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Research Article

The Environmental Impact of the Fourth Industrial Revolution: Assessing the Pros and Cons of Technologies on Renewable Energy Systems

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Abstract

The Fourth Industrial Revolution (4IR) has ushered in an era of technological advancements that profoundly impact various sectors, including renewable energy systems (RES). This paper critically examines the environmental implications of 4IR technologies, emphasizing the advantages and challenges associated with their integration into RES. Key technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, cloud computing, and cyber-physical systems can potentially enhance the efficiency, predictive maintenance, and overall management of renewable energy infrastructures. These innovations promise significant reductions in carbon emissions and operational costs while promoting sustainable energy consumption. However, the rapid deployment of these technologies also presents notable challenges, including increased electronic waste, higher energy consumption by data centres, and cybersecurity threats. This study highlights the need for rigorous assessment and strategic implementation of 4IR technologies to maximize their benefits while mitigating adverse environmental impacts. The findings underscore the importance of establishing comprehensive guidelines and policies. These are recommendations and necessary measures to ensure these technologies contribute positively to global sustainability goals. They are the guardrails that will steer us towards a more sustainable future.

Keywords	*Fourth Industrial Revolution; Renewable Energy Systems; Environmental Implications*
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Introduction

Conventional power systems are transitioning towards cleaner alternatives, incorporating the fourth industrial revolution into their roadmaps, investments, and policies (Korkmaz et al., 2020). Despite the significant development and acceptance of fourth-industrial technologies, the literature has primarily focused on analyzing the environmental impact of the Internet of Things and Artificial Intelligence on economic systems and buildings. This highlights the need to understand the opportunities and obstacles in renewable energy systems related to production, transmission, and consumption (Hoang & Nguyen, 2021). Understanding is crucial for making informed decisions, recognizing potential challenges and benefits, and taking responsibility for our choices. Our research demonstrates that data acquisition and pre-processing are critical in all technologies and services. They enhance our understanding of energy consumption and facilitate the reduction of consumption, the extension of components' lifetime, and the minimization of oil spills. Social networks, IoT, and energy segmentation control strategies have significantly improved awareness and control, enabling demand response and non-exploitative comparative strategies that may double the final cost of electricity bills. Such understanding is essential to minimize consumption peaks on arbitrary days, prevent equipment and component breaking failures, and model energy consumption profiles.

The fourth industrial revolution (FIR) involves various technologies and services developed to offer different stakeholders preferences and benefits. However, it is also associated with challenges preoccupying the academic and political realms (Jaiswal et al., 2022). While some authors support its acceptance of benefits like energy savings and network security, the environmental consequences may rise significantly. The fast development of less sustainable, less environmentally friendly technologies may pose several challenges to global sustainable development and environmental well-being. Therefore, an urgent and compelling need exists for in-depth reviews examining its impact on significant systems worldwide.

Understanding the Fourth Industrial Revolution

Overview of the Fourth Industrial Revolution and Its Technological Prospects

The Fourth Industrial Revolution (4IR) represents a transformative era characterized by the convergence of various advanced technologies. As illustrated in the provided figure, this revolution follows three preceding industrial transformations:

1. **First Industrial Revolution (1765)** - Marked by mechanization led by the steam engine.
2. **Second Industrial Revolution (1870)** - Characterized by mass production driven by electricity and oil-based power.
3. **Third Industrial Revolution (1969)** - Defined by automated production supported by electronics and information technologies.

The Fourth Industrial Revolution is driven by new technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data, cloud computing, and cyber-physical systems. These technologies have significant implications for various sectors, including renewable energy systems.

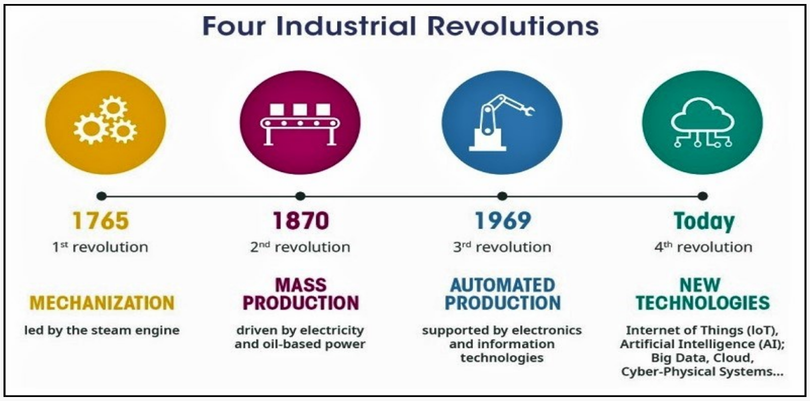

Figure 1: Stages of the Industrial Revolution

Technological Impact on Renewable Energy Systems

The Fourth Industrial Revolution brings several technologies that have the potential to transform renewable energy systems:

