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Renewable Energy Integration Using digital technologies to optimize solar, wind, and other renewable sources

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Abstract:
This research explored the connection between the implementation of renewable energy and digitalization in the sector by reviewing relevant literature published from 2010 to 2024. The aim was to assess the current application of digital technologies in the industry, the obstacles encountered during their adoption, and future opportunities. A variety of search engines, such as SCOPUS, Web of Science, and Google Scholar, were utilized to gather pertinent articles and documents. The results emphasized the vital importance of digital technologies in advancing the renewable energy sector, while also revealing significant challenges, including high costs and security concerns. Although the majority of the analyzed studies presented an optimistic outlook, they stressed the need for additional research and development to support a successful energy transition and establish resilient infrastructure. The factors driving the integration of digital technologies to enhance the adoption of renewable energy sources appear to extend beyond mere energy demand, encompassing various dimensions of sustainability and sustainable development. Unlike previous reviews, this study provides a unique perspective by investigating the broader interplay between digitalization and the renewable energy sector, focusing on critical areas that warrant further exploration within these interconnected fields. The relatively small number of relevant studies identified (69 out of 836 results) underscores the necessity for more extensive research in this area.

Keywords: blockchain; digital technologies; renewable energy; security; sustainability.

Introduction:

Digitalization is characterized as the integration of digital technologies to transform business models and create new opportunities for revenue and value generation; it represents the transition to a digital enterprise. Digital technologies are increasingly vital in the spread and adoption of renewable energy. In contrast to fossil fuels, renewable energy sources are not "dispatchable," meaning they are not always available when needed, and their production is influenced by daily and seasonal variations, which creates reliability challenges. Nevertheless, digital technologies have proven effective in addressing these challenges, offering significant potential for growth. This has led energy companies to make substantial investments in digital technologies in recent years. The International Energy Agency (IEA) reports that global investments in digital power infrastructure, particularly related to grid systems, have surged by over 50% since 2015. Data from the last decade indicates a 128% increase in renewable energy production from 2010 to 2022, alongside a 147% rise in the number of digital technologies integrated into power grids, highlighting a direct correlation between these developments. This study investigates the various ways digital technologies have impacted the spread and adoption of renewable energy. It also explores which industries have gained the most, the regions or countries that have made the most significant progress toward renewables through digitalization, and the challenges that arise, along with potential solutions. The relationship between digital technologies and the diffusion of renewable energy within the energy sector remains unclear to many stakeholders. This paper seeks to address this research gap by categorizing, evaluating, and analyzing findings through a comprehensive literature review.

In contemporary society, there is a significant reliance on a steady energy supply. As the global population continues to grow alongside increasing modernization and urbanization, the demand for dependable energy sources has consistently risen over the past few decades. The global energy landscape is currently undergoing a transformation, with renewable and low-carbon energy sources, such as wind and solar power, poised to supplant traditional fossil fuels like oil, gas, and coal. This shift is primarily driven by the resilience of renewable energy during crises and the commitment to utilizing clean and sustainable energy sources.

The recent Russia–Ukraine conflict has underscored the importance and implications of transitioning to renewable energy. The geopolitical risks associated with dependence on fossil fuels have prompted several nations and regions to invest significantly in clean energy and adopt energy transition strategies. For example, Germany, which previously relied heavily on fossil fuel imports, has expedited its shift to renewable energy in response to the potential cessation of energy imports from Russia. On a global scale, investments in renewable power capacity (excluding large hydroelectric projects over 50 MW) reached $281 billion in 2020, compared to just $111 billion for the fossil fuel sector.

In addition to enhancing resilience in the face of various crises, the push for low-carbon energy sources through renewables is influenced by factors such as health concerns related to air pollution, market dynamics, energy security, and efforts to mitigate climate change. While the long-term energy transition (LTE)—the movement away from non-renewable fuels toward renewable energy—is progressing, it remains a complex challenge for both businesses and nations. The four primary drivers of LTE, along with their associated challenges, are:

