TECHNO-ECONOMIC IMPACTS OF ENERGY TRANSITION: THE STATE OF THE ART

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Abstract. Achieving net-zero carbon emissions goals requires tangible actions that regions, countries, sectors, and organizations should take to accelerate the energy transition along with a growing trend toward renewable energy sources. Digitalization, a phenomenon introduced by the transformative power of digital technologies, plays a key role in the energy transition process. Providing advancements in technology leads to significant changes in the way energy is produced, transmitted, and consumed. In light of that, the paper discusses the impacts of digitalization on energy transition by highlighting its benefits and crucial incentives favoring investment processes. In terms of policy messages, the paper suggests that policies based on a more integrated assessment of the links between the transforming energy sector and the overall economy would be needed. Moreover, regulations promoting financial incentives to support investments would be recommended to satisfy the novel paradigm of energy transition.

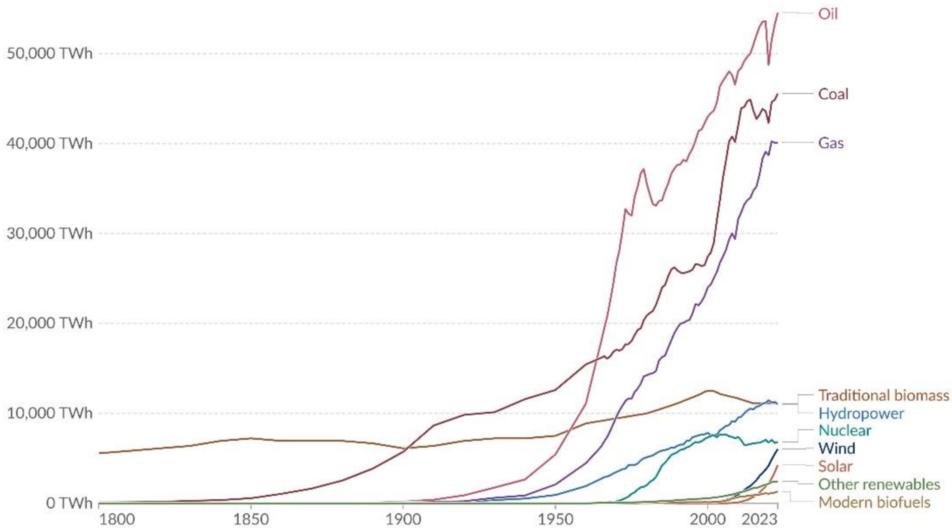
4 Introduction

The threats posed by climate change and the need to achieve global sustainable development goals (SDGs) necessitate a fundamental transformation of the global energy system. The SDGs report highlights the risks of climate change, including its impact on inequality and food security, which may undermine progress toward other SDGs. Given that energy use is the primary driver of global greenhouse gas emissions, transitioning to a sustainable global energy system is critical (Bogdanov et al., 2021).

Up until the mid-19th century, traditional biomass—such as wood, crop residues, and charcoal—was the dominant global energy source. The Industrial Revolution led to a major change, with coal becoming the leading energy source, followed by oil, gas, and hydropower by the early 1900s. Nuclear energy only became part of the mix in the 1960s, while "modern renewables" like solar and wind began to play a significant role in the 1980s (Figure 1).

Today, renewable energy sources are growing rapidly, with one-sixth of the world's primary energy coming from low-carbon sources like nuclear, hydropower, wind, solar, bioenergy, geothermal, and tidal power. However, oil remains the largest global energy source, followed by coal, gas, and hydropower. Fossil fuel combustion accounts for about 75% of global greenhouse gas emissions, highlighting the need for a shift to low-carbon sources to achieve decarbonization. This transition is essential for transforming the global energy sector from fossil fuels to zero carbon emissions by the second half of the 21st century (Ritchie and Rosado, 2020).

Figure 1 – *Global primary energy consumption by source.*



Source: Our World in data available at Global primary energy consumption by source (ourworldindata.org).

The transition towards a more efficient energy system implies access to higher shares of renewable energy (RE) by reducing GHG emissions and water scarcity.

Such process has already started with renewables providing more than 27% of the global electricity generation by the end of 2019, including about 11% generated by new renewable energy technologies, mainly wind turbines and solar photovoltaics (PV) (Bogdanov et al., 2021).

The future transition of energy systems largely depends on a set of assumptions, methods, and objectives that should be extensively applied from a global perspective. In light of that, studying energy systems from a multi-level perspective appears relevant to understanding the implications that the transition path might have. Especially the link between technological innovation and social aspects represents a key drive to ensuring the sustainability of energy systems (Hansen et al, 2019).

