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CHALLENGES AND OPPORTUNITIES OF DIGITALIZING MOROCCO'S RENEWABLE ENERGY SECTOR*

Jurga Vestertė ^{1*}, Ilona Skačkauskienė ², Najiba El Amrani El Idrissi ³, Kamal Zared ⁴

^{1*} Department of Business Technologies and Entrepreneurship, Faculty of Business Management, Vilnius Gediminas Technical University (VILNIUS TECH), Lithuania

² Department of Management, Faculty of Business Management, Vilnius Gediminas Technical University, (VILNIUS TECH), Lithuania

^{3,4} University of Sidi Mohamed Ben Abdellah (USMBA), Faculty of Sciences and Technology, Morocco

E-mails: ¹ jurga.vesterte@vilniustech.lt (Corresponding author); ilona.skackauskiene@vilniustech.lt; najiba.elamrani@usmba.ac.ma; kamal.zared@usmba.ac.ma

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Abstract. This paper explores the potential of digitalization to enhance Morocco's renewable energy sector. The primary objectives are to assess the current state of digitalization within the sector, identify key challenges and opportunities, and propose recommendations for overcoming barriers to digital transformation. The study integrates a literature review with the People, Process, Technology (PPT) and Triple Bottom Line (TBL) frameworks, alongside a case study approach, expert interviews, and document analysis to gather data and draw insights. Key findings highlight the critical role of human capital, robust digital infrastructure, and a supportive regulatory environment. The research underscores that effective change management strategies are essential to overcoming resistance to change, enabling the sector to embrace digital transformation fully. By investing in skills development, building digital infrastructure, creating a supportive regulatory environment, adopting a holistic approach to sustainability, and strengthening stakeholder collaboration, Morocco can successfully navigate the challenges and capitalize on the opportunities presented by digitalization. The study concludes that the successful digitalization of Morocco's renewable energy sector requires a multi-faceted approach that addresses the economic, environmental, and social dimensions of the transition. Through the lens of Morocco's experience, this research provides valuable insights into the digital transformation of renewable energy sectors in developing countries, offering practical guidance for policymakers and industry stakeholders.

Keywords: Artificial Intelligence (AI); Cyber Physical Systems (CPSs); machine learning; cyber attacks; faults; disturbances

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1. Introduction

The transition towards a sustainable future necessitates a fundamental shift in global energy production. Renewable energy sources, such as solar and wind power, offer a promising alternative to traditional fossil fuels by reducing greenhouse gas emissions and mitigating climate change. However, integrating these renewable sources into existing energy grids poses challenges due to their inherent variability. To ensure a stable and efficient energy supply, digitalization plays a crucial role in optimizing grid management, forecasting energy production, and facilitating the wider adoption of renewable energy solutions.

Digitalization in the energy sector offers well-explored opportunities for enhanced efficiency, better integration of renewable energy, effective demand-side management, and increased transparency in decision-making, etc. For instance, smart grids equipped with real-time data analysis can optimize energy distribution, reduce transmission losses, enhance grid stability, and facilitate a greater incorporation of renewable sources. Digital tools, such as smart meters featuring time-based pricing, can incentivize reduced consumption during peak hours, thereby alleviating strain on the grid. This approach can lead to significant reductions in energy waste across various sectors. Moreover, digital platforms empower consumers with greater control over their energy usage, enabling services like mobile apps for meter readings, bill payments, and the management of connected home devices for energy-efficient operation.

However, digital transformation in the energy sector also presents typical challenges. A more digitalized grid is susceptible to cyberattacks, making the investment in robust cybersecurity measures essential to protect critical infrastructure, albeit at a high cost. The collection and analysis of energy consumption data also raise privacy concerns. To maintain consumer trust, clear regulations and stringent data security protocols must be established. Furthermore, digitalization demands investment in new technologies and infrastructure, such as smart meters and communication networks, which can pose significant challenges for developing countries, including Morocco. Additionally, digital transformation requires a workforce skilled in using digital tools, data analysis, cybersecurity, and digital grid management. Consequently, investment in training and education is vital to equip the workforce with the necessary skills.

Despite the recognized importance of both renewable energy and digitalization, research exploring their intersection within the specific context of Morocco remains limited. Existing literature offers a broad picture of global trends or focuses on developed economies. There is a scarcity of information regarding the current digitalization status within Morocco's renewable energy sector. This lack of data makes it difficult to assess the specific challenges and opportunities this North African country faces.

Furthermore, current research on digitalization in the energy sector often adopts a fragmented approach, focusing on isolated aspects like on specific technologies or applications. This approach, while valuable, fails to capture the holistic picture of the sector as an ecosystem from the management point of view. A comprehensive understanding requires examining the digitalization process within a broader theoretical framework, considering not just technological advancements but also the interplay between various ecosystem factors, like resources, processes, policy and regulations, etc.

Therefore, to effectively address the knowledge gap and pave the way for future research, this study adopts a descriptive case study approach. By developing a robust theoretical framework, the study aims to investigate the challenges and opportunities associated with the digitalization of Morocco's renewable energy sector. This case study focuses on the Moroccan renewable energy sector, examining the challenges and opportunities of digitalization within this context. While the findings of this research may have broader implications, the scope of this study is primarily limited to the Moroccan experience. By concentrating on this specific case, the research aims to provide in-depth insights into the factors influencing the digital transformation of the renewable energy sector in a developing country context.

2. Utilizing Digital Technology for the Energy Transition

The global energy landscape is undergoing a transformation, shifting away from a heavy reliance on fossil fuels toward cleaner and more sustainable energy sources (International Renewable Energy Agency – IRENA, 2023). This transition is driven by a combination of factors, including the depletion of fossil fuel reserves, growing environmental concerns, and the political imperative driven by the worldwide organizations to mitigate climate change (Dwivedi et al., 2022; Wang & Azam, 2024). Morocco has positioned itself as a leader in this global transition, with ambitious targets for renewable energy integration (Fragkos, 2023). The country's abundant solar and wind resources, coupled with supportive government policies, have created a favorable environment for the development of the renewable energy sector (Kousksou et al., 2015; Fragkos, 2023).

Digitalization, on the other hand, is the integration of digital technologies across all aspects of society and the economy. This includes the adoption, application, and utilization of digital tools, leading to new business models, economic transformation, and a fundamentally altered socioeconomic environment (Gradillas & Thomas, 2023). For organizations, digitalization signifies a modernization. It involves infusing digital tools across all organizational functions, from management to customer service. It needs to be emphasized that digitalization stands as the most significant vector of innovation impacting science, technology, business, and governance (OECD, 2020). It drives the creation of new business models and fosters digital engagements. By effectively leveraging digitalization's potential, advancements in various mentioned fields can be accelerated. This holds the potential to improve living standards, enhance environmental protection, and inform policymaking, ultimately influencing economic landscapes.

As digital technologies permeate various fields, the renewable energy sector, in particular, stands to benefit immensely from digitalization. The International Energy Agency (IEA) recognizes digital technologies as a game-changer for the renewable energy sector (Sung et al., 2021). They emphasize how these technologies can unlock several key opportunities. For instance, digital tools can help integrate more renewable energy sources into the grid by managing their variability and ensuring system reliability. Additionally, digitalization can optimize energy consumption in buildings and industries, leading to significant efficiency gains. The IEA highlights that these advancements, coupled with data analysis and smart grids, can pave the way for a more sustainable and efficient energy future.

Digitalization in the energy sector goes beyond simply boosting reliability and efficiency. It also empowers consumers to become active participants in the market (Varela, 2017). Smart meters provide real-time usage data, enabling informed energy choices and even potentially facilitating peer-to-peer energy trading. This digital transformation also fosters the emergence of new players in the energy market. Innovative startups can leverage digital platforms to offer disruptive services, such as decentralized energy solutions or personalized energy management tools. Furthermore, digitalization fuels the development of entirely new products and services, such as smart appliances that automatically adjust energy consumption or AI-powered energy management systems for businesses. The vast amount of data generated by these technologies paves the way for data-driven business models. This allows energy providers to personalize offerings, predict demand fluctuations, and optimize resource allocation, ultimately leading to a more efficient and responsive energy sector.

The inquiry will now examine some of the key technologies used in the digitalization of the energy sector. According to the literature (Varela, 2017; Asif, 2022; Idries et al., 2022; Juszczak & Shahzad, 2022; Motlagh et al., 2020; Pandey et al., 2023; Pugna et al., 2022; Rizvi, 2019; Singh et al., 2022), the energy sector leverages a range of technologies such as artificial intelligence (AI), big data, internet of things (IoT), cloud computing, blockchain to accelerate the sustainable energy transition through digital transformation (Table 1).

Artificial intelligence (AI) and its subfield machine-learning (ML) are revolutionizing renewable energy by modeling, monitoring, and forecasting both production and consumption (Asif, 2022). This fosters a more sustainable transition through optimized resource allocation and improved grid management. Big data and tools in data analytics enable the analysis of massive datasets from smart meters, sensors, and weather patterns (Pugna et al., 2022). This analysis leads to deeper insights into renewable energy production and consumption. By understanding these patterns, companies can optimize energy generation, predict demand fluctuations, and

improve grid integration. Ultimately, big data empowers a more efficient and data-driven approach to renewable energy solutions.

