy systems generate and rely on large amounts of data: system status, user consumption, weather information, device performance. The governance of this data—who owns it, who uses it, who oversees it—is essential to ensure fairness, privacy, security, and trust.

The issue of explainability in energy AI has been addressed by Alsaigh et al. (2022), who highlight that many AI models are opaque "black boxes", which hinders their regulatory oversight and acceptance by operators and users (AI Explainability and Governance in Smart Energy Systems, 2022).

In addition, cybersecurity is a critical dimension: interconnected energy systems can be targets of attacks that compromise stability, privacy, or system integrity. The deployment of interoperability and security standards is a growing demand (ISA Reinforces Critical Nature of Automation, 2024).

An emerging innovation is *federated learning* applied to the energy sector: it allows collaborative AI models to be trained without sharing sensitive data. A recent study reviews applications of federated learning in renewable energy, pointing out its potential to preserve privacy and enable cooperation between actors (A review of federated learning in renewable energy applications, 2023) (Grataloup et al, 2023).

#### **5. Digital energy justice, divide and social transformation**

It is not enough to advance technologically: the energy transition must promote social justice. This is where concepts such as digital energy justice (equal access to digital infrastructure in energy systems), participation, community empowerment and gap mitigation come in.

A recent study in *Helyon* examines how workplace automation exacerbates energy poverty: by displacing jobs, it reduces the income of vulnerable households and makes it more difficult for them to cope with energy costs (Impacts of workplace automation on energy poverty, 2024). This evidence suggests that automation is not socially neutral: it can amplify the energy vulnerability of marginalized sectors.

Joint electrification and digitalization have been analyzed by a study that stresses that these forces are blurring the traditional boundaries between energy supply and demand, generating new socioeconomic challenges (Electrification and digitalization effects on sectoral energy demand, 2023).

In terms of business models, recent works examine how digitalization and renewable energies integrated into global value chains can promote sustainable development, although they also warn of possible capture effects and inequity in benefits (Connecting the sustainability: How renewable energy and digitalization, 2025).

#### **6. Challenges, emerging tensions and gaps**

Despite the potential, the literature points to critical tensions:

- **Energy rebound effect:** improvements in efficiency can induce greater use and a net increase in consumption (Automation and Its Influence on Sustainable Development, 2025) (Almusharraf, 2025)

- **Energy consumption of digital technologies:** data centers, data processing and transmission require electricity; if this is not renewable, it could counteract benefits (Sustainable Automation Trends Reshaping Industrial Energy Use, 2024).
- **Digital divide and inequality:** regions with less digital infrastructure may be excluded from the benefits of the digital energy revolution (Integrating Industry 4.0, 2024).
- **Technological obsolescence and dependency:** Rapid technological evolution can make expensive equipment obsolete and generate dependence on external suppliers.
- **Scalability and interoperability:** Many digital systems are not yet scalable or interoperable across platforms, restricting their widespread adoption.
- **Emerging regulatory governance:** Legal frameworks for energy data, algorithm ownership, fault accountability, and interoperability are just emerging.

These tensions point to the importance of adopting inclusive approaches, with a socio-technical vision (combining technology, institution and culture) and just transition policies.

### Methodology

The methodology of this article was designed based on rigorous literature review criteria, adopting elements of modified systematic reviews (or integrated reviews) to ensure transparency, reproducibility, and reduction of bias. We rely on recent guidelines on systematic review methodology and recent innovations in automating the review process.

### General methodological approach

This study corresponds to a **literature review with a systematic approach** (or rigorous integrative review), since the purpose is to synthesize technical and social evidence on digitalization, automation and renewable engineering. Although a statistical meta-analysis was not performed (due to heterogeneity of the studies), all the critical methodological steps of a systematic review, adapted for the interdisciplinary setting, were applied.

The adoption of explicit criteria, pre-protocols, and double review improves the quality of the review process (Brignardello-Petersen, Santesso, & Guyatt, 2024) and follows the recommendations of recent guidelines on systematic reviews (Guidelines for writing a systematic review, 2023).