- ➢ **Economics:** The principles of supply and demand are evident in the energy sector. While there remains a significant demand for non-renewable energy sources, the appetite for renewable energy is on the rise, leading public utilities to decrease their reliance on non-renewable options. This growing demand for renewable energy necessitates the development of new infrastructure and requires both companies and governments to make informed strategic choices regarding their energy consumption and production pathways.
- ➢ **Societal Factors:** The transition to renewable energy is influenced by individual preferences and the collective actions of various stakeholders, including consumers, investors, and businesses. Key determinants in this shift include the reliability of energy sources, the services they offer, and their overall cost.
- ➢ **Technological Advancements:** Recent technological innovations have facilitated the emergence of new energy sources, improved accessibility, enhanced energy efficiency, and reduced costs. For instance, the price of solar panels fell by 20% from 2010 to 2022. Additionally, advancements such as smart grids, solid-state batteries, and the digitalization of energy systems have played a crucial role in promoting the use of renewable energy, with digitalization being a key driver in transforming energy infrastructure.
- ➢ **Regulatory Environment:** Over the last decade, regulatory changes have been implemented to promote long-term energy transition (LTE), although the regulatory landscape

differs across countries. Various regions and nations have adopted distinct measures to encourage the shift towards renewable energy, influenced by their unique natural resources, priorities, and capabilities.

1.2. Key Forces in Energy Transition

The aforementioned drivers operate alongside five key categories of forces that promote energy transformation overall. Before delving into these categories, it is essential to recognize that energy transition—specifically the shift from conventional to renewable energy sources—is merely one aspect of energy transformation from a physical standpoint. Other related forms of energy transformation may involve broader social, organizational, and political shifts.

The five categories of forces, referred to as the '5 Ds', include Decentralization, Decarbonization, Democratization, Deregulation, and Digitalization. These forces are anticipated to significantly enhance the role of renewable energy in global electricity generation by 2035, projecting a 2.7-fold increase compared to 2010. Key considerations regarding these categories are as follows:

➢ **Decentralization:** Currently, decentralization is a pivotal characteristic of the ongoing energy transition, influenced by decreasing technology costs, concerns about climate change, and social innovation. In contrast to centralized systems, decentralized energy frameworks provide opportunities for numerous consumers to become "prosumers," meaning they can both consume and generate electricity. The success of energy decentralization is influenced by factors such as the restructuring of governance roles, inclusivity, capacity development, coherence, adaptability, and transparency.

➢ **Decarbonization:** This process involves harnessing and utilizing clean energy sources to lower the global average carbon intensity. Numerous nations have developed specific energy strategies to fulfil their international decarbonization commitments. For example, the United States aims to decrease its greenhouse gas (GHG) emissions by 2 percentage points (from 28% to 26%) by 2028, relative to 2005 levels. Meanwhile, the European Union, comprising 28 member states, has committed to a 40% reduction in emissions by 2030 compared to 1990 levels. According to the outcomes of COP21, several essential actions are necessary to support the 17 Sustainable Development Goals (SDGs). Common strategies include enhancing access to information, internet, and communication technologies, providing enabling technologies for various business models, and upgrading existing systems related to energy efficiency and infrastructure.

➢ **Democratization:** This concept primarily focuses on enhancing stakeholder participation, particularly among social actors, to promote acceptance. Energy companies and municipal utilities can adopt several measures to foster democratization, such as:

- Creating participation models that allow customers to invest in local renewable energy projects, like wind or solar farms;
- Empowering customers, including supporting prosumers;
- Maintaining transparency regarding strategies, objectives, and progress;
- Organizing on-site discussions with relevant community groups.

The active inclusion and engagement of affected stakeholders in decision- making processes are considered crucial for achieving democratization.

➢ **Diversification:** This aspect is as crucial as other force categories and aims to mitigate risks associated with disruptions in energy resource supply while preventing monopolistic control over specific energy types. This is achieved through various technological approaches and energy production management strategies. Examples include:

- Broadening the spectrum of primary energy sources (such as wind and solar);
- Implementing new types of power generation and supply systems (for instance, combined-cycle gas turbine units that utilize both gas and solid fuels with diverse thermal processes);
- Adopting innovative energy-saving techniques (like the integration of energy-efficient reserves in consumption and the development of advanced energy storage systems);
- Introducing supplementary sources of appealing fuels and energy (for example, increasing the natural gas reserve base by substituting electricity in processes that consume electricity) [12].

Challenges in diversification include the necessity to foresee technical capabilities early on to create valuable services with enhanced benefits [8].

➢ **Digitalization:** Over the last ten years, new digital infrastructures (NDI), driven by advanced information technologies, have emerged [13]. These NDI services integrate into the production and operational frameworks of businesses, enhancing the efficiency of industrial resource distribution and, crucially, offering innovative solutions for challenges in energy transition [13]. It has been suggested that the evolution of energy infrastructure, supported by NDI services, can expedite the energy transition process [13].

1.3 Digitalization Categories and Applications

When evaluating the impact of digital technologies, it is crucial to understand that the digitalization infrastructure consists of various types that serve distinct functions within the energy sector. Below is a summary of the primary digital technologies and their applications in this field.