Table 1. Key digital technologies used in the energy sector

Technology	Description	Application Examples	Explanation
Artificial Intelligence (AI) and Machine Learning (ML)	AI uses algorithms to mimic human intelligence, while ML allows machines to learn from data without explicit programming.	Demand forecasting	AI predicts energy demand fluctuations, enabling efficient resource allocation and grid management.
		Renewable energy integration	AI optimizes the integration of variable renewable sources like solar and wind into the grid.
		Predictive maintenance	ML identifies potential equipment failures in wind turbines or solar panels, enabling preventative maintenance.
		Automated energy trading	AI algorithms can participate in energy markets, optimizing buying and selling decisions.
Big Data and Data Analytics	This involves collecting, storing, and analyzing large datasets to uncover hidden patterns and insights.	Smart grid optimization	Analyzing data from sensors and smart meters helps optimize grid operations, improve efficiency, and minimize energy losses.
		Customer behavior analysis	Data analytics helps understand energy consumption patterns, enabling personalized energy plans and targeted energy-saving initiatives.
		Risk assessment	Analyzing historical data helps predict weather patterns and potential grid disruptions, allowing for proactive measures.
Internet of Things (IoT)	A network of physical devices embedded with sensors that collect and exchange data.	Smart meters	IoT-enabled meters provide real-time energy consumption data to consumers, empowering informed energy choices.
		Smart grid management	Sensors monitor and report on grid conditions, enabling real-time adjustments and improved reliability.
		Renewable energy monitoring	IoT sensors track performance and health of solar panels, wind turbines, and other renewable energy assets.
		Distributed energy management	IoT connects distributed energy resources like rooftop solar panels, enabling efficient control and integration with the grid.
Cloud Computing	Provides on-demand access to computing resources like storage, servers, and software over the internet.	Data storage and analysis	Cloud platforms offer scalable storage and processing power for massive datasets generated by the renewable energy sector.
		Remote monitoring and control	Cloud-based systems enable real-time monitoring and control of distributed energy resources and smart grid infrastructure.
		Advanced analytics and AI development	Cloud computing provides the resources and infrastructure for running complex AI algorithms and big data analysis tools.
Blockchain	A secure, distributed ledger technology that facilitates transparent and verifiable transactions.	Peer-to-peer energy trading	Blockchain can enable secure and transparent peer-to-peer trading between consumers with renewable energy sources.
		Renewable energy certificates (RECs)	Blockchain can track and verify the ownership of RECs, ensuring authenticity and preventing fraud.
		Decentralized grid management	Blockchain can support decentralized energy models where consumers can buy and sell energy directly from each other.

Source: created by the authors based on Asif (2022), Idries et al. (2022), Juszczuk & Shahzad (2022), Motlagh et al. (2020), Pandey et al. (2023), Pugna et al. (2022), Rizvi (2019), Singh et al. (2022), and Varela (2017).

IoT technology is a game-changer for renewable energy. The network of connected devices enabled by this technology fosters the creation an “Internet of Energy” for optimizing production, distribution, and consumption (Motlagh et al., 2020; Simion et al., 2023; Varela, 2017). The benefits of cloud computing are also being harnessed in the renewable energy sector. Energy companies are integrating cloud-based solutions into their operations, enabling a more efficient and data-driven approach (Pandey et al., 2023). The cloud's scalability allows for streamlined data analysis and resource allocation, while also facilitating remote monitoring of renewable energy systems. Additionally, the cloud's vast storage capacity unlocks the potential of big data, allowing companies to extract valuable insights for better decision-making. Finally, blockchain, initially popularized for its secure transactions in the financial sector, is now gaining traction in the renewable energy sector. This technology facilitates secure peer-to-peer energy trading and transparent record-keeping for renewable energy certificates (Idries et al., 2022; Juszczuk & Shahzad, 2022). By doing so, blockchain paves the way for innovative digital business models and services within the energy landscape.

While not strictly classified as “digital technologies” themselves, robotics and automation solutions also play a crucial role in the digitalization of the renewable energy sector (Rizvi, 2019; Simion et al., 2023). They are being strategically implemented, particularly in areas like energy distribution automation and field operations.

This integration allows for enhanced efficiency and data collection. For example, robots can be deployed for automated inspection and maintenance of wind turbines or solar panels, improving safety, and reducing downtime. Similarly, drones equipped with sensors can be used to collect data on grid infrastructure, facilitating predictive maintenance and optimizing resource allocation. Combined with digital technologies like AI and data analytics, robotics and automation become powerful tools that ensure the smooth functioning of renewable energy systems.

Digitalization is widely recognized as a key catalyst for accelerating the energy sector's transition to a more sustainable model (Ersoy et al., 2022). As previously discussed, various digital technologies, such as AI, big data, IoT, cloud computing, and blockchain, are transforming how energy is produced, managed, and consumed within the renewable energy sector. To effectively leverage these digital advancements, a comprehensive understanding of the current state of the digitalization of Morocco's renewable energy sector is crucial. This understanding should encompass both the challenges and opportunities that exist. The investigation necessitates a structured approach to data collection and analysis. A theoretical framework will be employed to achieve this. The following sections will outline this framework, detailing the methodologies and data collection strategies employed to analyze the current state of the sector and its ongoing digital transformation.

3. Theoretical Framework

Case studies delve deeply into specific contexts, aiming to understand complex phenomena within a particular setting (Swanborn, 2018). To achieve this, a well-defined theoretical framework serves as the cornerstone of the analysis (Collins & Stockton, 2018). This framework outlines the key concepts, theories, and models that will guide the research process. It acts as a lens through which the researcher examines the case study, ensuring a systematic and focused approach. By establishing a theoretical framework, the case study gains a stronger foundation, allowing for a more insightful and meaningful interpretation of the data collected.

For a comprehensive analysis of the opportunities and challenges surrounding the digitalization of Morocco's renewable energy sector, this study will employ two complementary frameworks: the People, Process, Technology (PPT) framework and the Triple Bottom Line (TBL) framework. This integrated approach, as recommended by Machado et al. (2024), can offer a richer understanding of the complex phenomena involved in the transformation studied. These phenomena encompass multiple goals, diverse stakeholders, the challenges of organizational change, and technology integration – all crucial aspects for successful digitalization in the renewable energy sector. Ultimately, by integrating the PPT and TBL frameworks, this study can more effectively investigate the potential benefits and challenges associated with digitalizing Morocco's renewable energy sector.

The People, Process, Technology (PPT) framework, originating in the 1960s from the field of business management, offers a practical lens for analyzing change initiatives (Simon, 2021). It emphasizes the need for a well-balanced interplay between three key elements: People, Process, and Technology. The “People” aspect focuses on the skills, knowledge, and leadership required to implement change effectively. “Process” examines the existing workflows and ensures their compatibility with new technologies. Finally, “Technology” considers the selection and implementation of appropriate digital tools to support the transformation.

In the context of Morocco's renewable energy sector digitalization, the PPT framework can serve as a valuable tool for identifying potential gaps and areas for improvement. By analyzing the capabilities of the workforce, the efficiency of current processes, and the suitability of planned technological solutions, the PPT framework can guide the development of a comprehensive digitalization strategy. This ensures that Morocco leverages the full potential of digital technologies to achieve its renewable energy goals.

The Triple Bottom Line (TBL) framework, encompassing Economic, Environmental, and Social dimensions – also sometimes referred to as 3Ps of Sustainability (People, Planet, Profit) – emerged in the mid-1990s as a response to the growing emphasis on corporate social responsibility. While its exact origin can be traced back to the work of various thought leaders and publications, John Elkington (Elkington, 1998) is widely credited with popularizing the concept. The TBL framework is commonly used to assess the social, environmental, and financial impacts of an organization's activities. The “Economic” dimension focuses on financial performance

and viability, considering factors like profitability, resource efficiency, and impact on the local and global economy. The “Environmental” dimension assesses the organization’s impact on the natural environment, taking into account factors like pollution, resource depletion, and climate change. The “Social” dimension examines the effects on people and society, including labor practices, community development, and human rights. The TBL framework encourages consideration of these three dimensions simultaneously, aiming for a balance between financial success, environmental responsibility, and social well-being. It promotes a more holistic approach to decision-making, ensuring long-term sustainability.

In the context of Morocco’s renewable energy sector and its digitalization, the TBL framework can provide a necessary lens for assessing the initiatives’ long-term impact. Evaluating the social impact on local communities – including job creation, training opportunities, and potential disruptions – ensures a more comprehensive approach. Additionally, it prompts consideration of the environmental impact of digital technologies on resource consumption, waste generation, and the potential for lifecycle assessments. This broader perspective enables policymakers and stakeholders to make informed decisions that not only achieve renewable energy goals but also promote social equity, environmental responsibility, and a balanced transition within Morocco.

Further, the two established frameworks – PPT and TBL – are merged to create a comprehensive analytical matrix (Table 2). By combining these frameworks, the key clusters within the resulting matrix are identified.