i. **Internet of Things (IoT)**: This enables intelligent grid technology, enhancing energy efficiency by connecting various energy-producing and consuming devices.
ii. **Artificial Intelligence (AI)**: Optimizes energy consumption and management through predictive analytics and automated decision-making processes.
iii. **Big Data**: Facilitates the analysis of large datasets to improve energy production forecasts and demand management.
iv. **Cloud Computing**: Provides scalable resources for processing and storing vast amounts of data generated by renewable energy systems.
v. **Cyber-physical systems Integrate** physical and digital worlds, allowing for real-time monitoring and control of renewable energy infrastructure.

Current Status and Future Enhancements of Renewable Energy Systems

These emerging technologies significantly impact traditional renewable energy systems like solar, wind, and hydropower. The integration of 4IR technologies can enhance their capabilities in the following ways:

i. **Improved Efficiency**: IoT and AI can optimize the performance of renewable energy systems, reducing waste and increasing output.
ii. **Predictive Maintenance**: Big data and AI enable predictive maintenance, reducing downtime and extending the lifespan of energy infrastructure.
iii. **Enhanced Grid Management**: Smart grids facilitated by IoT and cyber-physical systems improve the balance between energy supply and demand, enhancing overall grid stability.
iv. **Sustainability Reporting**: Advanced analytics and AI accurately report environmental impacts, aiding sustainability initiatives and regulatory compliance.

Environmental Impact and Challenges

The convergence of these technologies poses both opportunities and challenges:

i. **Opportunities**: Improved energy efficiency, reduced carbon emissions, and enhanced resource management contribute positively to environmental sustainability.
ii. **Challenges**: Deploying these technologies must be carefully managed to avoid potential negative impacts, such as electronic waste and cybersecurity threats.

Understanding the benefits and consequences of Fourth Industrial Revolution technologies is crucial for stakeholders in the renewable energy sector. Establishing criteria and guidelines for environmental performance will ensure that these technologies contribute positively to sustainability goals. As these technologies evolve, their integration into renewable energy systems will be critical in addressing global environmental challenges and advancing towards a more sustainable future.

Definition and Key Characteristics

Then, it is relevant to look at the definition of RES, as 25% of the world's primary energy supply is a combination of traditional biomass of Indigenous origin plus energy from large hydro projects of older construction, so at least one-quarter of the world primary energy supply derives from renewable energy (Halkos & Gkampoura, 2020). What are the renewable resources? This means that those energy sources are not derived from fossils. However, those energy sources are derived from things we can directly or indirectly see (the sun, the wind, the debris of meteorites, the hydraulic and wave motion, etc). In particular, in the case of widely spread use, such as heating, cooling, electricity production, and fuel production, examples of renewable energy sources are solar, wind, ocean, biomass fuel, hydro, and geothermal sources (Holechek et al., 2022). The evolution and tendency of renewable energy reflect a general evolution: from "the first wave that involved and used the forces of nature, to the second wave, which involved and used the energy of minerals. Still, the trend is increasing renewable energy sources, creating an environment of the third wave." The phenomenon of renewable energy, in other words, refers at least to the period of energy history that began with the oil shock of the early 70's (Perez & Perez, 2022). In this context, Renewable Energy Systems (RES) appear to be the final model of energy systems, established to respond to the necessity of producing a public commodity called energy and its environmental safeguard.