The methodological steps are described below:

### Stages of the review process

<i>Stage</i>	<i>Description</i>	<i>Specific procedures</i>	<i>Tools/Quality Criteria</i>
<i>1. Problem definition and research questions</i>	Specify scope, objectives, key variables, and guiding questions	Questions are established (see Introduction) and core variables (digitalization, automation, social impacts)	Preparation of a preliminary protocol; use of the PRISMA guide for transparency
<i>2. Inclusion and exclusion criteria</i>	Define which studies will be considered	(a) Year of publication: 2020–2025; b) language: English or Spanish; c) type of research: reviews, empirical studies, rigorous technical reports; d) explicitly address	Record of the protocol or review plan (improves transparency)

		digital/automatic technologies in renewable energy or their social impact	
3. <i>Bibliographic search strategy</i>	Locate relevant studies across multiple sources	Use of keywords, Boolean operators, and thematic combinations ("digitalization AND renewable energy", "automation AND social impact", etc.) in databases such as Scopus, Web of Science, ScienceDirect, Google Scholar, and institutional repositories	We manually reviewed bibliography cited in key articles (reverse chain)
4. <i>Selection and sifting of studies</i>	Incremental study filtering	Independent double review of titles and abstracts, with reconciliation of discrepancies; then reading in full text. Reasons for exclusion were recorded (applying a similar structure to PRISMA)	Use of bibliographic management software (e.g. Zotero, Mendeley) and sieving support (e.g. Rayyan)
5. <i>Data extraction</i>	Collect relevant information from each study	Data extracted: author, year, country, type of digital/automatic technology, scale (plant, network, consumer), technical indicators, social results, limitations, recommendations	Structured spreadsheet template (Excel / Google Sheets) with standardized fields
6. <i>Assessment of quality or risk of bias</i>	Rate the robustness of the included studies	Application of adapted criteria for technical and social studies (methodological credibility, clarity of results, replicability)	Critical peer comparison; Use of adapted checklists
7. <i>Synthesis and thematic analysis</i>	Group results by dimensions and draw conclusions	Grouping into thematic axes (technical mechanisms, efficiency, social impacts, risks) and contrast between studies	Structured qualitative narrative and cross-comparisons
8. <i>Iterative feedback and validation</i>	Verification of coherence and complementarity	Internal review of the team, comparison of findings with recent work not initially found, iterative retro-searches	Record of adjustments to the initial protocol and transparency in the report

This approach is inspired by current methodological standards, which highlight the importance of explicit criteria, dual review, and transparent reporting (Brignardello-Petersen et al., 2024) and guidelines for writing a systematic review (Guidelines for writing a systematic review, 2023).

### **Methodological innovations and the use of automation**

To improve efficiency and reduce manual load, automation elements typified in recent revisions were integrated:

- **Machine learning (ML)-assisted filtering/text mining:** Some studies have used ML to classify articles as relevant or not based on pre-trained criteria (Sundaram & Berleant, 2022).
- **Support tools for text extraction and tagging:** Recent projects such as *SyROCCo* show how ML can assist in topic identification, relationships, and metadata extraction (Fang et al, 2024).
- **Iterative review with snowballing:** After the initial analysis, we consulted the reference lists of included articles to locate additional studies not captured in the initial searches.

These innovations made it possible to accelerate selection and labeling stages, while maintaining human oversight to control for errors and biases (e.g., human oversight of automatically generated labels), as recommended by recent guidance on effective reviews (Evidence-based research, 2024) (Lund & Pieper, 2024).

### **Validation of methodological results**

In order to ensure the quality of the process, the following strategies were applied:

1. **Duplicate review:** At least two authors independently performed the selection, extraction and critical evaluation, with reconciliation of differences through discussion or intervention of a third reviewer.
2. **Record of decisions and traceability:** A record of the flow of studies (including exclusion reasons) was kept following a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) scheme to ensure transparency in selection (PRISMA, n.d.).
3. **Prioritization of higher quality studies:** In interpretation, greater weight was given to works with greater methodological soundness (better design, clarity of report, replicability).
4. **Expert consultation:** After the preliminary analysis, key findings were validated with one or two experts in energy digitalization, to verify that relevant work or misinterpretations had not been overlooked.

### **Expected methodological limitations**

- Due to methodological heterogeneity (simulated models, case studies, qualitative reviews) it was not feasible to perform a quantitative meta-analysis.
- Although automation techniques were used for attendance, human supervision cannot completely eliminate risks of bias in the automatic classification of studies.
- The time constraint (2020–2025) may exclude recent emerging jobs that are not yet indexed.
- The language of publication (English/Spanish) rules out contributions in other languages.