Table 2. Leveraging a combined (PPT and TBL) framework for data collection matrix

TBL \ PPT	People <i>Skills and training needed for workforce and consumers</i>	Process <i>Seamlines and optimization of existing processes</i>	Technology <i>Specific technologies that can be leveraged</i>
Economic <i>Economic benefits and costs associated</i>	Upskilling the workforce with digital knowledge can lead to increased efficiency, potentially lowering operational costs and improving productivity.	Optimizing processes through digital tools can lead to significant cost savings, improved resource allocation, and potentially lower energy prices for consumers.	Investing in digital technologies can lead to long-term cost savings through increased efficiency and potentially open new markets for innovative renewable energy solutions.
	Job displacement might occur if digitalization automates existing tasks, impacting some workers' economic security.	Implementing new digital processes can be expensive, with upfront costs in infrastructure and software potentially creating financial strain.	The upfront investment in digital technologies can be significant, possibly impacting short-term financial stability.
Environmental <i>Optimization of energy production and distribution, minimizing environmental footprint</i>	A digitally skilled workforce and consumers can be trained to operate and maintain renewable energy systems more effectively, potentially reducing energy waste.	Digital tools can help optimize energy production and distribution, minimizing waste and maximizing resource utilization.	Technologies (smart grids) can optimize renewable energy production and distribution, leading to reduced greenhouse gas emissions.
	If digital training programs are not widely accessible, it could create a skills gap hindering optimal environmental performance.	Lack of standardization and interoperability, leading to inefficient implementation of digital processes might result in increased energy consumption for data centers and computing needs.	Manufacturing and disposal of digital technologies can create an environmental footprint, so responsible lifecycle management is crucial.
Social <i>Impact on communities and stakeholders</i>	Digital skills development can empower workers, offering opportunities for career advancement within the renewable energy sector.	Streamlining processes through digitalization can improve overall system reliability, security standards, potentially leading to fewer disruptions and improved renewable energy accessibility for communities.	Digital technologies can facilitate the development of innovative renewable energy solutions and new business models, potentially creating new markets and new jobs, ultimately improving living standards.
	Digital training programs might inadvertently exclude certain demographic groups due to accessibility issues,	If digitalization leads to job losses, it could have a negative social impact on affected communities.	Digital technology access might be uneven across different regions, potentially

TBL \ PPT	People <i>Skills and training needed for workforce and consumers</i>	Process <i>Seamlines and optimization of existing processes</i>	Technology <i>Specific technologies that can be leveraged</i>
	exacerbating social inequalities.		exacerbating existing inequalities.

Source: created by the authors

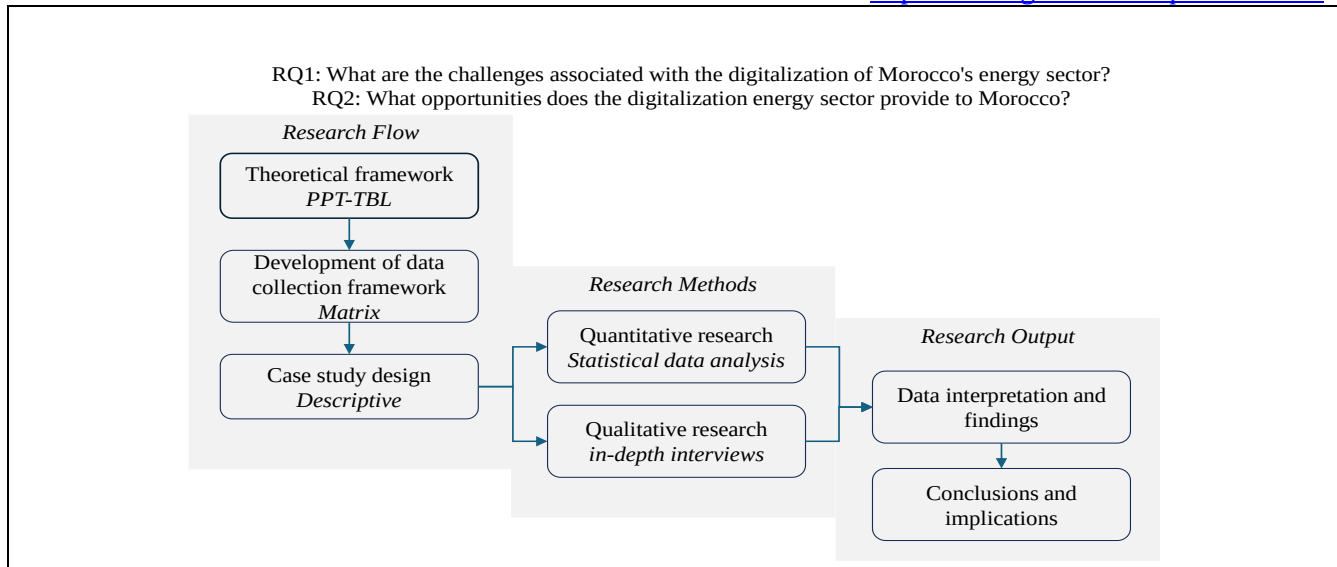
The transition to renewable energy presents a crucial opportunity for Morocco. However, digitalization, a key driver of this shift, can generate conflicting outcomes. Analyzing this process through the combined lens of the PPT and TBL frameworks (Table 2) reveals these potential contradictions. On the one hand, digitalization offers economic benefits. Optimizing processes (PPT) through data-driven decision making (TBL-Economic) can lead to cost savings. Technology (PPT) like sensor networks can improve energy production and distribution efficiency (TBL-Economic & Environmental). However, these advancements might come at the cost of job displacement (PPT-People & TBL-Social). Training existing employees or hiring new specialists with digital skills (PPT-People) could lead to short-term economic burdens (TBL-Economic). The environmental impact of digitalization also presents a complex picture. Digital tools for optimizing energy production (PPT-Process) can significantly reduce waste (TBL-Environment). However, the environmental footprint of the technology itself (e.g., manufacturing sensors, energy-hungry data centers, etc.) needs careful consideration (TBL-Environment). Additionally, ensuring accessibility to digital training for all employees (PPT-People & TBL-Social) is crucial to prevent exacerbating social inequalities.

The analysis conducted through the combined application of the PPT and TBL models highlights the importance of a nuanced strategy for digitalizing Morocco's renewable energy sector. Simply embracing technological advancements or economical pursuits without considering the potential downsides could lead to unintended consequences. Having established a theoretical framework to guide the analysis, the following section outlines the research methodology employed to investigate the challenges and opportunities of digitalizing Morocco's renewable energy sector.

4. Methodology

This research has adopted a descriptive case study method to investigate the challenges and opportunities associated with the digitalization of Morocco's renewable energy sector. The ability to investigate instances of the phenomenon being studied in depth, and to employ multiple sources of evidence, makes case study design a useful tool for descriptive studies where the focus is on specific situation or context (Rose et al., 2024). A descriptive case study is a case study whose purpose is to describe a phenomenon (the “case”) in its real-world context (Yin, 2018). The “case” may be an individual, or it can be some event or entity other than a single individual, and it can include a variety of topics, such as small groups, communities, decisions, programs, organizational change, etc. The appropriate case might be a country's economy, an industry in the world marketplace, an economic policy, or the trade or capital flow between countries (Yin, 2018). Thus, the unit of analysis for our case study is derived from the research aim – the digitalization of Morocco's renewable energy sector.

The unit of analysis is related to the research question. The selection of a descriptive case study is guided by the main empirical research question, which was formulated as follows – what are the prerequisites for the digitalization of Morocco's energy sector? To provide a structured approach to the research, the main research question is divided into two sub-questions: 1) what are the challenges associated with the digitalization of Morocco's energy sector? 2) what opportunities does the digitalization of energy sector provide to Morocco? These sub-questions permit a more detailed and comprehensive description of the research topic. Moreover, a linear-analytic research design was applied to ensure research rigor (see Figure 1).

**Figure 1.** Methodology of the research

Source: created by authors

A linear-analytic research design requires to follow the sequence of the research: it starts with the issue being studied and a review of the relevant literature, then proceed to cover the methods used, the data collected, and the data analysis and findings, ending with the conclusions and their implications (Yin, 2018).

Literature review can reveal important insights into the development of the research topic. Reviewing a particular (stream of) literature is essentially learning about the history, the present state, and the potential future developments of a specific realm (Michailova, 2023). A literature review revealed the key stakeholders in Morocco's renewable energy sector:

Government and Regulatory Institutions

This group, encompassing entities responsible for shaping the digitalization landscape through relevant policies, regulations, and investment plans, establishes the policy framework for renewable energy development and digitalization.

International Organizations

International organizations play a crucial role in supporting Morocco's digitalization efforts. They offer expertise and support for renewable energy initiatives by providing technical assistance, financial resources, and knowledge sharing. These contributions empower Morocco to achieve its economic, environmental, and social goals.

Private Companies

This category comprises energy and IT companies that act as the driving force behind digitalizing the renewable energy sector. They achieve this by developing, implementing, and investing in cutting-edge digital technologies within the sector.

Research Institutions and Academia

Universities and research institutions play a vital role in supporting the successful digitalization of the renewable energy sector. They achieve this by generating knowledge, developing innovative solutions, and training the future workforce.

Community and Consumers

The digitalization of the renewable energy sector directly impacts two key stakeholder groups: local communities residing near renewable energy projects and the general public who consume the generated energy.

Table 3 summarizes potential data contributions from the identified stakeholders within the context of the established theoretical framework.

