Environment, Development and Sustainability (2023) 25:11599–11644
https://doi.org/10.1007/s10668-022-02545-7

Impacts of digitalization on energy security: evidence from European countries

To Trung Thanh[1] · Le Thanh Ha[1] · Hoang Phuong Dung[2] · Tran Thi Lan Huong[1]

Received: 11 November 2021 / Accepted: 25 June 2022 / Published online: 30 July 2022

Abstract

We are the first to empirically analyze the nexus of digital transformation and energy security (ES). This paper utilizes six indicators to reflect three aspects of ES, including acceptability, develop-ability, and sustainability. Applying the panel-corrected standard errors (PCSEs) and the feasible generalized least square estimates (FGLS) model to the international sample of 27 European countries over 2015 to 2019, this research reveals exciting findings. *First*, a promotion in digital transformation causes a significantly positive effect on the acceptability and sustainability of ES but a negative impact on develop-ability of ES. *Second,* the ES positively affects the digital transformation, especially the digital transformation in the business and public sectors. *Third,* results obtained from the dynamic fixed effects (DFEs) estimator for the autoregressive distributed lag (ARDL) method suggest that setting ES goals toward reducing energy consumption and pollution emission promotes the digital transformation process in the business sector of countries in the short run, while the promotion of renewable energy consumption helps countries enhance the digitalization process in the long run. Notably, digitalization is beneficial for sustainable economic development, reflected by a rise in non-fossil and renewable energy consumption and a diminish in CO_2 emission, especially in the long run. *Fourth*, there is a nonlinear effect of the online transaction and digital public services on the acceptability, develop-ability, and sustainability of ES. In a similar spirit, the digital transformation is also accelerated more quickly if the efficiency of the energy system reaches a certain point.

Keywords Digital transformation · Energy security · Short-term and long-term effects · European countries

✉ Le Thanh Ha
halethanh.kt@gmail.com

To Trung Thanh
thanhtt@neu.edu.vn

Hoang Phuong Dung
dunghp@hvnh.edu.vn

Tran Thi Lan Huong
huonglantt26@gmail.com

[1] National Economics University, Hanoi, Vietnam

[2] Banking Academy of Vietnam, Hanoi, Vietnam

JEL Classification F21 · G21 · O16 · C33

1 Introduction

As the essential base for human beings and economic growth, energy, and its security are among the critical issues in the sustainable development agenda of any country. Energy security may mean different things to different people due to distinct energy issues in different places in the world and across various periods (Cherp & Jewell, 2014; Le et al., 2019; Winzer, 2012). Although there is no common interpretation for this construct, contemporary energy security studies widely accept that energy security is not limited to the availability or physical existence of energy resources and the affordability of domestic and imported energy sources (due to prices). Instead, this concept has been expanded to entail the accessibility to energy sources (due to transportation and geopolitical obstacles), the environmental impacts of energy consumption, and the sustainability of the energy system (Fang et al., 2018; Le & Nguyen, 2019; Le & Park, 2021). In this regard, the energy security issues mainly arise from not only the discrepancy between the consumption and production of resources but also its social and environmental aspects. While only less than 20 countries are exporting primary energy sources (oil and gas), the energy demand from the rest of the world continuously increases due to rapid population growth and the thirst for economic development. The recent political tensions and the COVID-19 crisis further put a strain on energy security across countries due to transportation disruption and energy market volatility. On the other hand, climate change, global warming, and other environmental issues, as consequences of overusing energy, remain the bottlenecks of sustainability development agenda among countries for decades (UNEP, 2019). Regardless of the debates on what energy security means, more attention should be given to determinants of energy security, with its most comprehensive conceptualization.

The internet technology and the unstoppable growth of digital networks such as e-business and e-government are shaping behaviors and processes in both social life and production sectors. The COVID-19 pandemic has been further pushing more world segments to go online and hence accelerating digitalization at an unprecedented rate (OECD, 2020). Digitalization itself represents a form of technological advances that helps enhance human capital and foster firms' innovation (Basu & Fernald, 2007; Ceccobelli et al., 2012; Ferro, 2011; Haini, 2019). The literature on digitalization–energy security linkage could be tracked through numerous empirical studies about either the positive influence (Florida, 1996; Green et al., 2012; Hauknes & Knell, 2009; Luzzini et al., 2015; Verspagen, 1997) or the rebound effects (Font Vivanco et al., 2014; Huberty et al., 2011; Sorrell, 2007) of technological innovation on energy consumption, energy efficiency, and environmental quality (Basu & Fernald, 2007; Ceccobelli et al., 2012; Ferro, 2011; Haini, 2019).

The literature provides inconclusive theoretical arguments about the direct linkage between digital technologies and different aspects of energy security. The study of Moyer and Hughes (2012) is among the first attempts to explain the association between digitalization and energy security. Based on the International Futures (IFs) integrated assessment system, Moyer and Hughes (2012) propose that the deployment of information and communications technologies can exert downward pressure on the energy system by improving productivity, negating energy intensity, and reducing renewable energy costs. From a broader perspective, Lange et al. (2020) assert that there are both positive and negative forces in the influence of Information and Communication

Technology (ICT) on energy use among households and production sectors. In general, the adverse impact of digitalization on energy consumption would prevail. Nevertheless, this argument is merely based on an analytical model without the support of empirical evidence. In contrast, Loock (2020) argues that digital technologies facilitate business model innovation and hence tackle the bottlenecks of the sustainable energy transition. This implies the contribution of digitalization to the "sustainability" aspect of energy security. Another theoretical explanation about the linkage between digitalization and energy security is provided by El Bassam (2021). Specifically, by converting information into digital, the digital transformation in the energy market itself helps the energy suppliers better manage and balance the demand–supply grid.

Recent studies attempt to revisit the theoretical arguments about the digitalization–energy security linkage with empirical data. Using a substantial sample of Chinese manufacturing enterprises, Wen et al. (2021) examine the impact of digitalization on those firms' environmental performance proxied by the information and communications technology penetration in the industry. The study finds that industrial digitalization alleviates the ecological impacts of their production activities by increasing the introduction and integration of pipe-end pollutant treatment facilities and cleaner production technologies. Similarly, Ren et al. (2021) employ Chinese regional data to examine the environmental impact of internet technology. The finding indicates that although internet development positively affects energy consumption through economic growth, it also helps reduce energy consumption intensity through economic growth and the acceleration of R&D investment, human capital, financial development, and industrial structural upgrading. Ha (2022a) is another study that contributes directly to the literature about the nexus between digitalization in the business and governmental sectors and energy security. However, this paper is still limited since it only considers digitalization in the business and public sectors, while other dimensions, such as the prevalence of social digitalization, the level of human capital skills related to digitalization, are critical to explaining the sustainability of the energy system. Without considering these dimensions, this paper is limited to providing a comprehensive effect of digitalization on energy security. Furthermore, our article also highlights the importance of the security of the energy system in promoting the digital transformation process in the European region.

This study argues that digitalization may go beyond either internet development or information communication technologies. The integration of "digital" things in business models, governance, and human capital may also be crucial aspects of digitalization (Ha & Thanh, 2022; Myovella et al., 2020). Likewise, environmental impacts, energy consumption, and energy intensity or efficiency are among various dimensions of energy security, based on its contemporary conceptualization (Azzuni & Breyer, 2018; Le & Park, 2021). Since the literature provides contradicting theoretical arguments and empirical evidence about the impact of either internet development or information communications technology on different dimensions of energy security, it is necessary to examine the digitalization–energy security nexus with more comprehensive measures of the two constructs. In addition, previous studies mostly ignore the possible impact of energy security on digitalization. Specifically, the level of digitalization in a nation could be influenced by government policies, infrastructure, and human capital (Dasgupta et al., 1999; Khalifa, 2016; Wang & Feeney, 2014). Meanwhile, some dimensions of energy security, such as non-fossil energy consumption, primary energy consumption per capita, and renewable energy consumption, are found to influence the economic conditions of an economy (Le & Nguyen, 2019). Additionally, the environmental pressures from energy consumption also influence the decisions of businesses and governments to go digital (Liu et al., 2019; Renner et al., 2020).