The Top 10 Technology Trends of the 4th Industrial Revolution

The Fourth Industrial Revolution trend Figure 2, characterized by a fusion of technologies blurring the lines between the physical, digital, and biological spheres, has introduced numerous ground-breaking trends. Here are the top 10 technology trends driving this revolution:

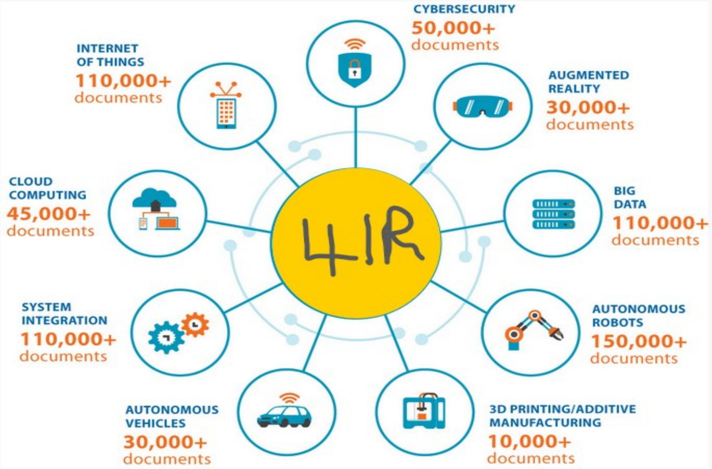

Figure 2: Technology Trends of the 4th Industrial Revolution Source. (IEEE Xplore Digital Library).

i. Artificial Intelligence (AI) and Machine Learning (ML): AI and ML are at the forefront of the Fourth Industrial Revolution, enabling machines to learn from data, make decisions, and perform tasks that typically require human intelligence. Applications range from autonomous vehicles to predictive analytics and personalized recommendations.

ii. Internet of Things (IoT): IoT involves connecting everyday objects to the internet, allowing them to send and receive data. This technology enhances smart homes, cities, and industries by improving efficiency, reducing waste, and providing real-time insights.

iii. Big Data and Analytics: The explosion of data from various sources is harnessed through advanced analytics to uncover patterns, predict trends, and inform decision-making. Big data is crucial in healthcare, finance, and marketing.

iv. Blockchain: Blockchain technology provides a decentralized and secure way to record transactions and manage data. It is revolutionizing finance, supply chain management, and healthcare industries by enhancing transparency and reducing fraud.

v. 5G and Next-Generation Connectivity: 5G technology promises faster, more reliable internet connections, essential for supporting IoT devices, autonomous vehicles, and other advanced technologies. It enables real-time communication and processing, paving the way for innovations in various sectors.

vi. Robotics and Automation: Advances in robotics and automation are transforming manufacturing, healthcare, and service industries. Robots are becoming more capable and intelligent, performing complex tasks precisely and efficiently.

vii. Augmented Reality (AR) and Virtual Reality (VR): AR and VR create immersive user experiences with gaming, education, training, and retail applications. These technologies enhance interaction with digital content and provide new ways to visualize and manipulate data.

viii. 3D Printing and Additive Manufacturing: 3D printing allows for the creation of complex structures layer by layer, reducing waste and enabling customization. It is used in aerospace, healthcare, and construction industries to produce parts and prototypes quickly and cost-effectively.
ix. Biotechnology and Genomics: Advances in biotechnology and genomics are revolutionizing healthcare by enabling personalized medicine, gene editing, and the development of new treatments for diseases. CRISPR technology, for instance, allows for precise modifications to DNA.
x. Quantum Computing: Quantum computing harnesses the principles of quantum mechanics to perform computations at unprecedented speeds. Although still in its early stages, it can potentially solve complex problems currently intractable for classical computers, impacting fields such as cryptography, material science, and drug discovery.

These technology trends reshape industries and society, drive innovation, and create new opportunities and challenges. Their convergence leads to a transformative era where the physical, digital, and biological worlds are increasingly interconnected.

Technologies Driving the Fourth Industrial Revolution

As a significant determinant of technological change, the impacts of industrial revolutions are generally analyzed regarding industry-level technology and, thus, sector dimension (Parmentola et al., 2022). While demonstrating the economic outcome of introducing a new generation of renewable energy systems is extensive, very few studies have linked and assessed the combined environmental impact of the technological advances in the fourth industrial revolution applied to renewable energy systems (Jeuland et al., 2021). A common platform for these types of renewable energy systems is the so-called concept of hybrid power system. A hybrid concept also refers to the utilization of renewable energy resources at multiple geographical locations (Akpan & Olanrewaju, 2023). Owing to the wide range of renewable energy system compositions, sizes, and applications, the impact that fourth industrial revolution technologies might have on renewable energy systems has not been thoroughly analyzed. This study aims to elaborate on the potential impacts of the introduction of fourth industrial revolution technologies on renewable energy systems with the expectation of promoting further collaboration and sharing of knowledge for implementing more thoughtful, more sustainable, and equitable energy technologies in developing regions. Additionally, the challenges facing the realization of this potential can be identified (Apfel et al., 2021).