Table 3. Key stakeholder groups and data contributions

Stakeholder Group	Data Contributions	Relevance to integrated PPT-TBL framework
Government and Regulatory Institutions	<i>Existing regulations and policies</i> This data will help identify potential hurdles or areas where adjustments might be necessary to facilitate the smooth integration of digital technologies within the sector.	Process (PPT), Economic (TBL)
	<i>Investment incentives</i> Understanding the existing and potential investment incentives offered by the government can inform strategies for attracting private sector participation in digitalization efforts.	Economic (TBL)
	<i>Potential roadblocks for digital transformation</i> By identifying potential roadblocks, such as infrastructure limitations or regulatory gaps, stakeholders can develop solutions and mitigate these challenges.	Process (PPT), Economic (TBL), Technology (PPT) (if infrastructure related)
	<i>Social concerns</i> Data from government agencies can offer insights into potential social concerns related to digitalization, such as job displacement or data privacy issues. Understanding these concerns allows for proactive measures to address them and ensure public acceptance.	Social (TBL)
	<i>Environmental regulations and monitoring</i> Government data on existing environmental regulations and monitoring practices can inform how digital solutions can be leveraged to ensure the environmental sustainability of the digitalized renewable energy sector.	Environmental (TBL)
International Organizations	<i>Technical assistance and expertise</i> International organizations can provide direct technical assistance by deploying experts to work alongside Moroccan counterparts on specific digitalization projects within the renewable energy sector.	Technology (PPT)
	<i>Financial resources or instruments</i> They can offer access to a variety of financial instruments such as grants, loans, or blended finance mechanisms to support investment in digital infrastructure and technology development for renewable energy.	Economic (TBL)
	<i>Knowledge sharing and best practices</i> International organizations can facilitate the creation of knowledge exchange platforms that connect Moroccan stakeholders with experts and practitioners from other countries who have successfully implemented digital solutions in the renewable energy sector. These platforms can foster collaboration, knowledge sharing, and the transfer of best practices. This could involve best practices for waste management associated with digital technologies, life-cycle assessments of different solutions, or promoting energy efficiency through digital tools.	Process (PPT), Environmental (TBL)
Private Companies	<i>Workforce Skills and Training Needs</i> Companies can contribute data on the specific skills and expertise required within their organizations to successfully implement digital solutions for renewable energy projects. This might include information on technical skillsets, data analysis capabilities, or project management expertise.	People (PPT)
	<i>Data management practices and cybersecurity considerations</i> Data on the challenges companies face when integrating digital solutions with existing infrastructure is crucial. This could involve aspects like data compatibility, cybersecurity concerns, or the need for upgrades to existing equipment.	Process (PPT), Technology (PPT)
	<i>Innovation and New Business Models</i> Companies are encouraged to share data on their ideas for innovative digital solutions and potential new business models with respective revenue streams within the digitalized renewable energy sector. This could involve novel applications of existing technologies, data-driven service offerings, or entirely new approaches to energy production or distribution.	Economic (TBL), Technology (PPT)
	<i>Investment plans for renewable energy integration</i> Data on how companies plan to integrate renewable energy sources into their digital solutions can contribute to the environmental dimension. This could involve information on using digital tools to manage and optimize the integration of renewable energy sources like solar or wind power.	Economic (TBL) Process (PPT)

Stakeholder Group	Data Contributions	Relevance to integrated PPT-TBL framework
	<i>Return on Investment (ROI) Expectations</i> Companies can provide data on their anticipated ROI for various digitalization projects. This data can help assess the financial feasibility of different technological solutions and identify areas where incentives or policy adjustments might be needed to support wider adoption.	Economic (TBL)
	<i>Data on the environmental impact of new technologies</i> Companies can provide data on the life-cycle assessments (LCA) of the digital solutions they propose to implement. LCAs evaluate the environmental footprint of a product or service throughout its life cycle, from resource extraction to disposal. This data can help assess the environmental impact of different digitalization options and identify solutions with a lower environmental footprint.	Environmental (BTL)
	<i>Data on waste management practices</i> Information on how companies plan to manage and dispose of any electronic waste generated by the new digital technologies can be valuable. Responsible waste management practices are crucial for minimizing the environmental impact of digitalization.	Environmental (TBL), Process (PPT)
	<i>Data on energy efficiency improvements</i> Companies can provide data on the potential energy efficiency gains expected from their proposed digitalization solutions. This could involve information on how digital tools can optimize energy production, distribution, and consumption, ultimately reducing the environmental impact of the renewable energy sector.	Environmental (TBL)
	<i>Social Responsibility Initiatives</i> Data on existing or planned social responsibility initiatives related to digitalization can be valuable. This might include data on workforce training programs, community engagement efforts, or plans to address potential job displacement or skill gaps arising from digital transformation.	People (PPT), Social (TBL)
Research Institutions and Academia	<i>Collaboration with industry</i> Data on existing or planned collaborative efforts between research institutions and industry stakeholders (including private companies) can be beneficial. This could involve collaborative research projects, joint development of practical solutions, or student internship programs that bridge the gap between theory and real-world application.	Process (PPT)
	<i>Development of environmentally sustainable digital solutions</i> Data on research efforts focused on developing or adapting digital solutions that minimize environmental impact can be valuable. This could involve research on energy-efficient hardware and software for digital technologies used in the renewable energy sector or exploring the use of recycled materials in these technologies.	Environmental (TBL), Technology (PPT)
	<i>Open-Source Technology Development</i> Data on research efforts related to the development and adaptation of open-source digital technologies suitable for the Moroccan renewable energy sector can be valuable. This information can inform companies about potential solutions that are readily available and adaptable to their specific needs.	Technology (PPT), Process (PPT)
	<i>Skills Gap Analysis</i> Research institutions can contribute data on their assessments of existing skill gaps within the workforce relevant to the digitalization of the renewable energy sector. This data can help identify areas where curriculum development or targeted training programs are needed to equip future generations with the necessary skills.	People (PPT)
	<i>Research on economic modeling for digitalization of renewable energy sector</i> Research institutions can contribute data on their existing or planned research addressing economic models for digitalization within the renewable energy sector. This could include data on cost-effectiveness analysis of different technological solutions or potential financial benefits for both companies and consumers.	Economic (TBL)
	<i>Social impact assessments</i> Data on existing or planned research methodologies for assessing the social impacts of digitalization on the renewable energy sector can be insightful. This could involve frameworks for evaluating potential job displacement, skills gaps, or the need for social safety nets during the transition.	Social (TBL)

Stakeholder Group	Data Contributions	Relevance to integrated PPT-TBL framework
	<i>Research on the environmental sustainability and environmental impact of digital renewable energy solutions</i> Research institutions can contribute data on the environmental impact of different digital solutions being considered for the renewable energy sector. This could involve life-cycle assessments (LCA) of specific technologies, comparative analyses of environmental footprints, or research on potential environmental risks associated with digitalization (e.g., e-waste management), frameworks for evaluating the environmental impact of different solutions or tools to measure the effectiveness of environmental risk mitigation strategies.	Environmental (TBL)
Community and Consumers	<i>Existing skills and knowledge within the community</i> Data on existing levels of digital literacy and access to technology within the communities served by private companies can be helpful. This could involve information on internet penetration, smartphone ownership, or comfort levels with using digital tools.	People (PPT)
	<i>Concerns about job displacement or traditional energy use</i> Data on community concerns regarding potential job displacement or changes in traditional energy use patterns can be informative. Additionally, understanding their expectations for increased participation in decision-making processes around digitalization can be valuable.	Social (TBL), Economic (TBL), Process (PPT)
	<i>Energy Conservation Practices</i> Data on existing energy consumption patterns and community attitudes towards energy conservation can be helpful. This could involve information on preferred communication channels for energy-saving tips or willingness to participate in demand-response programs facilitated by digital technologies.	Environmental (TBL), Process (PPT)
	<i>Access to technology and affordability concerns</i> Data on potential social equity concerns arising from digitalization can be valuable. This might involve concerns about unequal access to information or potential benefits within the community, particularly for low-income residents.	Social (TBL), Economic (TBL), Technology (PPT)

Source: created by the authors based on Bahgat (2013), Bakkari et al. (2024), Bouabid et al. (2019), Cantoni & Rignall (2019), Choukri et al. (2017), Fragkos (2023), Kousksou et al. (2015), Moore (2021), Plank et al. (2023), and Schinko et al. (2019).

To gather data for this study, a mixed-methods approach was employed, allowing for the triangulation of findings. A combination of qualitative (in-depth interview) and quantitative (statistical data analysis) methods permits the describe the energy sector situation in Morocco as well as gain insights associated with the digitalization of Morocco's energy sector. In-depth interviews are useful for deriving detailed information or to get insights into the lived experience of participants (Rose et al., 2024). According to De Massis & Kotlar (2014), interviews are often the primary data source in case studies, as they are a targeted, insightful, and highly efficient means of collecting empirical data. The in-depth interviews were conducted with five key experts representing Government and Regulatory Institutions, International Organizations, Research Institutions and Academia, and Private Companies. These interviews provided rich qualitative data on the sector's dynamics and informed the subsequent analysis. Additionally, a thorough analysis of relevant documents, including reports, strategies, and policies, was undertaken to supplement the interview data. To provide a broader context, secondary data, such as statistical information on Morocco's energy and digital landscape, was incorporated into the analysis. This triangulation of data collection methods enhanced the credibility and robustness of the research findings.

While pre-established theoretical frameworks, such as the PPT and BTL models, provide a valuable structure for analysis, it was essential to maintain methodological flexibility to capture the nuances of stakeholder perspectives. As suggested by grounded theory (Charmaz & Thornberg, 2021), allowing for emergent themes can enrich the research findings. By developing a set of initial guiding questions based on the chosen framework and remaining open to unforeseen insights, researchers could more effectively address the research objectives. During in-depth interviews conducted in English and French with stakeholder representatives, researchers adapted their questioning style based on the conversation's flow and the representative's insights. This flexibility allowed for deeper exploration of unforeseen issues or perspectives that emerged during the interview. Similarly, when analyzing reports and documents, the investigation was not limited to the initial

guiding questions. Instead, framework analysis was used to reveal new aspects or viewpoints not anticipated initially. The obtained data were carefully systematized to derive findings and draw conclusions.