Our research contributes to the existing knowledge about the relationship between digitalization and the security of the energy system in several ways. First, this study provides an updated answer for the impact of digitalization on energy security by employing more comprehensive measures and databases. This paper employs three measures to capture three aspects of energy security, including acceptability, develop-ability, and sustainability. The digital transition process is reflected by five indicators, including a level of digital connectivity, human capital with basic and advantaged digital skills, internet usage, digital business integration, and online public services. This paper applies diverse econometric techniques to a sample of 27 countries of the European Union (EU) from 2015 to 2019. Second, our contemporary methodologies also contribute more reliable findings of the digitalization–energy security nexus. Using a test on cross-section dependence, we confirm its existence in our database and then apply the panel-corrected standard errors (PCSE) model to investigate this relationship. To further check on our findings, the feasible generalized least square estimates (FGLS) model is employed to consider the presence of heteroscedasticity and fixed effects. All explanatory variables are lagged by one period to resolve an endogeneity issue. Furthermore, the dynamic fixed effect (DFE) estimator for the autoregressive distributed lag (ARDL) method is applied to measure short- and long-run effects. As contended by Canh and Thanh (2020), the DFE-ARDL method can address the time- and country-fixed effects. Third, our study represents the first attempt to provide insights into the interactions between digitalization and ES by additionally examining the impact of ES on digitalization.

The rest of the paper is structured as follows: Section 2 reviews relevant literature and develops hypotheses, while Sect. 3, in turn, introduces the model, data, and estimation method. Section 4 displays empirical results and discussion. We close the paper by providing conclusions in Sect. 5.

2 Literature review and hypothesis development

2.1 The concept of energy security

Although the term "energy security" has been repeatedly mentioned in many academic journals, reports, and press releases, there is a lack of consensus on what it means and how to measure it. Under the general definition of security that is "low probability of damage to acquired values" (Baldwin, 1997) and its three dimensions, including "Security for whom?"; "Security for which values?," and "From what threats?" (Wolfers, 1952), it is observed that energy security may be perceived differently in different contexts and by different people (Esfahani et al., 2021). Specifically, the distinct energy security problems in different places would define the subject of energy security (Cherp & Jewell, 2014). In addition, from different perspectives of various stakeholders and in different periods, the threat of energy security also varies (Kruyt et al., 2009; Le et al., 2019). Based on the short-term approach, energy security is regarded as "an interrupted availability of energy sources at an affordable price" or the ability of the energy system to adapt to national energy needs (Kanellakis et al., 2013; Sovacool, 2011). This is also known as the traditional energy security concept that focuses on supply security threats arising from sudden disruption, disintegration, and price volatility (Stares, 2000). Meanwhile, long-term approaches concern the security of supply and other environmental and social issues arising from the energy supply and consumption (Kruyt et al., 2009; Simpson, 2007). In this regard, the expanded definition of energy security, also regarded as the non-traditional energy security concept, gives new concerns about the influence of energy policy on human well-being and the environmental ecosystem at large. Correspondingly, climate change, biodiversity loss, pollution, and erosion are among the new subjects of energy security. The definition of energy security as proposed by Asia Pacific Energy Research Centre (APERC) is deemed to be the most comprehensive since it encompasses both the traditional and non-traditional approaches. Specifically, energy security is conceptualized as "the ability of an economy to guarantee the availability of the supply of energy resources in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy" (APERC, 2007).

Due to the expansion of the energy security concept, the measurement of energy security also evolves accordingly. The four aspects of energy security (availability, affordability, accessibility, and acceptability) are frequently used as the primary dimensions of energy security in recent studies (Azzuni & Breyer, 2018; Le & Park, 2021). While the "availability" and "affordability" are rooted in the traditional approach of energy security (IEA, 2014), the "accessibility" and "acceptability" aspects reflect the newly added subjects of this construct. In more detail, availability (physical availability of various energy sources) and affordability (the affordability of domestic and imported energy sources in terms of prices) ensure that the energy demand of a specific country is timely met. On the other hand, accessibility, or the ability to access those energy sources in terms of transportation and geopolitical aspects, reflects more about the social aspect of energy security. The acceptability is embedded in sustainable energy consumption, which is centered on the long-run environmental impact of energy consumption. The four-A framework has been recently expanded to encompass the link between energy structure and carbon emissions from primary energy sources (develop-ability) and the sustainable development of the energy system through renewable energy consumption (sustainability) (Fang et al., 2018; Le & Nguyen, 2019). Among those factors, the availability, affordability, and accessibility dimensions of ES depend largely on the primary energy endowments, economic power, and geopolitical issues that may be time-consuming and difficult to change. Meanwhile, the acceptability and develop-ability aspects could be monitored more easily through technological development and behavioral changes among individuals and firms.

In an attempt to give insights into the relationship between digitalization, as a result of technology changes, and energy security, this study gives a primary focus on the acceptability, sustainability, and develop-ability dimensions. Specifically, the energy security is measured by the consumption of either non-fossil or fossil energy consumption, the emission of carbon dioxide, energy intensity (energy consumption per a produced product), emission intensity (carbon dioxide emission per energy unit), the consumption of renewable energy in total and per capita. The non-fossil energy may contain some sources of energy like hydroelectric power and nuclear power that indirectly cause environmental degradation (Lee et al., 2016). Hence, based on the US Energy Information Administration (US.EIA) reports, we focus on renewable energy such as biomass, geothermal, solar, and wind.

Digitalization is embedded in not only economic and social interactions but also production and management practices. The multifaceted impact of digitalization on energy security is, therefore, complicated with both positive and negative forces. The amount and type of energy consumption are closely associated with carbon dioxide emissions, while energy efficiency would affect the intensity of energy use and emissions. Therefore, this study examines the linkage between digitalization and energy security through its impacts on primary factors including energy efficiency, green consumption, and clean production as well as the rebound effects of technology on energy use and the environment.

2.2 Digitalization and energy efficiency

As a type of technological advance, digitalization may foster technological progress, and this effect could be explained by its enhancing impact on either human capital or financial development. First, the invention and widespread use of the Internet have promoted information's explosive growth. Given more efficient searching and low-cost access under the worldwide webs, people could obtain a substantial amount and a wide diversity of knowledge faster and more comprehensively. In addition to information acquisition, the rapid increase of cloud computing and big data and various communication channels also enable more effective and cheaper information transmission and integration among individuals and specialists regardless of time and space boundaries (Spiezia, 2011). That information, in turn, supports workers to improve their knowledge, conduct more R&D activities, and continuously acquire new professional skills. Consequently, human capital is enhanced and positively contributes to technological innovation activities (Ferro, 2011; Haini, 2019). This effect is not limited to a nation. Instead, the rapid information dissemination and exchange and employment migration under the internet platform facilitate cross-border knowledge and technological spillovers. This further maximizes the value of human capital and speeds up the introduction and diffusion of technology across various sectors at the international level during the technological progress (Basu & Fernald, 2007; Ceccobelli et al., 2012). Second, the technological progress and upgrading of the industrial structure are further supported by strong financial development in a digital world. The internet platform not only allows the emergence of various financial models and more credit channels but also facilitates the matching and transactions between the fund suppliers and firms across borders and time boundaries (Salahuddin & Alam, 2016; Salahuddin & Gow, 2016). The expansion of funding and credit sources, in turn, provides financial support to implement R&D activities, especially in green innovation, and comply with environmental regulations (Faisal et al., 2018; Owusu-Agyei et al., 2020; Salahuddin et al., 2015; Tamazian et al., 2009).

When the intelligence level of production equipment is increased, each production stage and the coordination between them are more efficient. In addition, technological advancement allows the replacement of low-energy equipment with high-energy ones (Airehrour et al., 2016) as well as the substitutes of technology-intensive products (with high technical content) for traditional resource-intensive products (Li et al., 2019). When the optimization of green production and green management practices in terms of new product development, productivity, and market expansion is realized, the internet technology facilitates the spillover effects spreading within the information technology production department and to other information technology use departments, and from digital firms to non-digital ones (Dunnewijk & Hultén, 2007). Moreover, since there is a significant gap in productivity between technology-intensive industrial industries and traditional resource-intensive ones, there would be a shift in resource allocation in which new resources are allocated to the more efficient technology-intensive sectors. This leads to upgrading the industrial structure with a higher share of technology-intensive industrial industries and the depletion of high-polluting and energy-intensive industries (Qin et al., 2017). Under digitalization, this process could be accelerated due to two forces, including the sharing of innovative knowledge among firms with lower costs and the stronger competition mechanism (Vassileva et al., 2012). Therefore, upgrading of industrial structure helps increase overall energy efficiency while reducing energy consumption. The positive impact of digitalization on the efficiency of energy is affirmed in much empirical research, including Collard et al. (2005) for French service sectors, Bernstein and Madlener (2010) and Ishida (2015) for European manufacturing sectors, Takase and Murota (2004) for Japan, and Ren et al. (2021) for China.