- The quality and selection criteria, although explicit, contain a certain degree of research judgment, which can introduce interpretative biases.

## Results

This section presents the main findings organized into the following thematic axes: (a) technical integration and operation, (b) efficiency and demand, (c) social impacts and equity, and (d) emerging risks. Whenever possible, figures, percentages, or estimates drawn from recent literature are included to show comparative magnitudes.

### 1. Technical integration and operation of renewable systems

- A recent study by *Impacts of digitalization on smart grids, renewable energy, and demand response* documents that digital technologies contribute to improving grid flexibility, integrating better variable renewable sources and improving demand response (Mahmood et al, 2024).
- In *The role of digitalization in the impact of renewable energy on sustainable development in the Eurozone*, a PMG-ARDL model and GMM estimates were applied and it was found that a 1% increase in digitalization leads to a significant improvement in sustainable development, mediated by increased use of renewable energy (Zarrad et al, 2025).
- Another study, *Digitalization of renewable energy development*, used Bartik-type instrumental variables and robustness checks, and confirmed that digitalization has a positive effect on renewable energy development (Digitalization of renewable energy development, 2025).

**Table 1. Quantitative impacts reported in digitalization/operation literature (recent years)**

<i>Reference / Study</i>	<i>Measured variable</i>	<i>Observed magnitude/effect</i>	<i>Feedback</i>
<i>Mahmood et al. (2024)</i>	Network Flexibility/Demand Response	Improvement in renewables integration and demand response (qualitative results)	No exact percentage is reported in that study
<i>Zarrad et al. (2025)</i>	Digitalization → sustainable development	1% increase in digitalisation → significant positive effect on sustainability	Using PMG-ARDL and GMM
<i>Digitalization of renewable energy development (2025)</i>	Digitalization → renewable development	Positive Robust Effect After Robustness and Instrument Tests	Confirmation with instrumental variables

These results support the hypothesis that digitalization has a catalytic role for the integration of renewable sources and flexible operation of the electricity system.

### 2. Energy efficiency and demand management

- In the domestic sphere, a study on **smart home automation** (Data-Driven Smart Home Automation for Energy Efficiency, 2025) used data from four years of homes with connected devices and applied machine learning techniques. A reduction in

energy consumption was estimated at between 15% and 25% thanks to adaptive smart rules (AI + control) (Data-Driven Smart Home Automation, 2025).

- In large-scale buildings, the use of Building Automation Systems (BAS) has been widely documented. A review covering 143 articles indicated that these systems effectively contribute to energy and comfort management (Building automation systems for energy and comfort management in green buildings, 2023).
- In Europe, the *study Building Automation and Control Systems impact on EPC classes in Europe (2024)* reports that BACS can improve energy performance with relatively low costs: their implementation averages less than €10/m<sup>2</sup> in residential buildings and €7.5/m<sup>2</sup> in non-residential buildings. In addition, in those buildings where they are applied, it moves to higher energy classes according to energy performance certificates (EPC) (EUBAC, 2024).

**Table 2. Examples of efficiency achieved with intelligent automation/control**

<i>Context/Scale</i>	<i>Applied technology</i>	<i>Estimated savings/improvement</i>	<i>Source/comment</i>
<i>Smart homes</i>	AI + adaptive rules	15%–25% reduction in energy consumption	Data-Driven Smart Home Automation, 2025
<i>Green buildings</i>	BAS and climate control	Significant efficiency/comfort improvement	Review of 143 articles
<i>Residential/non-residential buildings</i>	BACS	Increase in EPC energy rating; Costs < 10 €/m <sup>2</sup>	EUBAC 2024

This data shows that automation and intelligent control have a measurable impact on energy efficiency, especially when the system can adapt its operation based on user behavior and system conditions.

### 3. Social impacts, equity and energy poverty

- A recent study, *Impacts of workplace automation on energy poverty (2024)*, looks at how automation in the workplace can affect energy affordability in homes. Although efficiency improves from a supply perspective, automation can reduce the income of vulnerable households and increase their vulnerability to energy costs (Impacts of workplace automation on energy poverty, 2024).
- In the broader area of economic development, *Automation and Its Influence on Sustainable Development (2025)* applied longitudinal data from 2000 to 2023. Their results quantify that automation increased labor productivity by 25%, reduced energy intensity (energy per unit of GDP) by 15%, and simultaneously increased the Gini index by 12%, suggesting growing income inequality (Ahlam, 2025).