5. Results

The following sub-sections present the findings of the research on the challenges and opportunities associated with digitalizing Morocco's renewable energy sector. By examining the country's energy landscape, stakeholder perspectives, and other relevant data, the study provides a foundation for understanding the current state of the sector and identifying key factors influencing its development.

Morocco's Energy Landscape

Morocco is experiencing a rapidly growing population, industrial development, and urbanization. These factors are driving a significant increase in the country's energy consumption. However, there was a slight decrease of 1.4% in total energy consumption in 2022, following an 8% increase in 2021 (Enerdata, 2024). Despite some fluctuation, Morocco relies heavily on imported hydrocarbons to meet its energy needs. Currently, the country imports approximately 90% of its energy needs (International Trade Administration – ITA, 2024).

Morocco uses six main resources for its energy supply: oil, coal, natural gas, hydropower, wind, and solar. Oil remains the dominant source, accounting for 56% in 2021, followed by coal (38.8%) (Figure 1). While oil consumption has been relatively stable since 2011, coal use has steadily increased by 43% between 2011 and 2021 (Figure 2). Conversely, renewable energy sources like wind and solar are experiencing significant growth. Their production has jumped from 2,372 TJ in 2010 to 37,370 TJ in 2021, a fifteenfold increase.

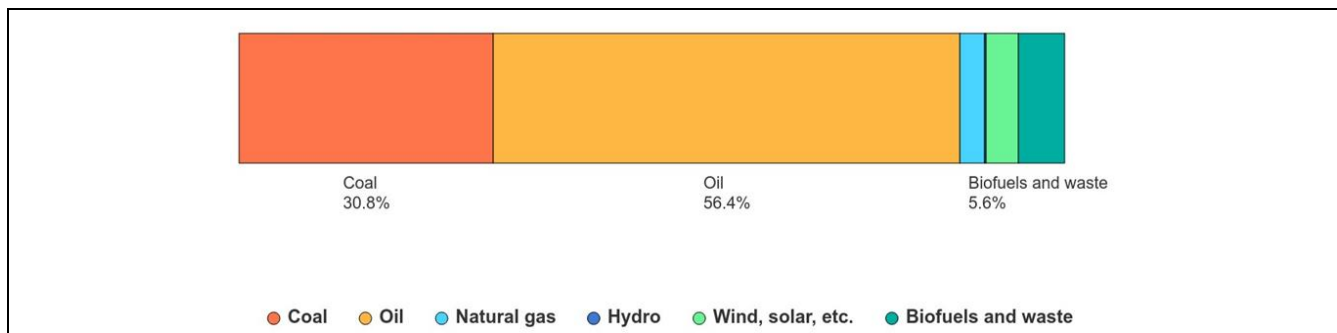


Figure 2. Total energy supply in Morocco during 2021

Source: International Energy Agency – IEA (2024)

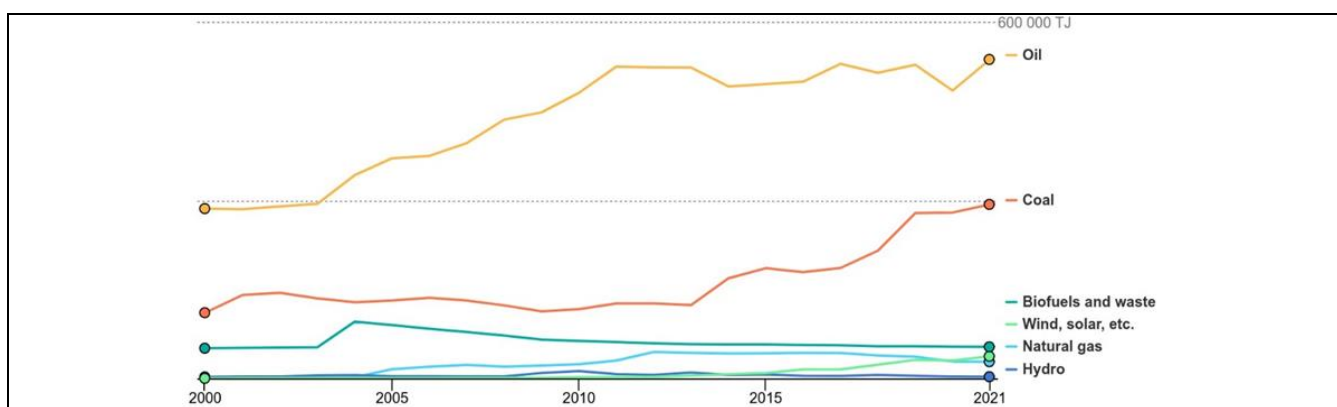


Figure 3. Evolution of total energy supply in Morocco (2000–2021)

Source: International Energy Agency – IEA (2024)

Recognizing the need for energy security and environmental sustainability, the Moroccan government aims to reduce dependence on imported fossil fuels and increase renewable energy use. This aligns with their commitment to the Paris COP21 agreement and Nationally Determined Contributions (NDCs). To achieve this, Morocco has launched several initiatives to boost the use of renewable energy sources for electricity production (Ministry of Energy Transition and Sustainable Development – METSD, 2024).

By 2022, Morocco had a total installed power capacity of 10,830 MW, with renewables contributing 38% (4,031 MW) according to the Ministry of Energy Transition and Sustainable Development – METSD (2024). This includes wind power (13.48%), hydropower (16.70%), and solar power (7.82%). This growth continued by the end of 2023, with the National Office of Electricity and Drinking Water – ONEE (2024) reporting a total installed power capacity of 11,474 MW. Notably, green installed power reached 4,672 MW, representing a 15.9% increase from 2022. This clean installed power is the result of 38 wind energy sub-projects, 23 hydropower sub-projects, and 19 photovoltaic plant sub-projects across different regions of Morocco (Ministry of Energy Transition and Sustainable Development – METSD, 2024).

Morocco's abundant renewable resources and favorable investment climate make it an attractive destination for international investors. Its impressive ranking of 2nd in Ernst & Young's Renewable Energy Country Attractiveness Index (RECAI) (Ernst & Young, 2023), specifically in the normalized index, underscores its significant potential in the renewable energy sector. The RECAI evaluates countries based on market attractiveness, technology-specific scores, and global market trends, adjusting for economic size to highlight exceptional performance in smaller markets. This high ranking reflects Morocco's robust policy support, favorable investment climate, and successful deployment of renewable energy projects, positioning it as a leading market for renewable energy investment and development. Consequently, the quality of renewable resources and the supportive investment climate have led to a significant drop in wind and solar power costs, making them competitive with fossil fuel-based electricity.

Morocco has experienced increasing electricity consumption in recent years, with figures indicating a steady growth trend (Rahhou, 2024). While total primary energy consumption has historically increased by 5% annually since 2004, Morocco aims to reduce consumption by 15% from 2016 levels by 2030 through energy efficiency measures (International Trade Administration – ITA, 2024). In 2022, the country's electricity production mix was diverse, with coal leading at 37.25%, followed by hydroelectricity (16.70%), natural gas (17.72%), wind (13.48%), solar (7.82%), and fuel oil (7.03%) (International Trade Administration – ITA, 2024).

Renewable Energy Integration

Morocco's energy sector has historically relied heavily on imported fossil fuels, leading to significant economic vulnerabilities. However, the country possesses abundant solar and wind resources, presenting a compelling opportunity to diversify its energy mix and enhance energy security.

In response to the energy crisis and the growing global focus on climate change, Morocco launched a comprehensive renewable energy program in 2009 (Alami, 2021). The Moroccan Solar Plan (MSP) emerged as a flagship initiative, aiming to develop large-scale solar power projects (Anouar, 2022; NDC Partnership, 2016). Furthermore, the country has set ambitious targets for increasing the share of renewable energy in its electricity mix, with a goal of exceeding 52% by 2030. With this strategy, Morocco aims to position itself as a key electricity hub for North and West Africa, leveraging its renewable energy initiatives to enhance regional energy connectivity and sustainability (Simpara, 2024; World Economic Forum, 2024).

To achieve these targets, the Moroccan government has established a supportive policy framework and initiated institutional reforms to implement the national energy strategy. Key reforms include the creation of the National Regulatory Authority (ANRE) and the Moroccan Agency for Sustainable Energy (MASEN), both of which play significant roles in developing renewable energy projects. The Moroccan Agency for Energy Efficiency (AMEE) is now responsible for implementing energy efficiency programs. Additionally, the Institute for Research in Solar Energy and Renewable Energies (IRESEN) conducts extensive research, development, and innovation activities in collaboration with the private sector. These efforts aim to ensure rapid technology transfer and translate research results into innovative products in renewable energies, energy efficiency, and new energy sources (Centre National pour la Recherche Scientifique et Technique – CNRST, 2021). Collectively, these institutions are crucial in driving renewable energy investments and facilitating the integration of renewable energy sources into the grid.