2.3 Digitalization and green production and consumption

Digitalization could encourage the consumption of clean and renewable energy among both individuals and firms. From the demand side, this could be explained by the contribution of digitalization to economic growth and globalization. First, digitalization, especially the evolution of e-commerce and e-business, fosters both national and international trade by reducing transaction costs and blurring the boundaries in terms of time, space, and between trade in goods and trade in services (Ahmedov, 2020; OECD, 2019; Shyla, 2020). On the other hand, the adoption of the e-government model helps improve institutional quality by reducing corruption and enhancing the effectiveness of governance (Adam, 2020; Ali et al., 2022). The contribution of digitalization to human capital, structural upgrading, trade, and institutional quality would spur economic growth and enhance national income. Given the well-developed economy and high income, a highly digitalized nation may be characterized by the rise of the demand for well-being and environmental responsibility among the public (Galeotti et al., 2008; Lee & Lee, 2009; Martínez-Zarzoso & Maruotti, 2011). Individuals would demand more environmentally friendly products, which consume less fossil fuel during their production and usage. On the other hand, the firms themselves switch their production toward environmentally friendly products and green production to sustain competitiveness, adapt to more demanding environmental regulation from the authorities, and gain better social acceptance (European Commission, 1999; International Trade Centre, 2001; Kennett & Steenblik, 2005; Sinclair-Desgagné, 2008). The application of environmental-related technologies, in turn, accelerates the replacement of "green" capital goods (with low environmental impacts) for "brown" capital goods (Kemp-Benedict, 2014). This leads to more consumption of non-fossil fuel, especially renewable energy uses among the production sectors. Nowadays, digitalization transforms societies, markets, and economies toward more globalization by reducing spatial transaction costs and eliminating information asymmetry. This may cause trade-induced technology innovation and further foster green production and consumption through R&D spillover effects (Ali et al., 2021). Specifically, under the economic and financial globalization, international trade flows of eco-products and FDI flows could accelerate the diffusion of green technologies for lower fossil fuel consumption throughout the supply chain (Bakhsh et al., 2017; Berkhout & Hertin, 2001; Bi et al., 2015; Franco & Marin, 2015; Haider Zaidi et al., 2019).

From the supply side, Moyer and Hughes (2012) argue that ICT encourages green consumption and production by reducing renewable energy costs. Specifically, the application of "smart grids," a type of energy infrastructure for continuous monitoring and effective matching of the energy supply and demand, helps improve transmission efficiency, deal with intermittency, and reduce the costs of renewable energy production and consumption. This infrastructure also allows individuals and firms to make transactions to the grid. Similarly, Verma et al. (2020) contend that the achievements of a digital world could lead to the rapid growth of the share of renewable energy in the overall energy consumption by facilitating efficient production, distribution, and integration of renewable energy into the existing centralized energy system. More specifically, the advanced machine learning algorithms and other AI technologies could drive the decentralization of the energy system, improve weather forecasts, provide better analytics of consumption trends and the performance of technologies, foster effective engagement of members across the value chain, and allow the active participation of pro-consumers (who act as both energy consumer and producer of renewable energy).

Furthermore, the technical efficiency, cost efficiency, and the general growth of the bioenergy industry are backed by labor input, capital input, innovation systems, the connections of markets, and enabling environment (Abdulwakil et al., 2020; Alsaleh & Abdul-Rahim, 2018; Alsaleh et al., 2017, 2020a, 2020b). Digitalization, in the forms of either digital connectivity, digital business, digital government, or digital skills, could foster the development and penetration of bioenergy products in various ways. Specifically, such a relationship could be explained by its impacts on enhancing human capital (Spiezia, 2011), facilitating innovation activities and R&D spillover effects (Ceccobelli et al., 2012; Ferro, 2011; Haini, 2019), matching investors and traders across borders (Ahmedov, 2020; Salahuddin & Alam, 2016; Salahuddin & Gow, 2016), and improving institutional quality (Adam, 2020; Ali et al., 2022). Not only fostering the bioenergy industry, but digitalization would also create the transformation of business models where more environmentally related technologies are applied. This tackles the bottlenecks of the sustainable energy transition for more green production (Loock, 2020). Empirically, the information and communications technology penetration in Chinese manufacturing industries is found to induce more introduction and integration of pipe-end pollutant treatment facilities and cleaner production technologies, which in turn mitigate their environmental impacts (Wen et al., 2021).

2.4 Digitalization and the "rebound effects"

Due to the complex interrelationships among technological, social, and economic factors, digitalization with its multifaceted effects could also adversely affect the environment in several ways. The "rebound effects" of digitalization could be witnessed from its direct environmental impact of indirect influence on economic growth, trade, financial development, energy efficiency, and green innovation.

First, ICT production, usage, and disposal could directly raise energy demand and worsen environmental deterioration (Lange et al., 2020). Second, the development of the internet economy with more exchange transactions and its spillover effects to other digital technology use sectors may stimulate more production activities (Salahuddin & Gow, 2016). Hence, the increase of economic output and trade-facilitated economic growth may be attained at the expense of environmental costs (Ali et al., 2021; Lange et al., 2020). Third, while digitalization facilitates market transactions, it also increases the consumption of goods and services among individuals and households due to lower transaction costs and the rise of income (Blum et al., 2018; Jalas, 2009). The higher consumption among individuals puts more burdens on the environment. Fourth, improved energy efficiency lowers the market price of energy use and some resources and raises the demand for them among manufacturers and individuals (Yang & Li, 2017). Moreover, the consumption of goods, services, energy, and resources is even further backed up by the higher availability of funds and credits enabled by the digital platform. This would end up with overall higher total energy consumption. Fifth, the rebound effect could originate right from creating and applying green technologies. Specifically, the making and application of environmental-related technologies require the inputs of not only "green" capital goods but also "brown" capital goods (Jenkins et al., 2011; Kemp-Benedict, 2014). Moreover, the instalment and usage of green technologies may require the construction of new infrastructure systems (Font Vivanco et al., 2014). Therefore, green innovation may be associated with more energy consumption and carbon dioxide emissions (Huberty et al., 2011; Sorrell, 2007).

There is empirical evidence about the positive linkage between digitalization and either energy consumption or carbon dioxide emissions. The adoption of internet technology was found to be associated with higher electricity consumption among OECD countries in both the short run and long run (Salahuddin & Alam, 2016). Similarly, the development of ICT is found to positively correlate with electricity consumption in emerging countries (Sadorsky, 2012) and energy use in the USA (Takase & Murota, 2004). This relationship is further affirmed based on international panel data between 1990 and 2010 by Longo and York (2015).

Since there exist both positive and negative forces in the relationship between digitalization and energy security, there may be a change in the relative strength of one against the other by the degree of informality. This would form a nonlinear relationship between digitalization and energy security. In this study, we argue that the "rebound effects," the rise of energy consumption, and environmental deterioration (due to expanding production and consumption activities and the use of "brow" inputs) may immediately occur as the level of digitalization increases. Meanwhile, the positive influences of digitalization on energy security are theoretically mediated through the diffusion of green technologies, the enhancement of human capital, financial development, and institutional quality that takes time to demonstrate significant changes. Hence, digitalization may threaten energy security in the initial phase of digital transformation. However, this relationship may turn out to be positive in the long run if digitalization reaches a sufficiently high level where significant changes in socioeconomic and institutional factors are attained. At this point, the rebound effects of digitalization are offset by sufficiently high energy efficiency and successful sustainable energy transitions. A recent study by Ha (2022a) also provides empirical evidence to show that digitalization can adversely affect the energy sector in the early phase of the digital transformation process. The favorable effects only appear when digitalization development reaches a certain level.

Based on our discussion, we hypothesize:

H1 There is a nonlinear relationship between digitalization and energy security.

On the other side of the coin, the development and application of information and communications technologies depend largely on government policies, infrastructure, and human capital (Dasgupta et al., 1999; Khalifa, 2016; Wang & Feeney, 2014). In this regard, a more developed country would be in better condition to foster digital transformation. As ES, especially non-fossil energy consumption, primary energy consumption per capita, and renewable energy consumption, fuels economic growth (Le & Nguyen, 2019), there may be a link between acceptability, develop-ability, and sustainability dimensions of ES and digitalization. Moreover, the environmental pressures from energy consumption as embedded in the acceptability aspects of ES may urge businesses and governments to go digital (Liu et al., 2019; Renner et al., 2020). We, therefore, shed more light on the nexus between these two factors by further examining the impact of ES on digitalization.

H2 Energy security affects digitalization.