The fourth industrial revolution is associated with a range of technological advances disrupting both the energy industry and the way industries interact with energy. Specific technologies driving the fourth industrial revolution include big data, artificial intelligence, machine learning, and the Internet of Things. Together, these technological advances form the backbone of Industry 4.0, characterized by the digitization of industrial processes at scale. These technologies have been in development since the mid-2010s and, in short order, provide breakthrough applications across sectors. For instance, deploying innovative grid technologies allows electricity networks to monitor and control grid operations, leading to better management of variable generation and improved system reliability. The deployment and uptake of these so-called enabling technologies have begun to enable the growth of prosumerism and are promoting collective awareness of energy usage patterns.

Renewable Energy Systems

The assessment of renewable energies refers to global or localized efforts and constitutes a methodology still beginning to develop in terms of the execution and measurement of the undertakings (Infield & Freris, 2020). The design of renewable energy systems presumes the participation of skilled people from different knowledge areas. Heated confrontations occur in cases of different capacities and governmental programs to define the most adequate forms of regulatory incentives to circumvent social disparities (Сотник et al., 2021). This exploration of alternatives should also delimit the adequate participation level for other social segments, such as a company from a particular place, to answer internal demand. Renewable energy sources, also known for their more succinct and friendly nomenclature "clean energy" resources, such as wind, sun, and water, come from nature (Husin & Zaki, 2021; Adebayo et al., 2024).

In contrast to demanding more time until start-up compared to traditional power plants running on fossil fuel, they have competitive advantages in terms of operation costs and maintenance (Egeland-Eriksen et al., 2021). Considering that investments shall behave according to climate trends, operating conditions, and energy policy objectives, this scenario conveys significant innovations due to the intensification and broadening of the clean energy concept. Thus, the competitive environment allows for the utility of analyzing collective situations.

Pros and Cons of Technologies on Renewable Energy Systems

Another important factor concerning renewable power plants is that the sources of supply operate asymmetrically, whereas the output is intermittent (Razmjoo et al., 2021). This can be a source of multiple design interactions between project options, such as fuel supply, excavation, modular design, resource capacity to realize the maximum capacity factor, and management capacity. The main delivered benefits of these installations include the potential to generate new jobs, the opportunity to reduce local and global air pollution, electricity supplied to off-grid people, including in areas remote from the grid, the lowering of the gap between short and long-term correlated CO2 policies, the stabilization of prices, and the reduction of electricity consumption losses due to lower transmission and distribution distances (Chien et al., 2021). It is also **essential** to consider the energy policy during policy development, including the existence of the political process, which reflects the configuration of interest groups, the public, and the nature of the State and market influence (Jebli et al., 2020). Moreover, life cycle emissions are a function of CO2 emissions from fuel combustion, CH4, NF3, and N2O emissions from polysilicon production, N2O emissions from phosphorus production, emissions associated with electricity use in the fabrication facility and transport of the panels, and electricity from fab transport (de et al., 2020). It is also linked with construction, pumping and electrodeposition, wafer production, module assembly (related to manufacturing), system components and installation. In contrast, nuclear emissions arise from construction, fuel fabrication, reprocessing, waste management, decommissioning, uranium enrichment, and upstream emissions (Lima et al., 2020).

Differences in cost per unit of capacity and levelized cost are due to capacity factors, lifetimes, learning rates, market risks, such as risks associated with commodity, credit, and tax policy, and financing considerations (Hoang & Nguyen, 2021). The high costs of nuclear energy can be explained by technology maturity, legal, regulatory, and architectural framework **costs**, the impact on the market, and the permanent disposal of radioactive waste or decommissioning (Yu et al., 2022). Renewable energy systems have a high potential for reducing air pollution and CO2 emissions. For example, a solar PV power plant with a 30-year life span has associated emissions of 48 g of CO2-eq/kWh (0.05-1.2), and for wind power, the values are 11-12 g of CO2-eq/kWh for onshore and 13-16 g of CO2-eq/kWh for offshore. Solar PV is far from the level of carbon emissions of a nuclear power plant when modelled with a thoroughly modern life cycle assessment, including future operations. The CO2 emissions of both are considerably less compared to fossil-fuel-based power plants. Similarly, for metals, the cumulative energy demand of renewable energy power plants is 70% less compared to the nuclear power plant LWR technology. Critically, both PV and wind power technologies have the lowest impacts compared to all the other power plants.