The development of renewable energy projects is primarily driven by the MSP, which is part of Morocco's energy strategy focusing on REs and sustainable development. Several other strategies and roadmaps support

Morocco's energy transition, including the Long-Term Low Emissions Development Strategy (LT-LEDS) Morocco 2050, Office of Electricity and Drinking Water (ONEE) Production Master Plan for 2040, PtX Roadmap, Biomass Energy Valorisation (VEB) Strategy, Roadmap for the Exploitation of Marine Energies, Cluster Green H2, National Sustainable Development Strategy (SNDD), National Energy Efficiency Strategy 2030, updated NDCs, National Climate Plan (PCN), Green Economy Strategy, National Water Plan 2050, and Morocco Vision 2050.

While the focus has primarily been on solar and wind energy, Morocco is also exploring the potential of other renewable sources, such as hydropower and biomass. Recent political debates indicate that Morocco also plans to develop a green hydrogen economy. The country aims to become an exporter of green hydrogen and its derivatives in the future, addressing domestic market needs, particularly the production of green ammonia. Energy partnerships with European countries and international hydrogen agreements underline the political support for developing a green hydrogen sector in Morocco.

Additionally, the announcement of the European Union (EU) and Morocco to establish a "Green Partnership" highlights the intentions to cooperate in advancing the energy transition (European Commission, 2021). The Moroccan government has expressed the intention to integrate more renewable energy sources into the energy mix, aiming for more than 52% renewable energy share in the capacity mix by 2030 (International Energy Agency – IEA, 2019). This share includes 20% from solar energy, 20% from wind energy, and 12% from hydro energy.

The energy transition is accompanied by many initiatives of National Center for Scientific and Technique Research (NCSTR), as encouraging Moroccan's researchers to develop studies, research and patents linked to renewable energy. According to the International Renewable Energy Agency – IRENA (2024), there has been a significant increase in patent filings in Morocco following its commitment to renewable energy in 2009. The report highlights that out of the 364 patents filed in the field of renewable energy between 2009 and 2020, 159 originated from Morocco, with the remaining patents primarily filed by European countries such as Spain (41), France (35), and Germany (31).

Morocco's Digital Landscape

Morocco's digital landscape has undergone significant transformations in recent years, driven by investments in infrastructure, government policies, and increased access to technology, according to the 2023 data of the globally recognized Network Readiness Index (NRI). This composite index is published annually by the World Economic Forum (WEF) in collaboration with academic institutions (European Commission, 2023; Portulans Institute, 2024). It aims to measure the degree of readiness of countries to exploit opportunities offered by information and communications technology (ICT). The Network Readiness Index (NRI) focuses on four key dimensions: technology, individuals, governance, and impact. Each pillar is comprised of three sub-pillars, supported by 58 indicators. These indicators encompass topics such as emerging technologies like artificial intelligence (AI) and the Internet of Things (IoT), as well as the role of digital transformation in advancing the Sustainable Development Goals (SDGs).

Morocco has traditionally occupied a mid-range position within the global NRI rankings, however, there has been a notable shift in its ranking in recent years. In an effort to align with emerging technologies and enhance its economic competitiveness, Morocco established the Digital Development Agency (ADD) in 2017. This autonomous public institution is responsible for driving the country's digital transformation and fostering digital literacy. In 2023 the country is positioned 77th out of a sample of 134 countries (Portulans Institute, 2023). Morocco has shown steady progress in improving its digital infrastructure and technological capabilities reaching the 72nd out of the 134 economies included in the NRI 2023 (Figure 4), but challenges remain in areas such as digital literacy, and e-participation.

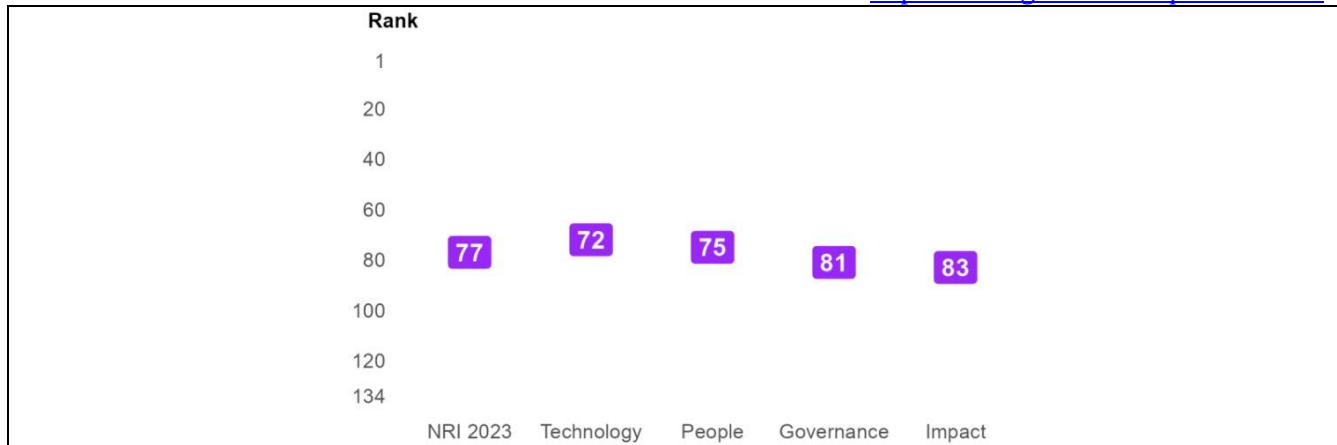


Figure 4. Morocco global NRI ranking, overall and by pillar

Source: Portulans Institute (2023)

Morocco's performance in the Technology pillar of the 2023 Network Readiness Index (NRI) is marked by significant progress. Morocco's solid foundation in digital infrastructure is evident in its high rankings for "International Internet bandwidth" (21st) and "FTTH/building Internet subscriptions" (43rd). This indicates a robust connectivity landscape that supports digital innovation and economic growth. The country's investment in emerging technologies is demonstrated by its strong performance in "AI scientific publications" (27th). This suggests a growing focus on research and development in cutting-edge technologies, positioning Morocco for future competitiveness.

Morocco has made significant progress in expanding mobile network coverage and improving international internet bandwidth. According to the country's Ministry of Economy and Finance (Simpara, 2023), the number of mobile subscriptions reached approximately 55.9 million in 2023, representing a penetration rate of 150.9%. This surpasses the penetration rate of developed countries and confirms Morocco's strong position in mobile telecommunications (26th). Despite improvements, fixed broadband subscriptions remain relatively low compared to some other countries in the region. This can hinder the adoption of data-intensive services and limit the potential for digital transformation. While mobile tariffs have decreased, the cost of mobile handsets and, in some cases, fixed broadband subscriptions can still be a barrier to access for certain segments of the population. The country's efforts to develop local digital content, including mobile applications, have been limited compared to other MENA nations. This impacts the diversity and relevance of digital services available to Moroccan users.

In the People Pillar, Morocco's performance reflects both progress and areas needing further development. This pillar assesses the readiness of individuals, businesses, and governments to use and benefit from ICT. Morocco has made significant strides in increasing internet access among its population. The country has a high percentage of individuals using the internet, which is a positive indicator of digital inclusion. According to the International Telecommunication Union (2023) estimates, 91% of the population was using the internet in 2022. This growth is driven by several factors, including improved infrastructure, and rising smartphone adoption. While internet penetration is high overall, there is a slight gender gap, with 90% of male and 86% of female populations using the internet in 2021. This suggests that efforts to bridge the digital divide should continue to ensure equal access for all. Internet usage is highest among younger age groups, with 99% of 15-24-year-olds and 85% of 25-74-year-olds online in 2021. However, internet penetration among the elderly (75+) remains relatively low at 28%, indicating a need for targeted initiatives to improve digital inclusion for older populations. Despite improvements, there is still a need to enhance digital skills and literacy across the broader population. The low ranking of "Government online services" (102nd) suggest that the extent to which a country's government has implemented and effectively delivered public services through digital channels is not satisfactory. The low ranking in "Knowledge intensive employment" (111th) indicates challenges in transitioning towards a knowledge-based economy, which is essential for long-term competitiveness. This suggests that both basic digital literacy and more advanced technical skills necessary for the workforce. Overall, Morocco's global ranking in the People Pillar indicates that while there has been progress, there is still room for improvement to match the leading countries in digital readiness.

In the Governance Pillar, Morocco demonstrates a mix of strengths and areas needing improvement. The country scores well in several key indicators, reflecting its commitment to enhancing digital governance and public services. The country's efforts to improve e-government services are evident in its strong ranking for “E-commerce legislation” (1st) and “Privacy protection by law content” (46th). These indicators demonstrate a supportive legal and regulatory framework for digital development. Though the regulatory environment in Morocco is improved to support digital transformation, the low ranking in “E-Participation” (111th) suggests opportunities for improving citizen engagement and participation in digital governance. There is a need to improve digital skills and literacy among government employees and the general population. The low ranking in “Online access to financial account” (124th) highlights challenges in promoting financial inclusion through digital channels, which can limit economic opportunities for many citizens.

Morocco's performance in the Impact pillar reflects its efforts to leverage digital technology for economic growth and social development. Morocco's strong ranking in “High-tech and medium-high-tech manufacturing” (23rd) indicates a growing capacity for technological innovation and industrial competitiveness. However, the country's performance in “High-tech exports” (83rd) suggests that there is room for improvement in leveraging digital technology to drive exports and foreign exchange earnings. Regarding the progress in areas related to the Sustainable Development Goals (SDGs), Morocco's commitment to sustainable development is demonstrated by its ranking for “SDG 7: Affordable and Clean Energy” (40th). However, challenges persist in achieving quality education (72nd) highlighting the need for improvements in educational systems to equip the population with the necessary digital skills. In general, Morocco's global ranking in the Impact Pillar indicates that while there has been progress, there is still room for improvement to match the leading countries in harnessing the full potential of ICT for sustainable development.