Artificial Intelligence (AI): AI stands out as the most commonly utilized digital technology in the energy sector. Broadly defined, AI encompasses a range of technologies and methods designed to perform tasks typically associated with human cognition, such as learning and problem-solving. This involves creating algorithms and software that can execute functions that once required human intelligence. In the energy sector, AI is applied in areas such as predictive maintenance, integration of renewable energy, energy forecasting and optimization, and management of the grid.

Blockchain: This innovative technology is gaining significant attention from energy suppliers, tech developers, government entities, financial institutions, and startups. Blockchain consists of decentralized and shared data structures that securely record digital transactions without relying on a central authority. This technology facilitates the automated execution of smart contracts within peer-to-peer (P2P) networks. In the energy sector, blockchain is typically used for managing renewable energy, overseeing grid operations, facilitating energy trading, and establishing decentralized microgrids.

Internet of Things (IoT): IoT technology connects physical devices, or "things," through the internet. By utilizing sensors and communication technologies to gather and transmit real-time data, IoT enhances energy efficiency, promotes the adoption of renewable energy, supports smart metering, and reduces negative environmental impacts through rapid computations and informed decision-making.

Big Data Analytics: This is crucial for effective smart grid management, encompassing power generation, transmission, distribution, and transformation. Big data refers to the vast amounts of information gathered for processing, characterized by three main attributes: volume, which indicates the quantity of data processed; velocity, which denotes the speed at which data is received; and variety, which pertains to the diverse formats and types of data involved. Significant applications of this digital technology include predictive maintenance, optimization of energy consumption, analysis of energy usage patterns, fault detection, and enhancement of supply chain processes within energy organizations.

Robotics: This digital technology merges computer science with engineering, focusing on the design, construction, and operation of robots to manage tasks, provide sensory feedback, and process information. Its applications span the inspection and maintenance of energy infrastructure, the production and distribution of renewable energy, and the manufacturing and upkeep of energy storage systems, such as batteries and fuel cells.
Additive Manufacturing (AM): Commonly referred to as 3D printing, this technology involves creating objects layer by layer from the ground up. The rapid advancement of computer-aided design (CAD) technology has significantly impacted the energy sector, facilitating various applications. Key uses include rapid prototyping and production of spare parts, customized manufacturing of components for renewable energy, enhanced monitoring and control of equipment, and the creation of high-temperature components.

Digital Twin (DT): This concept utilizes a combination of physics-based and analytical techniques to create models of individual components within a power plant and the overall system. These models can determine the operational limits of power generation units under various conditions, including different loads, fuel compositions, weather conditions, and ambient temperatures. The current DT architecture is designed to enhance reliability, availability, and maintainability (RAM) in the complex energy sector while also reducing costs.

Cloud Computing: Recently, cloud computing has garnered significant attention as a technology for hosting online services, thanks to its efficient service model that minimizes resource requirements for users. Systems leveraging cloud computing utilize virtualization to decouple software from the physical server characteristics, leading to optimization and reductions in energy-intensive features. Common applications of cloud computing encompass predictive maintenance, grid optimization, customer engagement, data analytics, and monitoring of renewable energy sources.

Internet of Service: This technology systematically employs the internet to create new value through the implementation of the Product-as-a-Service (PaaS) business model. Its applications span various areas, including enhancing energy efficiency, enabling predictive maintenance, supporting smart grids, integrating renewable energy, and managing energy data.

Augmented Reality: This technology enables the overlay of computer-generated graphics onto real-world environments in real-time. It provides professionals in the energy sector and smart cities with immediate access to repair instructions for specific parts or subassemblies. Additional applications include training and simulation, customer engagement, monitoring and control, and predictive maintenance.

Cybersecurity: This field addresses challenges associated with safeguarding IoT systems, including threats like ransomware attacks, cyberterrorism, and hacking. Major applications focus on securing energy infrastructures, which encompasses data protection and facilitating secure communications.