Positive Impacts

Artificial Intelligence (AI) can help monitor climate patterns, forecast natural catastrophes, or diagnose the effects of climate change on ecosystems. This wide range of AI applications can considerably contribute to the United Nations Sustainable Development Goal number 13, "Take urgent action to combat climate change and its impacts," and to the 17 Goals established by the United Nations (Hannan et al., 2021). AI has considerable potential to address some of the adverse environmental effects and energetic challenges by improving forecasting, management, and optimizing renewable energy sources. Applying AI techniques for forecasts and optimization makes renewable energy systems more reliable, stable, and cost-effective (Ahmad et al., 2021). Promising technologies and novel approaches have been developed through the latest advancements of the Fourth Industrial Revolution to provide environmentally friendly solutions to the ever-increasing energy demand. These technologies cover different domains, and this work will approach the technologies for renewable energy systems by establishing the context with the Sustainable Development Goals framework for energy (Chen et al., 2021). Indeed, progress in any technological domain also needs to consider its environmental assessment framed inside a comprehensive model, as technologies are not neutral, and their use can lead to several concerns. This is the case with AI and blockchain, which have the characteristics of enabler technologies for sustainable development (Nishant et al., 2020).

Negative Impacts

The TB viruses generated by mechanized electronics, which also rotate 50%, need energy that had its consumption at speed estimated at the same rate, i.e., around 4%, and in 2020, doubled the levels recorded in 2013 (Masanet et al., 2020). Since electronic equipment turns on and off without logic and is often left on even when not in use, turning off the electronics without using them is similar to turning off the water when the faucet is not in use. This type of idea is easily forgettable while enjoying the luxury, in this case, of turning on the computer and being able to work immediately. Data show that the possibility of not wasting instant energy can help to save up to 55% of the cost of using electricity (Koronen et al., 2020). Remember that some of the by-products generated by electronic devices are hazardous to public health. In other cases, the waste that results releases gases harmful to the atmosphere. The analysis of extensive data consumption requires massive processing, which directly impacts the carbon footprint related to technology (Siddik et al., 2021). The exponential growth rate of data centres was estimated to have reached 4.1 billion kWh and emitted at least 3% of the world's CO2 emissions, "with emissions expected to double every five years." The energy consumption of global data centres in 2020 is expected to be twice the 2010 levels (Yuan et al., 2020). Therefore, a substantial commitment is suggested, oriented towards constructing more efficient data centres, targeting reductions in the carbon footprint. As some of this infrastructure is cloud-based, proposals are suggested to manage the cloud resources, avoiding excessive consumption, which is considered unnecessary. The high levels of consumption are related to peak electric power generating plants; therefore, the inefficiency of the data centres in managing this peak is quite significant due to its mathematical nature.

Table 1 demonstrates examples of adverse environmental impacts of adopting Fourth Industrial Revolution technologies across different countries. While these technologies offer numerous benefits, they pose significant challenges related to energy consumption, electronic waste, and carbon emissions. Addressing these challenges requires concerted efforts to develop more efficient and sustainable technological solutions.

Table 1: Negative Impacts of Fourth Industrial Revolution Technologies by Country

Country	Negative Impact	Example
Kenya	Increased energy consumption and carbon footprint	IoT sensors used in precision agriculture require significant energy, contributing to emissions.
Nigeria	Hazardous electronic waste	Big data analytics for disaster management systems generate e-waste harmful to public health.
South Africa	Excessive data processing and carbon emissions	AI for sustainability reporting involves massive data centres, increasing carbon footprint.
Egypt	Environmental pollution from electronic waste	Conservation efforts using IoT devices lead to discarded electronics, releasing harmful gases.
Ghana	High energy consumption and inefficiency in data management	Methane tracking technologies require energy-intensive data centres, doubling emissions every five years.
Germany	Carbon footprint from data centres	Precision agriculture technologies involve large-scale data processing, contributing to CO2 emissions.
United Kingdom	Energy inefficiency and waste in disaster management systems	Big data for disaster management increases energy usage, doubling energy consumption over the years.
France	E-waste and hazardous by-products	Sustainability reporting tools generate electronic waste with hazardous materials.
Netherlands	High energy demands for water retention projects	IoT sensors and AI for flood management consume significant energy, impacting carbon footprint.
Spain	Environmental impact from extensive data processing	Marine biodiversity monitoring through IoT devices requires large-scale data processing, increasing emissions.