In conclusion, Morocco's digital landscape has evolved significantly, with notable strengths in digital infrastructure, emerging technologies, and necessary legislation for e-services. However, addressing challenges in education, knowledge-intensive employment, and e-participation is essential for building a more inclusive and competitive digital ecosystem.

Stakeholder Perspectives

This section presents key findings from expert interviews conducted to gain insights into the challenges and opportunities associated with Morocco's renewable energy transition.

Morocco's commitment to sustainability and renewable energy, as evidenced by the establishment of the Ministry of Energy Transition and Sustainable Development (METSD) and associated agencies. While this signifies a positive step, experts highlight the gap between ambitious goals and concrete achievements. Widespread energy waste, as highlighted by one expert's observation of “...a lot of energy being wasted...”, underscores the urgent need for efficiency improvements. To address these challenges, experts advocate for the accelerated deployment of smart grid infrastructure. This, they argue, is crucial for optimizing energy distribution, reducing waste, and facilitating the integration of renewable energy sources into the market. However, the centralized nature of Morocco's current energy system, as noted by experts, presents significant obstacles to this transition, requiring both technological and regulatory advancements.

The absence of robust smart grid infrastructure, coupled with a lack of comprehensive regulatory frameworks governing energy markets and pricing, poses significant challenges to Morocco's energy transition. As emphasized by experts, these deficiencies are particularly critical given the energy sector's pivotal role in the national economy. Furthermore, the limited availability of comprehensive economic and investment return models, as noted by one expert, who stated “economic and investment return models are not widely publicized, suggesting they might not be fully developed,” creates uncertainty for potential investors. To compound these issues, regulatory delays in adopting smart grid frameworks exacerbate investor concerns and hinder overall progress.

Morocco has actively sought international partnerships to advance its renewable energy agenda. While collaboration with foreign entities has been pursued through various projects, concerns have been raised regarding the nature of these partnerships. Experts have highlighted that foreign organizations often prioritize technology transfer rather than knowledge sharing, as evidenced by the statement: “foreign organizations often

prioritize importing and implementing their own technologies, with a focus on taking away the generated energy.” Furthermore, the lack of open-source technology sharing has been identified as a critical barrier to local capacity building, as emphasized by the expert's observation: “the technologies brought in by foreign partners are not open-source, meaning there is limited sharing of expertise with local stakeholders.”

Morocco boasts a strong intellectual foundation for driving innovation in the renewable energy sector, with numerous universities capable of conducting cutting-edge research. This potential is evidenced by the proliferation of renewable energy projects incorporating digital technologies. However, challenges persist in harnessing this capacity effectively. As highlighted by experts, fragmented digitalization initiatives, exemplified by the observation “...fragmented green energy sector digitalization initiatives...”, hinder the development of a unified national strategy. This lack of coordination among academia, industry, and government, coupled with a skills gap, has impeded progress. The expert noted the need for “...new competences and processes...” required for smart grid technologies, highlighting the need for targeted skills development and training programs.

Effective communication and collaboration are essential for driving innovation and policymaking in the energy sector. As one expert noted, “...lack of communication... with those who make decisions...” hinders progress. A lack of coordination among academia, industry, and government stakeholders, as evidenced by fragmented initiatives pursued by individual actors, has led to inefficiencies and missed opportunities, as highlighted by experts.

Long-term sustainability is often overlooked in the pursuit of rapid renewable energy development. Experts emphasize a tendency towards short-term thinking, as evidenced by the statement “...sustainability... is viewed narrowly...”. This neglects the critical issue of end-of-life management for renewable technologies, such as the disposal of solar panels and batteries. Additionally, the renewable energy sector has experienced political interference, hindering its responsible development. As one expert noted, “the current development of wind farms often leads to the emergence of unsustainable infrastructure and service providers in their vicinity.” This highlights the need for a holistic approach that considers both environmental and economic impacts.

Moroccan consumers, both residential and industrial, face significant challenges in optimizing energy consumption. A lack of real-time data, as highlighted by experts, hinders their ability to identify and address energy inefficiencies. The transition to a digitalized energy system necessitates significant behavioral changes and skill development across all stakeholder groups. This includes households, industries, and energy producers.

For instance, households will require training in utilizing smart meters to monitor and manage energy consumption effectively. Industries must enhance their data analysis capabilities to optimize operations and reduce energy waste. Energy producers will need to adapt to the dynamic nature of a smart grid and integrate renewable energy sources seamlessly. As one expert noted, “...resistance to change... new competences and processes...” will be a key challenge in overcoming these hurdles.

This underscores the need for stakeholders' education and awareness campaigns. By explaining the benefits of smart grids, such as potential cost savings and a more sustainable energy future, these campaigns can empower the stakeholders to actively participate in the energy transition.

While large corporations in Morocco have made significant strides in digital transformation, small and medium-sized enterprises (SMEs) face distinct challenges. As noted by experts, the primary obstacle for SMEs is not financial constraints but rather a reluctance to adopt new technologies and processes. The expert emphasized: “the main challenge is not the availability of funding but rather the reluctance of SMEs to change, adapt their processes, and acquire the necessary skills to utilize digital and smart technologies effectively.”

Despite the establishment of two energy innovation clusters, their impact on fostering industry collaboration has been limited. As one expert stated, “the two energy innovation clusters have not been able to fully bridge the gap and foster the necessary synergies among industry stakeholders.” Furthermore, regional disparities in development levels have hindered progress. As noted by experts, “there is a noticeable gap in the level of development between different regions, with some being far more advanced than others.”

On a positive note, the role of academia in promoting collaboration is acknowledged. Experts recognize the efforts of universities in fostering knowledge sharing and cooperation among industry stakeholders, as evidenced by the statement: “academia is actively working to enhance collaboration and knowledge sharing among various players in the energy sector.”

The expert perspectives presented in this section have provided valuable insights into the complexities and challenges associated with Morocco's renewable energy transition. The findings underscore the need for a comprehensive and multi-faceted approach to address the identified issues. The following discussion section will delve deeper into these challenges, explore potential solutions, and propose recommendations for policymakers, industry stakeholders, and researchers to advance Morocco's renewable energy agenda.

Discussion

This study aimed to assess the challenges and opportunities associated with digitalizing Morocco's renewable energy sector. By combining expert interviews with an analysis of secondary data, including statistics and relevant documents, this research sought to identify the current state of the sector and to understand the factors influencing its development. The following discussion delves deeper into the findings, analyzing them through the lens of the People, Process, Technology (PPT) and Bottom Triple Line (BTL) frameworks to elucidate the complexities and implications of digital transformation.

People: The Human Factor in Digital Transformation

The successful digitalization of Morocco's renewable energy sector is contingent upon a skilled and adaptable workforce. A significant skills gap, as highlighted by experts, exists within the sector, hindering its ability to fully harness the potential of emerging technologies. Upgrading the skills of both the existing workforce and consumers is paramount to ensuring a smooth transition to a digitalized energy landscape.

While digitalization offers numerous opportunities for innovation and efficiency, it also carries the risk of job displacement. As automation and artificial intelligence become increasingly prevalent, certain roles within the energy sector may become redundant. Therefore, it is essential to implement comprehensive retraining and upskilling programs to equip displaced workers with the necessary competencies for emerging roles.

Equitable access to digital training programs is crucial to prevent exacerbating existing social inequalities. Targeted initiatives should be implemented to ensure that all segments of the population, including individuals from rural areas, have the opportunity to acquire the digital skills required for the renewable energy sector.

Process: Optimizing Efficiency Through Digitalization

Digital technologies offer immense potential for optimizing processes within the renewable energy sector. By streamlining operations, reducing manual interventions, and enhancing data-driven decision-making, digital tools can significantly enhance efficiency. For instance, automation of routine tasks, such as data entry and report generation, can free up human resources for more strategic activities. Additionally, digital platforms can facilitate seamless communication and collaboration among stakeholders, accelerating project timelines and reducing costs.

However, the implementation of new digital processes is not without its challenges. Resistance to change, coupled with the need for substantial investments in technology and training, hinders the adoption. Furthermore, ensuring interoperability between different digital systems is crucial to avoid creating new inefficiencies. To overcome these challenges, a phased approach to digital transformation is essential, along with robust change management strategies.

Technology: Enablers of the Energy Transition

Digital technologies are emerging as indispensable tools for driving the energy transition. Technologies such as artificial intelligence, big data analytics, the Internet of Things (IoT), and blockchain offer unprecedented opportunities to optimize energy production, distribution, and consumption. For instance, AI-powered predictive analytics can enhance renewable energy forecasting, enabling grid operators to better integrate variable energy sources. IoT devices can facilitate real-time monitoring of energy systems, enabling efficient

troubleshooting and maintenance. Blockchain technology has the potential to revolutionize energy trading by creating transparent and secure peer-to-peer energy markets.

While the adoption of these technologies promises substantial benefits, it also comes with associated costs and potential environmental impacts. The initial investment in digital infrastructure and the ongoing expenses for data management and cybersecurity can be significant. However, these costs can be offset by increased efficiency, reduced operational expenses, and new revenue streams. Furthermore, the environmental impact of digital technologies, particularly in terms of energy consumption for data centers and the production of electronic devices, must be carefully considered and mitigated through sustainable practices.