**Table 3. Social indicators observed and estimated in recent literature**

<i>Social indicator</i>	<i>Observed/Estimated Change</i>	<i>Interpretation</i>	<i>Fountain</i>
<i>Labor Productivity</i>	+25 %	Automation improves production per worker	Ahlam (2025)

<i>Energy intensity (energy/GDP)</i>	-15 %	Greater energy efficiency with automation	Ahlam (2025)
<i>Gini Index</i>	+12 %	Rising income inequality	Ahlam (2025)
<i>Energy poverty (risk)</i>	Potential adverse impact on vulnerable households	Reduced income can hinder access to energy	Impacts of workplace automation, 2024

These results show that the social effects of automation are ambivalent: while there are efficiencies and productivity, there are also equity tensions that need to be mitigated through policies.

#### 4. Emerging risks and quantified trends

- In the field of AI and digital systems energy, Schneider Electric released a system dynamics model that projects scenarios of future electricity consumption attributed to AI. If not carefully managed, the growth of AI could increase the system's energy demand in the coming years (Schneider Electric, 2024).
- In the context of manufacturing, a study "The effects of industrial robots on firm energy intensity" (2024) analyzes how industrial robots impact the energy intensity of companies. Although its results are mixed, it indicates that some companies manage to reduce energy intensity through efficient robots, but others do not achieve net benefits depending on their production structure (The effects of industrial robots, 2024).
- In the field of digitalisation-renewables, *Connecting the sustainability: How renewable energy and digitalisation* (2025) analyses data from 20 countries with a high level of digital exports. It finds that increased digitalization is associated with decreases in emissions and a faster transition to clean energy, although it warns that the capture of benefits is not homogeneous (Connecting the sustainability, 2025).

**Table 4. Quantified or projected emerging risks**

<i>Risk/Trend</i>	<i>Projected/observed indicator</i>	<i>Key comments</i>	<i>Fountain</i>
<i>AI demand growth</i>	High electricity consumption scenarios	If AI grows without rules, it can increase energy load	Schneider Electric, 2024
<i>Energy Intensity in the Robotics Industry</i>	Reductions or stagnation depending on the company	Heterogeneous effects by sector and scale	The effects of industrial robots, 2024
<i>Emissions and digitalisation</i>	Correlated digitalization with lower emissions	Digitalization's role as a catalyst for transition	Connecting the sustainability, 2025

#### General synthesis of results

- Recent literature consistently suggests that digitalization has a catalytic effect on the integration and operation of renewable systems, reinforced by robust econometric evidence (Zarrad et al., 2025; Digitalization of renewable energy development, 2025).

- Intelligent automation and control systems achieve tangible energy efficiency improvements (15% to 25% in homes, building improvements).
- However, in the social sphere, challenging impacts are identified: automation can exacerbate inequality, affect the energy payment capacity of vulnerable households, and concentrate benefits if inclusive measures are not applied.
- Finally, emerging risks (AI energy load, heterogeneity of impacts, data governance) indicate that the deployment of these technologies must be accompanied by joint technical, social and regulatory planning.

### Conclusions

The convergence between **renewable engineering, digitalisation and automation** represents one of the most transformative pillars of the global energy transition. The literature review (2020–2025) confirms that these technologies, when implemented under inclusive and sustainable governance frameworks, can accelerate decarbonization, optimize operational efficiency, and improve socioeconomic resilience. However, its success depends on structural factors: digital infrastructure, coherent public policies, institutional capacities, and equity in access to technological innovation (Zarrad, Ben Mechichi, Bouattour & Helali, 2025; Mahmood et al, 2024).

Firstly, empirical evidence shows that **energy digitalisation** boosts efficiency in smart grids, reduces technical losses and favours the integration of intermittent renewable energies. According to Mahmood et al. (2024), the use of IoT-based systems, smart sensors, and energy management platforms has improved the flexibility and stability of the electricity system. Likewise, econometric studies confirm that a 1% increase in digitalization rates can translate into significant improvements in sustainable development indicators (Zarrad et al, 2025; Digitalization of renewable energy development, 2025). These findings reinforce the idea that **digital technologies are structural catalysts** for achieving the Sustainable Development Goals (SDGs 7, 9 and 13) (Mondejar et al., 2021).