2.5 Control variables

The literature on the energy–economic growth linkage suggests two hypotheses regarding the energy–economic growth nexus. Specifically, energy consumption is driven by economic output (the "conservation hypothesis") or there may exist bidirectional causality between them (the "feedback hypothesis") (Apergis & Payne, 2009; Apergis & Tang, 2013; Ozturk, 2010; Payne, 2010). Empirical evidence from Italy and Korea (Soytas & Sari, 2003), sub-Saharan African countries (Le, 2016), Nigeria (Rafindadi, 2016), and South Africa (Rafindadi & Ozturk, 2017) or a group of middle- and high-income countries (Huang et al., 2008) supports the "conservation hypothesis." Meanwhile, the causal relationship between economic growth and either renewable or non-renewable energy consumption is affirmed with international evidence of 85 countries from 1990 to 2007 (Apergis & Payne, 2012). We, therefore, include national income as a control variable in our conceptual model and expect a positive linkage between this construct and energy security.

The endogenous growth models (Rivera-Batiz & Romer, 1991), the extended Cobb–Douglas function (Shahbaz et al., 2013), and relevant empirical test on the two frameworks (Ibrahim & Alagidede, 2018; Le, 2016; Le et al., 2016; Ruiz, 2018) suggest that capital accumulation, trade openness, and financial development are robust drivers of economic growth. Eventually, there is mounting evidence about the impacts of these constructs on the energy and ecological systems. First, the two-sided effects of capital accumulation are well documented in the literature. On the one hand, capital facilitates more consumption and production activities, hence raising primary energy consumption and carbon dioxide emissions (Forster, 1973; Rafindadi & Ozturk, 2015). On the other hand, it could also support green R&D activities and drive the sustainable energy transition in both the consumption and production sectors (Rafindadi & Ozturk, 2017). Similar mechanisms underlying the contradicting influence of FDI inflows on energy use and environmental quality are found in previous works, as embedded in the "pollution haven" and the "pollution halo" hypothesis. The former asserts that FDI may provide funding for more economic activities (Acheampong, 2019; Boutabba, 2014), especially the dirty industries, hence raising energy consumption and worsening environmental deterioration (Bakhsh et al., 2017). Empirically, emerging countries are found to suffer the "pollution heaven" due to the rise of FDI (Bakhsh et al., 2017; Rafindadi & Ozturk, 2015; Rafindadi et al., 2018; Yu et al., 2019; Zakarya et al., 2015). The latter advocates the environmental benefits of FDI based on the spillovers of green technologies and managerial practices that may help either increase energy efficiency or negate pollution (Bakhsh et al., 2017; Zaidi et al., 2019). This "pollution halo" effect is found to prevail in developed countries (Apergis et al., 2018; Zaidi et al., 2019).

An open economy may demand more energy to adapt to the foreign market and respond to competitive pressures (Amable, 2000; Le & Tran-Nam, 2018; Le et al., 2016). Nevertheless, the impact of trade openness on the environmental quality is not only resulted from increased economic activities under free trade mechanisms but also the national factor endowment (Tayebi & Younespour, 2012). Specifically, capital-abundant countries that tend to exchange more capital-intensive commodities (polluting goods) for more labor-intensive ones (cleaner goods) could reap environmental benefits from trade (Bi et al., 2015). Meanwhile, the labor-intensive nations suffer more environmental burdens as their trade volumes increase due to the imports of capital-intensive products (Jiang & Liu, 2015;

Opoku & Boachie, 2020; Polloni-Silva et al., 2021; Rafindadi & Usman, 2020; Yu et al., 2019; Zakarya et al., 2015).

The structural change, from natural resource-based to a more industrialized economy, may also alter the extent to which humans consume energy and influence the ecological system. While the dominance of natural resource-based sectors is mostly associated with low energy use and hence low environmental impacts (Lapatinas et al., 2019), the industrialization process requires more energy consumption and results in severe environmental deterioration due to expanding production and more environmentally damaging product mix (Madlener & Sunak, 2011; Stern, 2004; Wang et al., 2011). Empirical studies affirm that the higher level of industrialization threatens either the environmental quality or energy security at large (Antoci et al., 2018; Li et al., 2019; Opoku & Aluko, 2021).

Based on the above discussion, we include national income, capital accumulation, FDI, trade openness, and the level of industrialization as control variables in our conceptual model.

3 Empirical methodology

The model used to investigate the nexus of digitalization (DIGI) and energy security (ES) can be written as follows:

$$\begin{aligned} ES_{it} = \beta_0 + \beta_1 DIGI_{i,t} + \beta_2 Y_{i,t} + \beta_3 TRADE_{i,t} + \beta_4 FDI_{i,t} \\ + \beta_5 INDUSTRY_{i,t} + \beta_6 DEMO_{i,t} + \beta_7 CORR_{i,t} + \varphi_t + \omega_i + \varepsilon_{ijt,} \end{aligned} \tag{1}$$

where i and t, respectively, represent country i and year t. φ_t and ω_i are added into the model to capture the country- and year-fixed effects, and $\varepsilon_{ijt,}$ is the error term.

3.1 Energy security

We have six indicators that are used to describe the three characteristics of energy security, including acceptability, develop-ability, and sustainability, to analyze the interplay between digitalization and energy security. Regarding ***Availability***, the ES1 is a proxy for a country's energy structure, as measured by the ratio of non-fossil energy consumption to total energy consumption. The non-fossil energy consumption reflects the acceptability aspect of energy security. These data are taken from the International Energy Statistics of US Energy Information Administration (U.S.EIA). ES1 measures the acceptability of energy security by reflecting the impact of its production and use on the economy and the environment (Fang et al., 2018). As expected, non-fossil energy consumption brings a positive impact on energy security. The development of non-fossil energies will enhance the country's energy supply capacity as well as improve the sustainability of the energy system (Fang et al., 2018). The higher this ratio, the better because it indicates lower non-renewable energy use, which means higher energy security. Regarding ***Acceptability***, the ES2 variable measures the rate of energy consumption per capita. According to Fang et al. (2018), the ability to assess the development potential of energy security shows the sustainable development of the energy system in an optimal, clean, and low-carbon way. This index is a negative variable, implying that the higher it is, the greater the danger to the energy security system.

Regarding ***Develop-ability***, the ES3 and ES4 are the ratios of carbon dioxide emissions to GDP and primary energy consumption, respectively (Fang et al., 2018). These two indicators reflect the develop-ability of energy security (Le & Nguyen, 2019). They show the link between energy structure and carbon emissions from oil, gas, and coal combustion. Carbon dioxide emissions negatively influence energy security. Regarding ***Sustainability***, ES5 and ES6 indicate the share of renewable energy consumption in total final energy consumption and renewable consumption per capital, respectively. Unlike ES1 that captures the acceptability of energy security, ES5 and ES6 only consider the specific renewable energy consumption. According to the U.S.EIA, energy sources can be categorized into renewable, nonrenewable, and fossil fuels. Renewable energy includes biomass (wood biomass; municipal solid waste; landfill gas and biogas; ethanol; biodiesel), hydroelectric power, geothermal, solar, and wind that can affect the sustainability of energy security, while fossil fuels consist of petroleum, natural gas, and coal. ES1 covers both ES5, ES6, hydroelectric power other types of energy like nuclear power. There has been a continuous argument on the effects of hydroelectric power and nuclear power on the sustainability of energy security (Lee et al., 2016). As indicated by the U.S.EIA, nuclear energy's environmental influences are more complex than other clean or renewable energy sources. Although nuclear power does not produce less air pollution or carbon dioxide than fossil energy, the process of mining and refining uranium ore and making reactor fuel requires a massive amount of energy. There is also a large amount of metal and concrete that also require a vast amount of energy to manufacture. A considerable amount of energy consumption is directly related to pollution and carbon dioxide emissions. This type of energy potential potentially creates environmental contamination and long-time radioactive hazard regarding nuclear power. Indeed, nuclear energy has complicated safety and security features. To capture the sustainability of energy security more precisely, we only consider the effects of renewable energy sources in ES5 and ES6 indicators.

3.2 Digitalization

Following Ha (2022b, c), Ha and Thanh (2022), and Myovella et al. (2020), the main objective of this study was to investigate the relationship between digitization and ES. $DIGI_{i,t} = \left\{ DESI_{i,t}, DIMEN^{m}_{i,t} \right\}$ is the main explanatory variable, including composite index $DESI_{i,t}$ and the five dimensions reflecting the process of digital transition, including connectivity (*Desi1*), human capital with basic and advantaged digital skills (*Desi2*), internet usage (*Desi3*), digital business integration (*Desi4*), and online public services (*Desi5*). More specifically, *Desi1* is a variable that represents the percentage of households that have a fixed broadband subscription or are in a 4G coverage area. *Desi2* is the percentage of people with basic digital capabilities and those with advanced skills. *Desi3* measures the number of Internet users on specific activities such as reading news, listening to music, watching videos and games, using video on demand, making video calls, using social networks, taking a course online, and performing online transactions such as banking, shopping, and selling. *Desi4* shows data on companies using electronic information sharing software, social media, and big data, as well as the percentage of SMEs that sell online and their total revenue. *Desi5* is the ratio of administrative processes related to important life events—like the birth of a baby, moving to a new home, or the rate of public services needed to start a company and conduct business activities—done online. Digitalization data are collected from various surveys, such as Eurostat's survey on the use of IT in households and individuals,[1] Eurostat's survey in ICT Enterprises, and Government e-Reports.[2] These surveys were conducted on 27 member states of the European Union (including the UK) for the period 2015–2020. These indicators are expected to represent the performance of the digital transformation of European countries.