Economic Implications of Digitalization in the Renewable Energy Sector

The integration of digital technologies into the renewable energy sector holds significant potential for economic benefits. By streamlining operations, reducing costs, and enabling data-driven decision-making, digitalization can enhance the sector's overall efficiency and profitability. For instance, the optimization of energy distribution and consumption patterns through digital platforms can lead to substantial cost savings for both energy providers and consumers. Moreover, the development of new digital solutions and services can create job opportunities and stimulate economic growth.

However, the transition to a digitalized energy system also involves economic risks and challenges. The initial investment in digital infrastructure and workforce training can be substantial, potentially impacting short-term financial performance. Additionally, the potential for job displacement due to automation must be carefully considered to mitigate negative social and economic consequences. To maximize the economic benefits of digitalization while minimizing risks, it is essential to develop strategies for managing costs, mitigating risks, and fostering innovation.

Social Implications of Digitalization

The social implications of digitalization in Morocco's renewable energy sector are multifaceted and require careful consideration. While digital technologies offer the potential to empower individuals and communities, the country's socio-economic landscape presents significant challenges. High illiteracy rates, particularly in rural areas, coupled with regional disparities in development, create a complex environment for digital inclusion.

To maximize the social benefits of digitalization, targeted interventions are necessary to bridge the digital divide. This includes investing in digital literacy programs, expanding internet access, and developing culturally appropriate digital tools.

Moreover, the fear of job displacement due to automation is prevalent among the workforce. This social anxiety poses a dilemma for policymakers, who must balance the benefits of digitalization with the need to protect vulnerable population. While new job opportunities may emerge in the digital economy, it is crucial to implement effective retraining and upskilling programs to mitigate the negative social impacts of this transition. By addressing these challenges and ensuring equitable access to digital technologies, Morocco can harness the full potential of digitalization to create a more inclusive and sustainable society.

Environmental Implications of Digitalization

The environmental impact of digitalization in the renewable energy sector is a complex issue with both positive and negative dimensions. On the one hand, digital technologies offer significant potential for reducing the environmental footprint of the energy sector. By optimizing energy production and distribution, digital tools can contribute to minimizing waste and maximizing resource efficiency. For instance, smart grids can enable the integration of renewable energy sources, reduce energy losses, and optimize grid operations.

However, the growing reliance on digital technologies also raises environmental concerns. The energy consumption associated with data centers and the production of electronic devices can contribute to greenhouse gas emissions. Additionally, the disposal of electronic waste, if not managed properly, can have detrimental effects on the environment. To mitigate these negative impacts, it is crucial to adopt sustainable practices in the design, production, and disposal of digital technologies.

To fully realize the environmental benefits of digitalization while minimizing its drawbacks, a holistic approach is necessary. This includes promoting energy efficiency in data centers, encouraging the reuse and recycling of electronic waste, and supporting research and development of low-carbon digital technologies.

Overall Assessment and Recommendations

The digital transformation of Morocco's renewable energy sector presents both significant challenges and opportunities. While the analysis through the PPT and BTL frameworks highlights the potential benefits of digitalization in terms of efficiency, economic growth, and environmental sustainability, it also underscores the importance of addressing key challenges such as skills gaps, infrastructure limitations, and social inequalities.

To fully realize the potential of digitalization, a comprehensive and coordinated approach is essential. This includes investing in human capital development, further building robust digital infrastructure, and creating supportive regulatory frameworks. Additionally, it is crucial to prioritize research and development in emerging digital technologies and to further foster collaboration among government, industry, and academia.

Crucially, successful implementation necessitates a robust change management strategy. Overcoming resistance to change, fostering a culture of innovation, and ensuring stakeholder buy-in will be critical to the overall success of the digital transformation. By adopting a holistic perspective and addressing the identified challenges, including the effective management of change, Morocco can position itself as a leader in the renewable energy transition and reap the rewards of a digitalized energy sector.

Conclusions

This case study aimed to identify the challenges (RQ1) and opportunities (RQ2) associated with digitalizing Morocco's renewable energy sector. By examining the perspectives of key stakeholders and analyzing relevant data, the study sought to understand the sector's digitalization prerequisites and to identify strategies for overcoming barriers to digital transformation.

The research findings underscore the significant potential of digitalization in driving Morocco's renewable energy transition. While the country has demonstrated a strong commitment to renewable energy, the realization of its full potential is hindered by several challenges. Firstly, the study highlights the critical role of human capital in the digitalization process. A skilled workforce is essential for the successful implementation and operation of digital technologies. However, the current skills gap, particularly in relation to digital competencies, poses a significant barrier to progress. This is further compounded by the uneven distribution of digital skills across the population, with certain demographics, such as youth and women, facing greater challenges. Secondly, the importance of robust digital infrastructure and supportive regulatory frameworks is evident. The absence of these elements impedes the effective integration of renewable energy sources and the optimization of energy systems. Additionally, the lack of interoperability between different digital systems can hinder the overall efficiency of the energy sector. Thirdly, the study emphasizes the need for a holistic approach to digitalization that considers both economic and environmental implications. While digital technologies offer opportunities for cost reduction and efficiency gains, their impact on jobs, social equity, and the environment must be carefully managed. The potential for job displacement due to automation, as well as the environmental consequences of digital technologies, require careful consideration and mitigation strategies. Finally, the research underscores the importance of effective change management and stakeholder engagement in driving digital transformation. Overcoming resistance to change, fostering collaboration among various stakeholders, and ensuring equitable access to digital technologies are crucial for realizing the full potential of digitalization.

The findings of this study underscore the complex interplay of technological, economic, social, and environmental factors in the digitalization of Morocco's renewable energy sector.

Economically, the transition to a digitalized energy system offers opportunities for economic growth, job creation, and increased efficiency. However, the initial investments in digital infrastructure and workforce development may pose challenges for some stakeholders. It is essential to develop strategies to mitigate these costs and maximize the economic benefits of digitalization.

Environmentally, digital technologies present both opportunities and risks. While they can contribute to the optimization of energy production and distribution, reducing overall environmental impact, their own energy consumption and waste generation must be carefully managed. A circular economy approach, emphasizing the reuse and recycling of electronic waste, is crucial to minimize the ecological footprint of digitalization.

Socially, the implications of digitalization are far-reaching. While digital technologies can enhance access to energy services and create new economic opportunities, they also risk exacerbating existing inequalities. Efforts to bridge the digital divide, invest in digital literacy, and ensure equitable access to the benefits of digitalization are essential to achieve a just and inclusive energy transition.

Based on the findings of this study, several key recommendations emerge for advancing Morocco's renewable energy transition through digitalization. Firstly, investing in human capital development is paramount. This includes targeted training programs to equip the workforce with the necessary digital skills, as well as initiatives to bridge the digital divide. By fostering a digitally literate population, Morocco can maximize the potential benefits of digital technologies. Secondly, building a robust digital infrastructure is essential for enabling the effective integration of renewable energy sources. This requires significant investments in smart grid technologies, data centers, and high-speed internet connectivity. Thirdly, a supportive regulatory environment is crucial for stimulating innovation and investment in the renewable energy sector. Streamlining regulatory processes, creating incentives for digital adoption, and establishing clear guidelines for data privacy and security are essential for unlocking the full potential of digitalization. Fourthly, a holistic approach to sustainability is required. While digital technologies offer numerous benefits, their environmental impacts must be carefully managed. Promoting circular economy principles, investing in clean energy for data centers, and encouraging the development of sustainable digital technologies are essential steps. Finally, strengthening the collaboration among government, industry, academia, and civil society is vital for successful digital transformation. By working together, stakeholders can address challenges, share knowledge, and accelerate the transition to a sustainable energy future.

This study has made significant contributions to the understanding of the challenges and opportunities associated with digitalizing Morocco's renewable energy sector. By examining the perspectives of key stakeholders and analyzing relevant data, the research provided a nuanced understanding of the sector's dynamics.

While the study offers valuable insights, further research is needed to explore specific aspects of the digitalization process in greater depth. For example, in-depth case studies of successful digitalization initiatives could provide valuable lessons for other developing countries. Additionally, long-term monitoring and evaluation of the impacts of digitalization on Morocco's energy sector are essential to inform ongoing policy and decision-making.

In conclusion, the successful digitalization of Morocco's renewable energy sector requires a multi-faceted approach that addresses the economic, environmental, and social dimensions of the transition. By addressing the identified challenges and capitalizing on the opportunities presented by digitalization, Morocco can position itself as a leader in the global renewable energy transition.

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Jurga VESTERTĖ

ORCID ID: <https://orcid.org/0000-0002-4831-1102>

Ilona SKAČKAUSKIENĖ

ORCID ID: <https://orcid.org/0000-0002-5078-3678>

Najiba EL AMRANI EL IDRISI is Ph.D professor coordinator of the research team Signals, telecommunications and smart grids at the Faculty of Science and Technology of Fez, Sidi Mohamed Ben Abdellah University. Research interests: Microstrip Antenna, Antenna Arrays, Electromagnetics, UMTS, Telecommunications.

ORCID ID: <https://orcid.org/0000-0001-5603-1306>

Kamal ZARED

ORCID ID: <https://orcid.org/0000-0003-0612-2052>

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