Japan	Increased electronic waste from agricultural technologies	Precision agriculture using IoT and AI leads to discarded electronic devices that harm the environment.
China	Carbon emissions from energy-intensive disaster management systems	AI and big data for disaster response contribute to high energy consumption and emissions.
India	Waste generation and carbon footprint from sustainability reporting	Advanced analytics and AI tools produce electronic waste and increase data centre emissions.
South Korea	High energy consumption in water management systems	IoT and big data for water retention projects require extensive energy, doubling emissions every five years.
Singapore	Electronic waste from conservation technologies	IoT sensors for urban green space monitoring lead to discarded devices releasing harmful gases.
United States	Significant carbon footprint from methane tracking systems	IoT and big data analytics for greenhouse gas reduction consume large amounts of energy, impacting emissions.
Canada	High energy demands and inefficiency in precision agriculture	IoT and AI for agricultural productivity increase energy consumption and carbon footprint.
Brazil	Hazardous waste and carbon emissions from disaster management systems	Big data and AI for disaster response contribute to e-waste and CO2 emissions.
Mexico	Environmental impact from data centres used in sustainability reporting	Advanced analytics for environmental performance lead to increased data centre emissions.
Argentina	Increased energy consumption and waste from water retention projects	IoT and AI for water conservation in agriculture require significant energy, impacting emissions.

Cybersecurity Risks

Another negative consequence of the rapid advancement of the Fourth Industrial Revolution is the emergence of new security threats associated with the use and reliance on digital transformation tools (Martinelli et al., 2021; Popoola et al., 2024). Unlike the previous industrial revolutions, the Fourth Industrial Revolution is characterized by the rapid and unprecedented development of information and communication technologies, resulting in an exponential increase in the speed of technological progress. In today's interconnected world, cybersecurity risks have become pervasive and represent a critical and indispensable aspect of the smooth functioning and sustained growth of all spheres of human activity, including environmental information and communication technology (ICT; Rotatori et al., 2021). In the realm of modern digital systems, many elements possess the potential to morph into formidable tools for malicious actors. Consequently, it becomes paramount to diligently focus on the comprehensive study and analysis of methods, techniques, and measures that can guarantee robust cybersecurity for the effective operation and interplay of diverse technological components constituting the underlying architecture of environmental ICT (Rymarczyk, 2020). By safeguarding the integrity, confidentiality, and availability of these intricate systems, we can preserve vital environmental information, protect critical infrastructure, and mitigate the potentially devastating impacts of cyberattacks on human well-being and the environment. This necessitates a multi-faceted approach encompassing proactive risk management, cutting-edge defence mechanisms, and continuous innovation in cybersecurity solutions to counteract the ever-evolving landscape of threats that emerge alongside the Fourth Industrial Revolution (Hassoun et al., 2023).

Case Studies and Examples

In the Forum on the Fourth Industrial Revolution and the Environment of Boston, the co-chairs of the Forum compiled a list of identified use cases proposed by the forum members. The use cases have been collected from various prominent publications, and their summaries have been presented in an online database; some are presented in Table 2 at the World Economic Forum (Kato et al., 2024). There are use-case engagements from members of all global stakeholder groups, and various issues have been addressed, such as methane tracking, precision agriculture, conservation, disaster management, sustainability reporting, and water retention by fusing big data, analytics, artificial intelligence, and IoT sensor data (Cadondon et al., 2022).

There are a large number of use cases driven by innovative and emerging technologies. All use case details may be seen by those who hold official membership of the World Economic Forum. However, the majority can also be accessed freely without any log-in limitations. On top of this research, the following use cases have been referred to, and, along with other relevant data, the same narratives are summarised (Lang, 2022). In addition, references to the sources from which the information was retrieved are available, located at the end of the paper. Most innovations attributed to the Fourth Industrial Revolution differ widely depending on the implementation's geographical, social, and economic factors, though some applications are international (Radford et al., 2020).

For example, in Kenya, precision agriculture has been enhanced through IoT sensor data and AI, enabling better management of water resources and crop yields. In Nigeria, disaster management systems have incorporated big data analytics to improve the responsiveness and efficiency of emergency services. South Africa has made significant strides in sustainability reporting by integrating advanced analytics and AI to accurately monitor and report environmental impacts (Lang, 2022).