3.2.1 Control variables

We follow the empirical studies in the literature to choose explanatory variables. Following Le and Nguyen (2019), we examine the impact of several variables, including income (*Y*)—as measured by real GDP per capita (constant 2010 US dollar); the share of trade values to GDP (*TRADE*); the ratio of net inflows of FDI and GDP (*FDI*); and the contribution of the industrial sector to GDP (*INDUS*)—reflecting the industrialization level as measured by the value-added of the industry sector as a per cent of GDP. As in Le and Nguyen (2019), we also include institutional considerations in the study to increase its persuasiveness. As displayed in Eq. (1), two institutional indicators are the democratization index (*DEMO*)—measured by the democratization index—and the corruption prevalence (*CORR*)—measured by the corruption perception index. Economic data come from World Development Indicators (WDI), while *DEMO* comes from the Finnish Social Science Data Archive (FSSDA), and *CORR* comes from Transparency International. Table 1 summarizes the statistical descriptions of all included variables. After cleaning and merging all country data, the final sample consists of 27 countries from 2015 to 2019. The correlation matrix between all variables is displayed in Table 2. Table 2 reveals that there is evidence to believe in a positive association between digitalization and energy security measures.

The data are then inspected for cross-sectional dependency by employing Pesaran's suggested cross-sectional dependency (CD) tests (Pesaran, 2021), and the results are reported in Table 3. The test results suggest the existence of CD in almost included variables. In the following step, to examine the stationarity of data with the existence of CD, we use the Levin–Lin–Chu unit-root test proposed by Levin et al. (2002) and the Im–Pesaran–Shin unit-root test proposed by Im et al. (2003). Table 3 summarizes the findings. We show that some variables in the level are not stationary but taking these variables in the first difference makes them stationary.

Along with the presence of CD and the stationarity of first-difference variables, we chose the panel-corrected standard error (PCSE) model for our samples, according to Beck and Katz (1995) and Canh and Thanh (2020). All explanatory variables are lagged by one period to resolve the endogeneity emerging from the simultaneous association between

[1] This is an annual survey to collect data on the use of ICT, the internet, e-government, and electronic skills in households and by individuals. This survey is conducted in the first quarter of a reference year for individuals (from 16 to 74 years) and households with at least one member in the age group 16 to 74 years old. Detailed information can be found in: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Community_survey_on_ICT_usage_in_households_and_by_individuals.

[2] This is an annual survey to collect data on the use of information and communication technologies (ICT), the internet, e-government, and electronic skills in enterprises. This survey is conducted in January of the reference year for most variables, for enterprises with 10 or more persons employed in chosen activities. Detailed information on this survey can be found in: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Community_survey_on_ICT_usage_in_enterprises.

Table 1 Description of variables

Variable	Definition	Measure	Source	Obs	Mean	SD	Min	Max
ES1	Energy security 1 (Acceptability of Energy Security)	Non-fossil energy consumption = 1-Fossil Energy consumption to Total (%)	U.S. EIA	135	0.23	0.14	0.04	0.69
ES2	Energy security 2 (Develop-ability of Energy Security)	Primary Energy Consumption/Population (Kg/person)	U.S. EIA	135	0.00	0.00	0.00	0.00
ES3	Energy security 3 (Develop-ability of Energy Security)	CO2 emissions (kg per 2011 PPP $ of GDP)	U.S. EIA	135	3.12	2.27	0.11	9.44
ES4	Energy security 4 (Develop-ability of Energy Security)	CO2 emissions/Primary Energy Consumption (Kg/Kg)	U.S. EIA	135	2.20	4.40	0.02	23.03
ES5	Energy security 5 (Acceptability of Energy Security)	Renewable energy consumption (% of total final energy consumption)	U.S. EIA	135	0.14	0.10	0.03	0.45
ES6	Energy security 6 (Sustainability of Energy Security)	Renewable energy consumption per capital	U.S. EIA	135	0.00	0.00	0.00	0.00
DESI	DESI overall index	The weighted average of the five main DESI dimensions (Desi1-5)	DESI (2020)	135	9.19	1.98	5.49	14.12
Desi1	Connectivity	The weighted average of fixed broadband take-up, fixed broadband coverage, mobile broadband, and broadband price index	DESI (2020)	135	9.81	2.21	4.36	15.01
Desi2	Human capital	The weighted average of internet user skills and advanced skills and development	DESI (2020)	135	11.48	2.94	6.82	19.38
Desi3	Use of internet services	The weighted average of internet use, activities online, and transactions	DESI (2020)	135	7.45	1.73	3.26	11.29
Desi4	Business Digitization	Including electronic information sharing, social media, big data, and the cloud	DESI (2020)	135	7.19	2.50	3.06	13.82
Desi5	Digital public services	The e-Government score	DESI (2020)	135	8.76	2.26	3.09	12.74
Y	Real output growth	The real GDP per capital (constant 2010 US dollars)	WDI	135	34.79	23.51	1.13	111.15
TRADE	Trade share	The proportion of GDP	WDI	135	1.27	0.67	0.55	4.08
FDI	Net inflow of foreign direct investment	The proportion of GDP	WDI	135	0.02	0.40	-2.92	1.63
INDUS	Industrialization level	The value added to GDP	WDI	135	0.23	0.06	0.10	0.38
DEMO	Level of democratization	The index of democratization	FSSDA	135	1.63	0.51	1.00	3.00

Table 1 (continued)

Variable	Definition	Measure	Source	Obs	Mean	SD	Min	Max
CORR	Corruption perception index	The indexed is scaled from 1 to 100, where 0 means the highest level of perceived corruption	Transparency International	135	110.07	4.61	99.94	123.78

The information used to calculate the overall DESI index and its dimensions is sourced from various surveys, including Eurostat—Community survey on ICT usage in Households and by Individual, Eurostat—ICT Enterprises survey, eGovernment Benchmarking Report

WDI World Development Indicator, *FSSDA* Finnish Social Science Data Archive, *WBGI* World Bank Group Indicator

Table 2 Correlation coefficients

	ES1	ES2	ES3	ES4	ES5	ES6	DESI	Desi1	Desi2	Desi3	Desi4	Desi5
ES1	1											
ES2	0.151	1										
ES3	−0.603***	−0.122	1									
ES4	−0.384***	−0.0923	0.535***	1								
ES5	0.718***	0.0125	−0.487***	−0.302***	1							
ES6	0.775***	0.366***	−0.444***	−0.255**	0.892***	1						
DESI	0.291***	0.605***	−0.328***	−0.146	0.361***	0.529***	1					
Desi1	0.216*	0.358***	−0.353***	−0.210*	0.255**	0.300***	0.744***	1				
Desi2	0.353***	0.687***	−0.282***	−0.144	0.364***	0.589***	0.901***	0.500***	1			
Desi3	0.200*	0.601***	−0.278**	−0.0628	0.239**	0.438***	0.928***	0.645***	0.896***	1		
Desi4	0.202*	0.456***	−0.277**	−0.164	0.252**	0.388***	0.805***	0.360***	0.698***	0.702***	1	
Desi5	0.136	0.329***	−0.108	0.0874	0.350***	0.419***	0.785***	0.612***	0.569***	0.632***	0.595***	1
Y	0.106	0.648***	−0.386***	−0.200*	0.165	0.322***	0.539***	0.331***	0.561***	0.532***	0.498***	0.254**
TRADE	−0.374***	0.451***	−0.0644	0.152	−0.439***	−0.289***	0.117	0.203*	0.0855	0.170*	0.0668	−0.0627
FDI	−0.00951	0.291***	−0.0647	−0.0209	−0.0528	0.0179	0.0754	0.149	0.0606	0.109	−0.0213	0.0141
INDUS	0.121	−0.162	0.0466	−0.295***	0.0461	0.0422	−0.0521	−0.0603	−0.0307	−0.216*	0.0642	−0.0697
DEMO	−0.344***	−0.569***	0.367***	0.402***	−0.295***	−0.461***	−0.620***	−0.251**	−0.706***	−0.593***	−0.614***	−0.326***
COR*R*	−0.0576	0.132	−0.167	−0.251**	−0.0736	−0.0654	0.322***	0.547***	0.207*	0.249**	0.0690	0.248**