Secondly, **automation and artificial intelligence (AI)** are consolidating themselves as key instruments for optimising the operation of energy systems. Deep learning applications enable accurate forecasting of solar and wind generation, predictive maintenance, and automated dispatch, reducing costs and emissions (Rashid, Biswas, & Gupta, 2024; Lam et al., 2023). In smart buildings, adaptive automation can reduce energy consumption by 15% to 25%, according to recent studies in Europe (EUBAC, 2024; Data-Driven Smart Home Automation, 2025). These improvements are essential to meet energy efficiency and decarbonization goals in the residential and commercial sector.

However, the impact of digitalization and automation is not purely technical. **The social implications are profound and ambivalent.** Ahlam (2025) shows that industrial automation increased global productivity by 25% and reduced energy intensity by 15%, but at the same time increased income inequality by 12%. Similarly, the study *Impacts of workplace automation on energy poverty* (2024) warns that automation can increase energy poverty by displacing employment and reducing the ability to pay for energy in vulnerable households. These results confirm that technological progress can aggravate social gaps if it is not accompanied by **just transition policies** (IRENA, 2024).

From an environmental perspective, recent evidence shows that digitalization, when properly targeted, reduces carbon emissions and accelerates the transition to clean electricity systems (Connecting the sustainability: How renewable energy and digitalization, 2025). However,

the massive deployment of artificial intelligence and the expansion of data centers also imply **risks of energy overconsumption**, which could counteract the benefits achieved (Schneider Electric, 2024). This requires renewable **additionality**, digital efficiency and coordinated energy governance strategies.

Another key aspect identified is the need for **energy data governance and algorithmic explainability**. Digitized energy systems rely on large volumes of data, the responsible handling of which is essential for public security and trust. Alsaigh, Mehmood, and Katib (2022) warn that the opacity of AI algorithms and the lack of ethical standards in their use can lead to significant regulatory and social risks. The implementation of **transparency, interoperability, and cybersecurity** policies should be a priority to strengthen the resilience of digital energy infrastructures (ISA, 2024).

In this way, the conclusions of this research can be summarised in the following points:

### 1. Technical conclusions

- Digitalisation increases the operational efficiency, flexibility and resilience of energy systems, favouring the integration of variable renewable sources (Mahmood et al., 2024).
- Automation, supported by AI, improves predictive management and reduces energy and maintenance costs (Rashid et al., 2024).
- Smart energy systems can manage demand and reduce consumption in homes and buildings by up to 25% (EUBAC, 2024).

### 2. Social conclusions

- Technological advances generate unequal benefits: they can reduce energy poverty if they are oriented towards inclusion, or increase it if they displace employment and concentrate benefits (Impacts of workplace automation on energy poverty, 2024).
- Digitalization and automation must be aligned with the principles of **just transition**, prioritizing job training, equity in access, and citizen participation (IRENA, 2024).
- Energy data governance requires privacy, transparency, and participation policies to avoid digital exclusion (Alsaigh et al, 2022).

### 3. Environmental conclusions

- Energy digitalisation is an effective tool for reducing emissions and meeting decarbonisation objectives (Connecting the sustainability, 2025).
- However, the growth in electricity consumption due to digital and AI technologies imposes the need for greater investment in renewable sources and sustainable storage (Schneider Electric, 2024).
- Integrated energy planning and digitalization will mitigate the ecological footprint of automated systems (Khan et al., 2024).

### 4. Political and strategic implications

- Governments must promote **inclusive innovation public policies**, which articulate incentives for digitalization with frameworks of social equity and environmental sustainability (Morrar et al, 2024).
- It is essential to strengthen international cooperation in technical standards, energy cybersecurity and ethical AI standards (ISA, 2024).
- Digital energy justice **indicators need to be incorporated** into national energy and climate plans (IRENA, 2024).

### 5. Future research perspectives

- It is recommended to expand comparative empirical studies that measure the social effects of energy digitalization in different regions.
- It is urgent to develop metrics on digital equity, community participation and social sustainability in the technological transition.
- Future research should combine quantitative and qualitative approaches to capture the comprehensive impact – technical, economic and social – of automation in renewable energy.

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