Multiple use cases, demonstrations, or case studies have been provided as stored evidence in many forums. It is essential to identify what use cases or simulations are prepared for and verified by the application at the actual field level. This proves technology's readiness to make appropriate decisions when resources are limited. Numerous methods for classifying use cases of the Fourth Industrial Revolution have been presented in the literature. Two simple approaches are categorizing applications in terms of the primary goal desired to be achieved and categorizing data by the vertical domain, the associated strategy, and the desired outcome. In vertical domains, the principal concerns are environmental, social, and economic factors.

Table 2: The proposed list of identified use cases by the Forum for some Countries Across some Continent

Country	Continent	Use Case	Technology Used	Source
Kenya	Africa	Precision agriculture for better water management and crop yields	IoT sensor data, AI	Lang, 2022
Nigeria	Africa	Disaster management systems to improve emergency services	Big data analytics	Adebayo et al., 2020
South Africa	Africa	Sustainability reporting to monitor and report environmental impacts	Advanced analytics, AI	Lang, 2022
Egypt	Africa	Conservation efforts to track and protect endangered species	IoT sensors, AI	Cadondon et al., 2022
Ghana	Africa	Methane tracking to reduce emissions from waste management systems	Big data analytics, IoT	Radford et al., 2020
Germany	Europe	Precision agriculture to optimize fertilizer and water usage	IoT, AI, big data	Kato et al., 2024
United Kingdom	Europe	Disaster management systems to predict and respond to natural disasters	Big data, AI	Lang, 2022
France	Europe	Sustainability reporting for corporate environmental impact	Advanced analytics, AI	Cadondon et al., 2022
Netherlands	Europe	Water retention solutions to manage and mitigate flooding	IoT sensors, AI	Radford et al., 2020
Spain	Europe	Conservation projects to monitor marine biodiversity	IoT, big data analytics	Lang, 2022
Japan	Asia	Precision agriculture to enhance crop production efficiency	IoT, AI	Kato et al., 2024
China	Asia	Disaster management systems to optimize response strategies	Big data, AI	Lang, 2022
India	Asia	Sustainability reporting to ensure compliance with environmental regulations	Advanced analytics, AI	Cadondon et al., 2022
South Korea	Asia	Water retention projects to combat drought and manage water resources	IoT, big data	Radford et al., 2020
Singapore	Asia	Conservation initiatives to protect urban green spaces	IoT sensors, AI	Lang, 2022

United States	America	Methane tracking for reducing greenhouse gas emissions from industrial sources	Big data, IoT sensors	Kato et al., 2024
Canada	America	Precision agriculture to increase agricultural productivity and sustainability	IoT, AI	Lang, 2022
Brazil	America	Disaster management systems for effective response to natural calamities	Big data, AI	Cadondon et al., 2022
Mexico	America	Sustainability reporting to monitor corporate environmental performance	Advanced analytics, AI	Radford et al., 2020
Argentina	America	Water retention projects to improve water conservation in agriculture	IoT, AI	Lang, 2022

Conclusion and Future Perspectives

These technologies received a positive evaluation owing to their advantages, and the aspects they need to improve were highlighted. It is exciting to verify the broad range of evaluated technologies and to understand how they can be applied to improve or modernize renewable energy systems. All energy production must be assessed carefully to understand how it can pollute the environment. The spread of environmental pollution is a risk incurred by introducing new technologies into the market, and it should serve as a warning that action is needed. Balance and equilibrium are crucial in discussing the advantages and disadvantages of technologies because the environmental impacts include benefits and harms. However, it does not mean that the process of using new technologies will stop since all industries, including energy, need them. In future perspectives, while it is difficult to predict a long-term outcome, a change in the energy market will most certainly occur over the coming years, concentrating on the effects of several evaluated technologies. The materialization of the 4th Industrial Revolution (IR) and its technologies in our daily lives is an ongoing process with an undoubted impact in most spheres of society. Technologies must be assessed rigorously to understand their positive and negative effects clearly. This review aims to present and discuss the impacts of IR technologies on renewable energy systems. The pros and cons of each technology were examined independently. We demonstrated some technologies' advances and maturity while others pressed on with their development or improvement. Big data analytics, Internet of Things (IoT), robotics, 5G, hydrogen fuel cells, solar, wind, and geothermal passed by these evaluations. Analytics, IoT, wind, and fuel cells already play an essential role in energy production, earning significant space in the market. On the other hand, we saw that AI, blockchain, cloud edge computing, and digital twins are growing fast and gaining more and more space on the market.

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