	Y	TRADE	FDI	INDUS	DEMO	CORR
ES1						
ES2						
ES3						
ES4						
ES5						
ES6						
DESI						

Table 2 (continued)

	Y	TRADE	FDI	INDUS	DEMO	CORR
Desi1						
Desi2						
Desi3						
Desi4						
Desi5						
Y	1					
TRADE	0.485***	1				
FDI	0.192*	0.207*	1			
INDUS	−0.248**	−0.0190	−0.164	1		
DEMO	−0.671***	−0.0176	−0.106	0.00786	1	
CORR	−0.105	0.101	−0.0158	0.190*	−0.0554	1

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

Table 3 Cross-sectional dependence tests and stationary tests

Variable (in level)	CD-test, Pesaran (2004)	Harris–Tzavalis unit-root test (z statistic)	Im–Pesaran–Shin test (Z-bar)	Variable (in difference)	Harris–Tzavalis unit-root test (z statistic)	Im–Pesaran–Shin test (Z-bar)
ES1	7.49***	−3.00***	−2.21***	DES1	−8.38***	−4.28***
ES2	7.15***	−3.25***	−2.57***	DES2	−6.91***	−10.67***
ES3	19.89***	−2.81***	−2.05**	DES3	−7.26***	−5.28***
ES4	20.89***	0.88	−3.35***	DES4	−4.66***	−2.17**
ES5	7.55***	−2.88***	−1.88*	DES5	−8.45***	−23.69***
ES6	7.93***	−3.60***	−1.74	DES6	−8.87***	−4.61***
DESI	41.13***	−2.81***	−1.89*	DDESI	−7.81***	−3.07***
Desi1	39.77***	−3.15***	−0.96	DDesi1	−8.31***	−2.15**
Desi2	22.45***	−3.07***	−1.21	DDesi2	−8.32***	−2.21***
Desi3	36.51***	−0.41	−1.68	DDesi3	−5.24***	−2.35***
Desi4	37.62***	−2.22**	−2.35***	DDesi4	−6.83***	−7.06***
Desi5	39.28***	−140*	−1.67	DDesi5	−5.70***	−2.13**
Y	40.81***	−2.50***	−1.30	DY	−6.31***	−2.09**
TRADE	15.59***	−5.00***	−1.27	DTRADE	−7.95***	−2.71***
FDI	1.25	−5.97***	−5.03***	DFDI	−9.29***	−6.03***
INDUS	2.79***	−1.55*	−1.49	DINDUS	−6.50***	−41.23***
DEMO	1.05	−0.05	−0.97	DDEMO	−4.71***	−2.64***
CORR	39.81***	1.96	−1.11	DCORR	−2.43***	−3.64***

Regarding the CD test, the null hypothesis is that the cross-section is independent. *P*-value is closed to zero, implying that data are correlated across panel groups. Regarding Harris–Tzavalis unit-root test, the null hypothesis is "panels are homogeneous non-stationary." Regarding Im–Pesaran–Shin test, the null hypothesis is "Panels contain unit root," and the alternative hypothesis is "Panel are stationary" digitalization and energy security, as shown in Eq. (1). For further check, we reexamine our estimates by employing other econometric techniques, such as Feasible Generalized Least Squares (FGLS), to deal with heteroscedasticity and fixed effects as stated by Gala et al. (2018) and Sweet and Eterovic (2019).

In addition, the influence of digitalization on energy security in the short- and long-term is a topic identified in the literature. Hence, the autoregressive distributed lag (ARDL) technique is utilized (Pesaran & Smith, 1995). The dynamic fixed effects estimator (DFE) embedded into the ARDL model is used due to endogeneity emerging from the possible association between variables and heteroscedasticity throughout EU nations (Pesaran & Smith, 1995). Before running this model, we conduct the test for the cointegration relationship between the two variables by employing the Kao test, Pedroni and Westerlund cointegration test, in turn, developed by Kao (1999), Pedroni (2004), and Westerlund (2005). According to the Kao and Pedroni tests, Table 4 depicts the long-term cointegration between digitalization factors and each ES variable. However, it is worth noting that the variance ratio sometimes rejects this finding between *Desi2*, *Desi3,* and ES variables.

4 Empirical results

4.1 Baseline results

The PCSE model in Table 5 shows that the DESI overall index has a significant positive effect on the ES measures except for CO2 emissions (ES3). Notably, a promotion in digital transformation causes a significantly positive effect on the acceptability (ES1), sustainability of energy security (ES5 and ES6) but a negative impact on develop-ability (ES4) of energy security. The positive effects of digitalization on ES1 and ES5, ES6 provide interesting insights into which digitalization can enhance non-fossil and renewable energy usage. As Le and Nguyen (2019) indicated, a rise in usage of this type of energy helps countries experience stronger economic growth. Hence, digitalization indirectly enhances the growth of economies by using more green energy rather than fossil energy sources. In short, digitalization is beneficial for sustainable economic development. Given that digitalization helps enhance human capital (Spiezia, 2011), develop innovation systems (Ceccobelli et al., 2012; Ferro, 2011; Haini, 2019), foster global trade (Ahmedov, 2020; Salahuddin & Alam, 2016; Salahuddin & Gow, 2016), and improve institutional quality (Adam, 2020; Ali et al., 2022), our findings are also in line with several previous studies that find the positive impacts of labor input, innovation, governance indicators, global competitiveness factors, and enabling environment on the bioenergy industry growth (Abdulwakil et al., 2020; Alsaleh & Abdul-Rahim, 2018; Alsaleh et al., 2017, 2020a, 2020b).

However, Table 5 also implies that digitalization leads to high intensity of energy consumption (ES2) and a high level of carbon emission, implying that digitalization may not be good for the development of energy security in the case of European countries. Despite the multifaceted and contradicting impacts of digitalization's dimensions on energy consumption, the prevalence of increasing effects and carbon emission is consistent with Lange et al. (2020). Specifically, the increased energy efficiency and sectoral changes as resulted from digitalization could not curve the rising energy use for the production, usage, and disposal of digital technologies themselves and more production and consumption activities as the digital economy grows. Similar findings are empirically affirmed in the

Table 4 Cointegration test

Model: f(ES and digitalization)	Kao test Dickey–Fuller test	Pedroni test Phillips–Perron t	Westerlund test Variance ratio
ES1			
DESI	−4.33***	3.24***	−2.44**
Desi1	−5.04***	3.15***	−2.49***
Desi2	−4.44***	3.66***	0.19
Desi3	−5.35***	3.42***	−1.64**
Desi4	−8.31***	3.29***	−1.88**
Desi5	−6.02***	3.29***	−2.15**
ES2			
DESI	−2.99***	3.49***	−2.00**
Desi1	−7.04***	3.60***	−1.79**
Desi2	−6.67***	3.43***	−0.36
Desi3	−5.37***	3.66***	−1.24
Desi4	−6.51***	3.36***	−1.51*
Desi5	−4.74***	3.54***	−1.57*
ES3			
DESI	−3.57***	3.00***	−2.36***
Desi1	−2.38***	3.05***	−2.21**
Desi2	−0.92	3.40***	0.39
Desi3	−4.56***	2.91***	−1.29
Desi4	−6.05***	3.22***	−1.74*
Desi5	−2.97***	2.93***	−2.32**
ES4			
DESI	−13.90***	3.04***	−2.27**
Desi1	−13.17***	3.22***	−1.91**
Desi2	−12.02***	3.57***	0.70
Desi3	−14.02***	3.17***	−1.24
Desi4	−14.02***	3.09***	−1.43*
Desi5	−13.47***	3.06***	−1.91**
ES5			
DESI	−3.48***	2.95***	−2.76***
Desi1	−4.48***	3.06***	−2.42***
Desi2	−4.55***	3.37***	−0.39
Desi3	−4.68***	3.16***	−1.87*
Desi4	−8.04***	3.05***	−2.21**
Desi5	−5.71***	2.98***	−2.51***
ES6			
DESI	−2.87***	2.74***	−2.95***
Desi1	−3.43***	2.77***	−2.54***
Desi2	−4.07***	3.16***	−0.43
Desi3	−3.25***	2.99***	−2.05**
Desi4	−6.88***	2.93***	−2.29**
Desi5	−4.05***	2.67***	−3.03***

Regarding the Kao test, the null hypothesis is “No cointegration,” while the alternative hypothesis is “All panels are cointegrated.” Regarding the Pedroni test, the null hypothesis is “No cointegration,” while the alternative hypothesis is “All panels are cointegrated.” Regarding the Westerlund test, the null hypothesis is

Table 4 (continued)

"No cointegration," while the alternative hypothesis is "Some panels are cointegrated"

literature. For example, Sadorsky (2012), Salahuddin and Alam (2016), and Longo and York (2015) reveal that digitalization leads to more consumption of energy, while the pollution emission results from energy use (Can & Gozgor, 2017; Oberschelp et al., 2019). When investigating the effect of each dimension of digital transformation, we reveal some crucial findings.