In that context, digital transformation reveals a top priority for both businesses and society.

Digital transformation is a phenomenon regarding the transformative power of digital technologies which have become integral to our daily lives, influencing households' work, communication, and behaviour as consumers. Specifically, digital technologies by connecting the physical and digital worlds, can satisfy individualized needs of consumers. Historically, digitalization has been helping to improve the energy sector. Indeed, the energy system has long been at the forefront of embracing novel technologies to produce assets, including reservoirs and pipelines, and, to improve quality and yields by minimizing energy use (Nazari and Musilek, 2023). The main goal of this technologically-driven dimension of the energy transition is the creation of Smart Energy Systems (SES, hereafter), i.e., providing inter-linkages between energy sectors to improve the efficiency and sustainability of future energy systems (Cantarero 2020). The rapid digital transformation in the energy sector, including smart grids and the energy internet, promotes a path toward more resiliency and flexibility in sustainable energy systems. Indeed digitalization addresses multi-energy connectivity and complementarity across regions through instant data collection, analysis, and sharing (Zhang et al, 2023).

However, the energy system's technological transformation requires consumer awareness, commitment, and active participation to ensure a fair and equitable distribution of its benefits (Cantarero 2020).

In light of the significance of digital transformation in shaping the future, it is relevant to study the current status and impacts of this trend on energy sector and anticipate future developments and their potential consequences.

This paper first reviews the literature on the economic growth-energy transition nexus to investigate the relationship between economic growth and renewable energy consumption. Second, it studies the impacts of digital transformation on the energy sector through a review of existing studies focusing on the technology-energy transition nexus. Moreover, it offers an overview of digital transformation at the EU countries level by assessing the impact of digital trends both on the demand and on the supply side.

This study emphasizes the importance of coordinating energy storage and digitalization in the energy transition, highlighting the need for global attention to the relationship between energy and society. Policies should integrate the energy sector with the broader economy, promoting innovation in distribution systems and offering financial incentives to support smart grid investments in line with the energy transition.

The remainder of the paper is organized as follows. Section 2 provides an overview of existing studies focusing on energy transition and its digital transformation. Section 3 discusses the main implications of digitalization in the energy sector both on the demand and the supply side. Section 5 presents the conclusions and policy implications.

5 Literature review

A growing body of studies focuses on the energy transition economic growth nexus. Khan et al. (2021) conducted an econometric analysis across thirty-eight IEA countries and found a positive relationship between economic growth and renewable energy consumption. They highlighted that the shift from non-renewable to renewable energy has significant economic externalities, with energy use acting as both a cause and facilitator of growth. Indeed, renewable power generation technologies accelerate new job creation. In this regard, Ram et al. (2020) estimate that global direct employment in the electricity sector raises from about 21 million in 2015 to nearly 35 million in 2050. Tzeremes et al. (2023) observed that higher economic activity in BRICS countries leads to increased carbon emissions, driving environmental degradation and emphasizing the need for a renewable energy transition. Economic growth, therefore, facilitates renewable energy consumption and accelerates the transition process.

Another strand of the literature, instead, reveals a negative relationship between economic growth and renewable energy. Tsagkari et al. (2021) analyze how renewable energy can support both economic growth and degrowth through local energy projects on islands, using case studies from El Hierro (Spain) and Tilos (Greece). They suggest that these projects' goals—such as energy democracy, self-sufficiency, and revitalization of local economies—align with degrowth principles. The study demonstrates that transitioning to renewable energy can enhance local control over resources and energy independence, leading to either economic growth or degrowth depending on community priorities. Similarly, Muazu et al. (2022), using a panel threshold regression model in 54 African countries, find a non-linear, negative relationship between renewable energy consumption and economic growth, with the impact varying at different stages of development. Bhattacharya et al. (2016) also report that while renewable energy generally promotes long-term growth, it may hinder short-term growth in countries with underdeveloped infrastructure or where investments in renewables divert resources from other sectors. Indeed, the energy transition process calls for higher and more diversified investment both by states and private investors. In this regard, Dong et al. (2022) highlight that renewable energy faces structural challenges in promoting sustainable development due to high capital and technology costs. They argue that financial incentives can improve factor allocation efficiency and enhance renewable energy technologies, positively impacting carbon emission efficiency. Tian et al. (2022) suggest that green stimulus plans are crucial for economic recovery and energy transition, playing a key role in restarting renewable energy development. To address financing gaps, Qadir et al. (2021) propose involving financial institutions to support renewable energy investments through soft loans or crowdfunding platforms. Bayulgen (2020) examines the political and socio-economic factors influencing US local governments' energy transition policies, emphasizing that citizen concerns about the unpredictability of local reforms highlight the importance of a well-coordinated policy champion configuration for successful clean energy implementation.