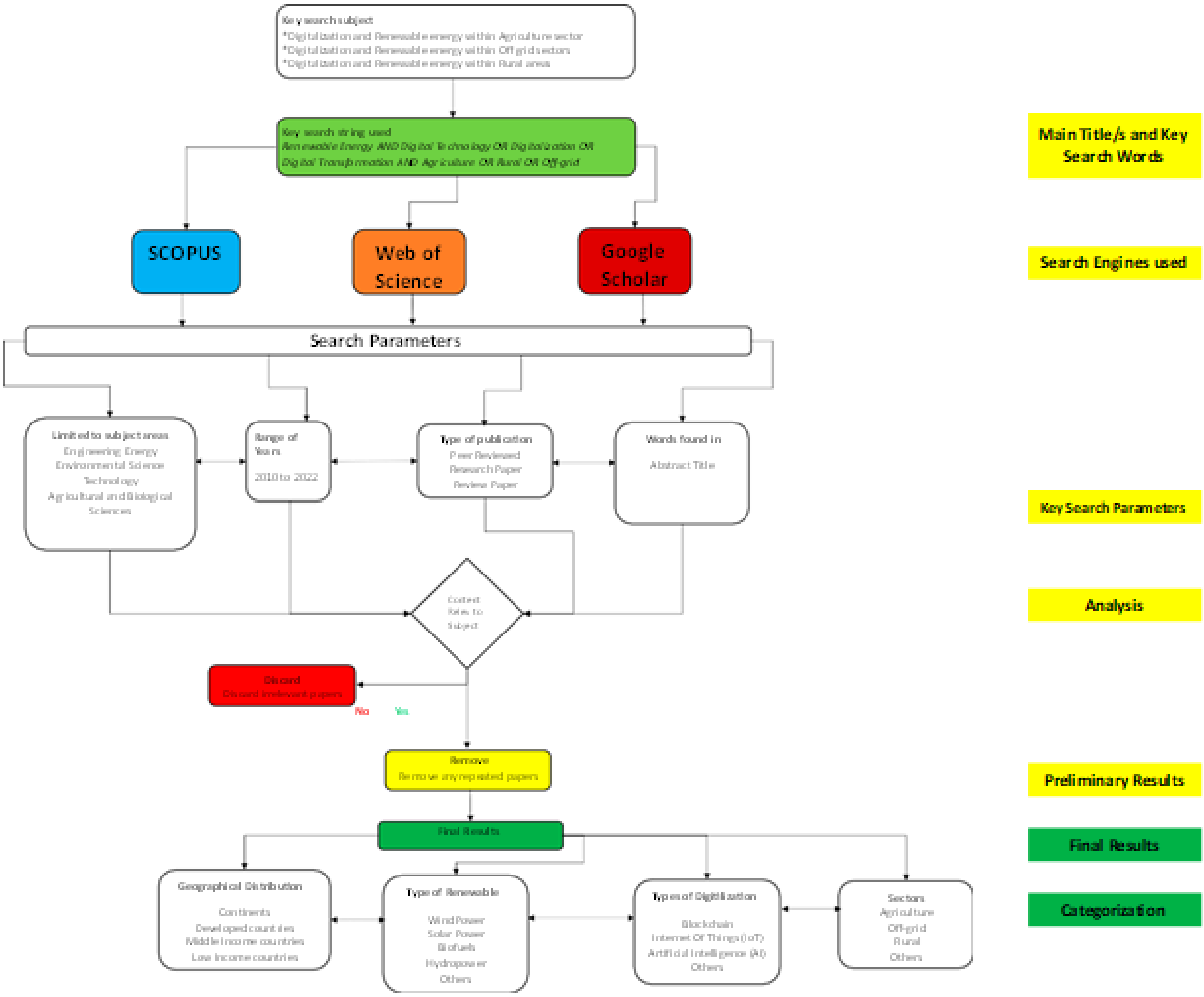
2. Objective of the Current Review

The primary goal of this study was to examine recent literature (published between 2010 and 2022) related to digitalization and renewable energy. This review aimed to assess the current application of digital technologies in the renewable energy sector and the challenges associated with their adoption. The specific objectives of the review included:

(1) Identifying the key digital technologies utilized in the renewable energy sector (RES);
(2) Determining the primary areas within the RES where digitalization is being implemented;
(3) Mapping the geographical distribution of digital technologies in the RES;
(4) Highlighting the main obstacles to the adoption of digital technologies in the RES;
(5) Exploring the implications of integrating and disseminating digital technologies within the RES.

Literature Review:

This study used a literature review methodology to examine the link between digitalization and renewable energy. The integrative review approach was chosen due to its alignment with the analysis's objectives. The search strategy involved analyzing recent literature on digitalization and its application in various sectors, including renewable energy. The search string was applied across multiple search engines, including Scopus, Web of Science, and Google Scholar, with parameters such as subject areas, publication years, type of publications, and language. The integrative review aimed to enhance knowledge and theoretical frameworks.