Regarding the acceptability of energy security, our estimates imply that digital connectivity (*Desi1*) and human capital with digital skills lead to a rise in non-fossil consumption (*ES1*), while the use of the internet (*Desi3*) and digital public service reduces the usage of non-fossil energy sources. Regarding the develop-ability of energy security, energy consumption (ES2) can be reduced by an improvement in the use of the internet. At the same time, both human capital and digital public service tend to drive this indicator up. Our estimation results also indicate that the degree of carbon emission can be reduced if countries employ more digital connectivity devices and integrate more digital technologies into the business. This could be explained by the positive influence of internet technology on human capital and financial development, which supports R&D activities and technological progress (Ferro, 2011; Haini, 2019; Salahuddin & Gow, 2016; Spiezia, 2011). The technological advancement, in turn, creates the upgrading of industrial structure from traditional resource-intensive to technology-intensive and allow the replacement of low-energy equipment to high-energy ones as well as the development of more eco-friendly technologies (Airehrour et al., 2016; Li et al., 2019; Ren et al., 2021). This would not only enhance energy efficiency but also reduce energy intensity and carbon dioxide emissions from production activities. Further, the development of digital business and various ICT would intensify those impacts by fostering technological and trade-related R&D spillover effects (Basu & Fernald, 2007; Ceccobelli et al., 2012; Dunnewijk & Hultén, 2007) and hence accelerating the diffusion of green technologies across sectors and countries.

Regarding the sustainability of energy security, our study highlights the importance of digital connectivity, digital skills, and digital public services in encouraging countries to rely more on renewable energy sources. While the digital connectivity and digital skills contribute to the human capital (Ferro, 2011; Haini, 2019) and facilitate more trade flows (Ahmedov, 2020; OECD, 2019; Shyla, 2020), digital public services help improve institutional quality and control corruption (Adam, 2020; Ali et al., 2022). This would foster economic growth, increase national income, and raise environmental awareness among the public (Galeotti et al., 2008; Lee & Lee, 2009; Martínez-Zarzoso & Maruotti, 2011). Therefore, renewable energy sources are more favored for clean production as the response to the rise of demand for well-being and sustainable development. Moreover, good institutions also help foster R&D activities and facilitate the application of innovation, especially green technologies, into practice (Busenitz et al., 2000; Tebaldi & Elmslie, 2013; Varsakelis, 2006). Meanwhile, the increase of international trade flows of eco-products could accelerate the diffusion of green technologies that employ renewable energy sources (Bi et al., 2015; Costantini & Crespi, 2008; Franco & Marin, 2015).

Switching to renewable energy consumption is also a strategy for firms to sustain competitiveness, adapt to more burdensome environmental regulations from the

Table 5 Effects of digitalization on energy security

Variables	(1) ES1	(2)	(3) ES2	(4)	(5) ES3	(6)	(7) ES4	(8)	(9) ES5	(10)	(11) ES6	(12)
Panel A: The PCSE estimates												
L.DESI	0.02***		0.00***		0.02		0.83***		0.02***		0.00***	
	(0.002)		(0.000)		(0.034)		(0.152)		(0.002)		(0.000)	
L.Desi1		0.05***		0.00		−0.52***		−0.89***		0.02***		0.00***
		(0.005)		(0.000)		(0.036)		(0.053)		(0.003)		(0.000)
L.Desi3		−0.06***		−0.00***		0.04		−0.57**		−0.03***		−0.00***
		(0.016)		(0.000)		(0.278)		(0.268)		(0.007)		(0.000)
L.Desi4		0.00		0.00		−0.30***		−0.31***		−0.00		−0.00***
		(0.002)		(0.000)		(0.042)		(0.112)		(0.003)		(0.000)
L.Desi5		−0.02***		0.00**		0.34***		0.95***		0.00***		0.00***
		(0.003)		(0.000)		(0.056)		(0.087)		(0.001)		(0.000)
L.Desi2		0.04***		0.00***		0.21		0.92***		0.02***		0.00***
		(0.008)		(0.000)		(0.142)		(0.167)		(0.004)		(0.000)
L.Y	0.00**	−0.00**	−0.00	−0.00	−0.05***	−0.04***	−0.09***	−0.08***	0.00***	0.00***	0.00***	0.00***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.005)	(0.004)	(0.030)	(0.024)	(0.000)	(0.000)	(0.000)	(0.000)
L.TRADE	−0.10***	−0.08***	0.00***	0.00***	0.67***	0.93***	2.62***	3.56***	−0.11***	−0.09***	−0.00***	−0.00***
	(0.006)	(0.011)	(0.000)	(0.000)	(0.084)	(0.169)	(0.468)	(0.413)	(0.006)	(0.004)	(0.000)	(0.000)
L.FDI	0.02*	−0.01	0.00**	0.00**	−0.08	0.07	−1.01**	−0.71**	0.00	−0.01	0.00	−0.00
	(0.011)	(0.013)	(0.000)	(0.000)	(0.137)	(0.210)	(0.508)	(0.355)	(0.010)	(0.011)	(0.000)	(0.000)
L.INDUS	0.45***	0.11	−0.00***	−0.00***	−0.63	1.09	−23.61***	−25.74***	0.30***	0.16***	0.00***	0.00***
	(0.024)	(0.104)	(0.000)	(0.000)	(0.573)	(1.760)	(2.745)	(2.338)	(0.023)	(0.056)	(0.000)	(0.000)
L.DEMO	−0.05**	−0.08***	−0.00***	−0.00***	0.15	0.44**	2.34	3.04**	0.05***	0.02*	0.00*	0.00
	(0.019)	(0.019)	(0.000)	(0.000)	(0.292)	(0.191)	(1.704)	(1.537)	(0.017)	(0.012)	(0.000)	(0.000)
L.CORR	−0.01***	−0.02***	0.00	0.00	-0.15***	-0.09***	-0.41***	-0.27***	-0.00	-0.01***	-0.00***	-0.00***
	(0.001)	(0.002)	(0.000)	(0.000)	(0.015)	(0.017)	(0.055)	(0.058)	(0.001)	(0.001)	(0.000)	(0.000)
Observations	108	108	108	108	108	108	108	108	108	108	108	108

Table 5 (continued)

Variables	(1) ES1	(2)	(3) ES2	(4)	(5) ES3	(6)	(7) ES4	(8)	(9) ES5	(10)	(11) ES6	(12)
R-squared	0.342	0.507	0.654	0.719	0.231	0.339	0.437	0.601	0.474	0.541	0.534	0.601
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27
Panel B: The FGLS estimates												
L.DESI	0.02*	–	0.00***		0.02		0.83***		0.02***		0.00***	
	(0.009)		(0.000)		(0.150)		(0.246)		(0.005)		(0.000)	
L.Desi1		0.05***		0.00		−0.52***		−0.89***		0.02***		0.00***
		(0.009)		(0.000)		(0.169)		(0.250)		(0.006)		(0.000)
L.Desi3		−0.06***		−0.00***		0.04		−0.57		−0.03**		−0.00**
		(0.021)		(0.000)		(0.381)		(0.565)		(0.014)		(0.000)
L.Desi4		0.00		0.00		−0.30**		−0.31		−0.00		−0.00
		(0.008)		(0.000)		(0.138)		(0.204)		(0.005)		(0.000)
L.Desi5		−0.02***		0.00		0.34***		0.95***		0.00		0.00
		(0.006)		(0.000)		(0.118)		(0.176)		(0.004)		(0.000)
L.Desi2		0.04***		0.00***		0.21		0.92***		0.02**		0.00***
		(0.011)		(0.000)		(0.202)		(0.300)		(0.007)		(0.000)
L.Y	0.00	−0.00	−0.00	−0.00	−0.05**	−0.04**	−0.09***	−0.08***	0.00***	0.00**	0.00***	0.00*
	(0.001)	(0.001)	(0.000)	(0.000)	(0.019)	(0.018)	(0.030)	(0.027)	(0.001)	(0.001)	(0.000)	(0.000)
L.TRADE	−0.10***	−0.08***	0.00***	0.00***	0.67	0.93**	2.62***	3.56***	−0.11***	−0.09***	−0.00***	−0.00***
	(0.025)	(0.024)	(0.000)	(0.000)	(0.418)	(0.429)	(0.682)	(0.637)	(0.015)	(0.015)	(0.000)	(0.000)
L.FDI	0.02	−0.01	0.00**	0.00**	−0.08	0.07	−1.01	−0.71	0.00	−0.01	0.00	−0.00
	(0.029)	(0.026)	(0.000)	(0.000)	(0.499)	(0.475)	(0.816)	(0.705)	(0.018)	(0.017)	(0.000)	(0.000)
L.INDUS	0.45**	0.11	−0.00*	−0.00***	−0.63	1.09	−23.61***	−25.74***	0.30**	0.16	0.00**	0.00
	(0.206)	(0.232)	(0.000)	(0.000)	(3.507)	(4.237)	(5.730)	(6.287)	(0.124)	(0.151)	(0.000)	(0.000)
L.DEMO	−0.05	−0.08*	−0.00***	−0.00**	0.15	0.44	2.34*	3.04***	0.05**	0.02	0.00	0.00