In light of that, capacity for successful of energy transition depends from several aspects of a nation such as energy mix, potential for diffusing renewable energy, infrastructure, technological innovation and capacity to transform; as well as societal values and political ambition. Deshmukh et al. (2023) stress the need for international collaboration to address the unequal distribution of pollution's impacts, with countries reliant on fossil fuels, particularly coal, facing higher pollution and health consequences, while those shifting to renewable energy generally experience lower pollution levels. Neofytou et al. (2020) find that Sweden has the most favorable conditions for energy transition, followed by Western Europe and Canada. Developing countries, which are more dependent on fossil fuels, play a critical role in achieving a low-carbon economy (Cantarero, 2020; Murshed et al., 2021). Nam and Jin (2021) advocate for energy efficiency regulations as an effective and low-cost tool for carbon mitigation.

Starting from the key role that innovation technology plays in the sustainable energy process, another strand of literature studies the link between digital technology and sustainable energy development. Wang et al. (2022) develop a measurement index system for digital technology levels and use a VAR model to demonstrate its role in reducing energy-related pollution in China. Similarly, Tzeremes et al. (2023) find that innovation and communication technology significantly influence energy transition in BRICS countries. Green technology innovation helps lower pollution from fossil energy, boosts clean energy use, and increases productivity, while also controlling waste emissions in production processes (Du et al., 2021). Renewable energy technologies not only mitigate environmental impacts but also generate new wealth and jobs (Ram et al., 2020).

However, the effects of green technology on carbon productivity in less developed countries remain unclear. Du and Li (2019) show that technological progress enhances carbon productivity in high-income countries, but its impact in other economies is limited due to high costs. Similarly, Shahbaz et al. (2022) find that technology innovations contribute to the energy transition in high-income countries, but their impact varies regionally.

The global trend towards digitalization has created substantial demand for advanced technologies in energy storage and other emerging sectors. Digitalization, by promoting technological innovation, supports the transition to a low-carbon economy, especially in energy storage (Zhang et al., 2023). Look (2020) notes that digitalization fosters sustainable energy transitions by driving business model innovation. Bergman and Foxon (2023) show that digitalization influences energy demand, with its effects on energy consumption being shaped by individual and collective choices. Policymakers should focus on social well-being and environmental protection when promoting digitalization. Finally, Hansen et al. (2019) emphasize that the interaction of social and technical elements in models can vary significantly.

6 Digitalization of energy system

Digital technology plays a crucial role in the energy transition by driving decentralization and increasing connections between devices, producers, distributors, and users. This supports investments in renewable and distributed energy resources such as solar photovoltaics, energy storage, and electric mobility. The European Green Deal and the Digital Decade Policy Program 2030 outline goals for digitalizing the EU energy system, including installing solar panels on all commercial and public buildings by 2027, deploying 10 million heat pumps, and replacing 30 million fossil fuel-powered cars with zero-emission vehicles by 2030. Achieving these targets requires the adoption of digital technologies like smart IoT devices and 5G/6G connectivity (EU Commission, 2023).

The term “Digitalization” refers to the increasing use of Information and Communication Technology (ICT) across various sectors, particularly in energy. It includes innovations like smartphones, mobile internet, GPS for location tracking, and real-time traffic data. Digitalization has been enhancing the energy sector for decades by integrating IT systems to manage assets such as reservoirs and pipelines, while also improving quality and efficiency by reducing energy consumption (IEA, 2017).

As for energy demand, digital technologies play a predominant role for sectors of transport, buildings and industry. For transport, connectivity allows entailing new mobility-sharing services by making the transport system more intelligent, efficient, reliable, and sustainable. Advances in vehicle automation and electrification, driven by digitalization, could transform transportation, with uncertain effects on energy use and emissions (Noussan and Tagliapietra, 2020). In the building sector, digital technologies can help reduce energy use by around 10% by 2040, especially in heating and cooling through smart thermostats and sensors (Asif et al., 2024). Digitalization also offers potential energy savings in the industrial sector, improving process evaluations and leading to significant energy reductions with short payback periods (Erdogan, 2021).