The results from each search engine were analyzed for content relevance, leading to the removal of non-relevant papers from the compiled lists. Initially, the relevance of the subjects was assessed through the titles and abstracts of the papers. In instances where uncertainty arose, a more detailed examination of the main text was conducted. Once the relevance was confirmed, comparisons and cross-checks were performed across all search engine results to eliminate any duplicates in the final consolidated list. Additionally, a review was conducted to ensure that only journal articles were included, excluding conference proceedings, book chapters, and reports.

The final phase involved organizing the selected papers into five primary categories:

Geographical distribution: Continents, developed countries, middle-income countries, and low-income countries;

Type of renewable energy: Wind Power, Solar Power, Biofuels, etc.;

Type of digitalization: Blockchain, Internet of Things, Artificial Intelligence, etc.;

Sector: Agriculture, Off-grid, Rural, etc.;

Emerging challenges.

Methodology:

1. Literature Review Approach

The methodology employed for data collection was a literature review, which encompassed searching, identifying, reading, summarizing, compiling, analyzing, interpreting, and referencing existing literature. Three primary approaches are available: systematic review, semi-systematic review, and integrative review. For this study, the integrative review approach was chosen due to its alignment with the analysis's objectives. This approach focuses on established topics by providing an overview of the existing knowledge base, critically evaluating, potentially re-conceptualizing, and expanding the theoretical framework as it evolves. In the case of emerging topics, the goal is to develop initial conceptualizations and theoretical models rather than revisiting established ones. However, the most crucial aspect of the integrative review is its potential to enhance knowledge and theoretical frameworks, which is particularly significant for the current study.

2. Search Strategy

This research examined the critical links between digitalization and renewable energy by analyzing recent literature. To find pertinent articles related to digitalization and its application in various sectors and industries involving renewable energy, the following search string was employed across multiple search engines:
"Renewable Energy AND Digital Technology OR Digitalization OR Digital Transformation AND Agriculture OR Rural OR Off-grid."
Figure 1 illustrates the methodological framework utilized. To ensure a comprehensive collection of journal articles, three search engines—SCOPUS, Web of Science, and Google Scholar—were utilized. The search string was applied with the following parameters and filter settings:
- Subject areas restricted to: Engineering, Energy, Environmental Science, Technology, and Agricultural and Biological Sciences;
- Publication years limited to: 2010 to 2022;
Type of publications: Peer-reviewed, research paper, and review paper; Words found in both: Abstract and title;
Language: Only English.

Results:

Papers Identified

The findings from the three search engines are presented in Table 1. Initially, there were 836 results across all three platforms. Following a thorough evaluation of these results, which involved eliminating irrelevant studies and duplicates, 69 journal articles were chosen for further analysis. Articles were deemed irrelevant if they did not pertain to the main topic of interest—digitalization in the renewable energy sector—or if they focused exclusively on one of the two areas (either digitalization or renewable energy). The selection process involved reviewing the title, abstract, and, when necessary, the conclusions section to identify papers that integrated both fields. A significant number of the initial results concentrated solely on agriculture, off-grid systems, renewable energy, or general digital technologies, failing to explore the connections between digital technologies and renewable energy, and were therefore excluded. Among the 69 pertinent journal articles identified from the original 836 results, more than 60% originated from two publishers: 32% from the Multidisciplinary Digital Publishing Institute (MDPI) and 29% from Elsevier journals.

Discussion:

This review stands out from previous studies due to its broader perspective on the relationship between digitalization and the renewable energy sector, with a particular emphasis on critical areas that require attention. While it identifies specific urgent technical challenges, the research also underscores the importance of sustainability in achieving improved outcomes. The limited number of relevant papers included in this literature review (69 out of 836 identified) indicates a need for more comprehensive research on this topic. Many papers that were excluded addressed digital technologies using vague terms like "technology" or "technology development," which lack clarity and may confuse readers.

The incorporation of digital technologies has significantly facilitated the spread of renewable energy sources within the energy sector, where there is an increasing interest in various digital innovations such as blockchain, IoT, and AI. These technologies are being utilized not only in developed nations with sophisticated energy infrastructures but also in numerous developing countries. The current factors driving the adoption of digital technologies to enhance the proliferation of renewable energy sources seem to go beyond mere energy demand, encompassing a broader range of sustainability and sustainable development issues.

However, the further integration of digital technologies into the renewable energy sector encounters several challenges, including technological issues like security vulnerabilities, as well as economic and management hurdles such as high costs and the need for suitable policies. Tackling these challenges with a comprehensive approach focused on sustainability, along with ongoing research and development efforts, can foster a more conducive environment for a successful energy transition and a robust infrastructure..

Conclusion:

A summary of the study's main findings, contributions to the literature, and suggestions for future research.

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