On the supply side, digital technologies have been used for years to enhance fossil resource recovery, improve production processes, reduce costs, and increase safety. The widespread adoption of digital technologies could lower oil and gas production costs by 10% to 20% (IEA, 2017). Additionally, it could improve geological modeling and optimize automation in the coal sector. In the power sector, digitalization may result in annual savings of approximately USD 80 billion by reducing operation and maintenance costs, thus minimizing unplanned outages and downtime (IEA, 2017).

Table 1 describes the main contributions of the most important digital technologies in the EU energy sector. Based on the literature, Światowiec-Szczepańska and Stępień (2022) highlight that digitalization enhances the energy sector by improving system stability, environmental protection, energy demand reduction, revenue, cost efficiency, and customer satisfaction. These benefits are driven by digital applications such as smart grids, optimized procedures, flexible systems, anomaly detection, and improved process efficiency, trust, and transparency.

Table 1 – *Advantages of digital transformation in the energy sector.*

Main advantages of digital technologies	1. System protection and stability	2.Environmental safeguard	3.Minimized cost	4.Customer satisfaction
Applications in energy sectors	- Smart grid and optimized operations - Smart market and flexibility combination - Anomaly detection and prediction - Trust and transparency	- Smart grid and optimized operations - Smart market and flexibility combination - Anomaly detection and prediction -Process efficiency	- Smart grid and optimized operations - Smart market and flexibility combination - Smart home	- Smart home - Trust and transparency
Types of digital technologies	Blockchain, Artificial neural networks (ANN), Internet of Things (IoT), Artificial intelligence (AI), Big data, among many others.			

[1]*Source: Our elaboration from Światowiec-Szczepańska and Stępień (2022)*

As well, digitalization through the increasing application of information- and communication technology (ICT), also impacts energy efficiency. Specifically, ICT technologies can help reduce energy demand through two main factors:

2. Energy efficiency: ICT technologies optimize processes and improve efficiency, reducing energy consumption.
3. Sectoral change: ICT can shift economic dynamics, reducing energy use in certain sectors or introducing more energy-efficient business models.

In this regard, using analytical methodology, Lange et al. (2020) find that digitalization enhances energy efficiency and reduces consumption, although the extent of these reductions is uncertain due to "rebound effects." These effects occur when efficiency improvements lead to increased energy use, either through re-spending savings or substituting other production factors with energy, limiting overall reductions in demand. Estimates of rebound effects vary, but they are generally significant enough to prevent substantial energy savings. Similarly, Xu et al. (2022) show that in high-income countries, digital transformation has driven innovation and system changes, resulting in smarter energy distribution and lower consumption. They also highlight how digitalization fosters low-carbon transitions in other regions through technology spillovers, promoting reduced energy intensity and improved efficiency. Overall, digitalization entails three main cross-cutting threats to the energy system including cybersecurity, privacy, and economic turmoil. Specifically, the digitalization of energy systems can make them more vulnerable to digital troubles, namely geomagnetic storms, and cyber-risks. Moreover, privacy and data ownership represent a major concern since more detailed information is collected, especially data about household energy use. Eventually, digitalization is influencing jobs and skill requirements in the energy sector by changing job patterns and tasks, causing work losses in some areas and creating new opportunities in others (IEA, 2017).

4 Conclusions

The threats of climate change require a fundamental transformation of the global energy system since energy use is the major responsible for global greenhouse gas (GHG) emissions. The rapid digital transformation in the energy sector, including smart grids and the energy internet, promotes a path toward more resiliency and flexibility in sustainable energy systems. Indeed, there is now widespread awareness that to achieve national and European objectives it is essential to increasingly integrate non-renewable sources programmable - a key element of the energy transition - safely and reliably in electrical systems, modernizing and strengthening them with the support of information and communication technologies (Valenti and Graditi, 2020).

In light of that, assessing the impacts of digital transformation on the energy sector appears relevant. Accordingly, the study investigates the role of technology innovation in the energy market by studying the techno-economic impacts of the digital trend on energy sectors.

Given the relevant impacts that digitalization in energy transition entails throughout the economy, the paper suggests that such transformation cannot be considered far away from the broader socio-economic context. In light of that, policies based on a more integrated assessment of the links between the transforming energy sector and the overall economy would be needed. Finally, regulation should promote innovation in the distribution system and provide financial incentives to support investments in technology innovation projects and satisfy the novel paradigm of energy transition. In terms of future perspective, an integrated and multi-carrier energy networks based on digital logic, advanced and more complex that will allow integrated and coordinated management of energy needs (thermal and electrical) will be needed. This, in turn, will favour an even more effective exploitation of generation from renewable sources and ensure adequate levels of resilience and flexibility in the energy system by facilitating the achievement of the targets set to pursue energy transition at the global level.

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