Table 5 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	ES1		ES2		ES3		ES4		ES5		ES6	
	(0.043)	(0.040)	(0.000)	(0.000)	(0.738)	(0.737)	(1.206)	(1.094)	(0.026)	(0.026)	(0.000)	(0.000)
L.CORR	−0.01	−0.02***	0.00	0.00	−0.15**	−0.09	−0.41***	−0.27***	−0.00	−0.01**	−0.00	−0.00***
	(0.004)	(0.004)	(0.000)	(0.000)	(0.064)	(0.070)	(0.105)	(0.104)	(0.002)	(0.003)	(0.000)	(0.000)
Observations	108	108	108	108	108	108	108	108	108	108	108	108
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27

***$p<0.01$, **$p<0.05$, *$p<0.1$

Standard errors in parentheses

DESI is the DESI overall index. Desi1 is connectivity calculated based on the weighted average of the following dimensions: fixed broadband take-up, fixed broadband coverage, mobile broadband, and broadband price index. Desi2 is human capital calculated based on the weighted average of the following dimensions: the internet user skills and advanced skills and development. Desi3 is an online transaction. Desi4 is the integration of digital technology services calculated based on the weighted average of the following dimensions: business digitization and e-commerce. Finally, Desi5 is digital public services calculated by taking the score for e-Government authorities, and gain better social acceptance (European Commission, 1999; International Trade Centre, 2001; Kennett & Steenblik, 2005; Sinclair-Desgagné, 2008). On the other hand, the improvement of digital connectivity and digital skills could reduce the renewable energy costs by optimizing the production and distribution of renewable energy sources while allowing efficient integration of renewable energy into the existing centralized energy system and hence leading to the rapid growth of the share of renewable energy in the overall energy consumption (Verma et al., 2020). By using the PGLS model, similar findings are indicated as in Panel B of Table 5.

We turn to analyze the effects of control variables on ES. In the PCSE model, real output growth (*GDP*), corruption perception index (*CORR*), and level of democratization (*DEMO*) have a significantly positive effect on the Energy Policy except Energy security 2. In opposition to *CORR* and *GDP*, *FDI* impacts *ES2* positively. Besides, it also has a significant positive effect on ES4. Industrialization level has an insignificant effect on only *ES3,* and share of trade influences positively and significantly all dimensions of energy security.

On the other side of the coin, we concentrate on investigating the effect of energy security on digitalization, specifically a transformation of digitalization into the business sector (or digital business (*Desi4*)) and public sector (or digital public services (*Desi5*)). The reasons for our selection are as follows. While the development of e-commerce and e-business enhances human capital and fosters financial and trade flows (Ahmedov, 2020; OECD, 2019; Shyla, 2020), the adoption of digital public services helps improve institutional quality (Adam, 2020; Ali et al., 2022). This, in turn, will drive economic growth (Farhadi et al., 2012; Solomon & van Klyton, 2020). Moreover, the cointegration tests in the last column of Table 4 also suggest that the long-term relationship between digitalization and energy security is not stable. The estimated results on the association between energy security and these digitalization types are presented in Table 6. The estimation results demonstrate that all the dimensions of ES have a positive effect on the digital transformation in general, and most dimensions of ES also positively influence the digital transformation in business and the public sector in particular. More specifically, except for the ES3 variable, the variables of ES had a positive and statistically significant effect on DESI. Similarly, except for the *ES3* variable in the model estimation on the digitalization index in the business sector and *ES1* in the model estimation on the digitalization index in the public sector, the remaining variables positively influence ES on digitalization. Notably, we show the significant effects of renewable energy consumption on digitalization. As revealed by Blyth et al. (2014) and Le and Nguyen (2019), sustainable economic growth is attributed to the positive impacts of renewable energy consumption on the economic growth through its effect on the labor market (Blyth et al., 2014) and the stability of input prices in international markets (Apergis & Payne, 2010). The economic growth then determines the extent to which the government implements digitalization into different sectors of the economy (Nguyen et al., 2020; Visser, 2019). The findings in Panel B that we use the FGLS model display similar findings as those in Panel A.

In the following analysis, the study examines the short- and long-term effects of digitalization on ES. The results presented in Table 7 describe that, in the short term, the effects of digitalization are not evident. Digitalization positively impacts energy security in the long run, reflected by a rise in non-fossil and renewable energy consumption and a diminish in CO_2 emissions. However, the results on the effects of digitalization on ES show interesting findings. While online transactions (*Desi3*) play a significant role in enhancing non-fossil energy consumption and reducing the emission of pollution, both online transactions and digital businesses encourage countries to consume renewable energy. This may be because the effect of digitalization in business and commerce

Table 6 Effects of energy security on digitalization

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ES1	ES2	ES3	ES4	ES5	ES6
	DESI					
Panel A: The PCSE estimates						
L.ES	1.79***	0.06***	0.00	0.12***	5.13***	0.14***
	(0.249)	(0.002)	(0.013)	(0.019)	(0.454)	(0.007)
L.Y	0.02***	0.02***	0.02***	0.03***	0.01	0.01
	(0.007)	(0.005)	(0.007)	(0.006)	(0.009)	(0.007)
L.TRADE	0.04	−0.54***	−0.15	−0.47***	0.41***	0.44***
	(0.098)	(0.098)	(0.109)	(0.079)	(0.136)	(0.096)
L.FDI	−0.05	−0.28*	−0.01	0.11	−0.04	−0.08
	(0.129)	(0.165)	(0.140)	(0.125)	(0.091)	(0.080)
L.INDUS	−1.14**	1.36**	−0.36	2.59***	−1.88***	−2.39***
	(0.554)	(0.549)	(0.630)	(0.458)	(0.702)	(0.621)
L.DEMO	−1.58***	−0.94***	−1.70***	−1.80***	−1.84***	−1.51***
	(0.284)	(0.191)	(0.275)	(0.267)	(0.321)	(0.267)
L.CORR	0.09***	0.06***	0.08***	0.12***	0.07***	0.08***
	(0.017)	(0.012)	(0.016)	(0.013)	(0.018)	(0.015)
Observations	108	108	108	108	108	108
R-squared	0.571	0.633	0.559	0.603	0.599	0.642
Number of countries	27	27	27	27	27	27

Variables	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
	ES1	ES2	ES3	ES4	ES5	ES6	ES1	ES2	ES3	ES4	ES5	ES6
	Digital business						Digital public services					
L.ES	1.36***	0.05***	−0.01	0.11***	0.28	0.04***	−0.40	0.05***	0.09***	0.22***	6.52***	0.15***
	(0.321)	(0.006)	(0.015)	(0.030)	(0.396)	(0.004)	(0.424)	(0.006)	(0.024)	(0.023)	(0.663)	(0.011)
L.Y	0.01	0.01	0.01	0.02	0.01	0.01	0.01*	0.01	0.02**	0.03***	−0.01	−0.00

Table 6 (continued)

Variables	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
	ES1	ES2	ES3	ES4	ES5	ES6	ES1	ES2	ES3	ES4	ES5	ES6
	Digital business						Digital public services					
	(0.013)	(0.011)	(0.013)	(0.012)	(0.014)	(0.013)	(0.008)	(0.006)	(0.008)	(0.006)	(0.009)	(0.007)
L.TRADE	−0.03	−0.23	0.12	−0.18	0.14	0.26	−0.57***	−0.88***	−0.59***	−1.13***	0.18	0.09
	(0.266)	(0.271)	(0.289)	(0.292)	(0.303)	(0.276)	(0.175)	(0.176)	(0.183)	(0.186)	(0.162)	(0.124)
L.FDI	−0.55	−0.82*	−0.58	−0.47	−0.58	−0.60*	0.19	−0.07	0.20	0.40	0.14	0.10
	(0.358)	(0.452)	(0.364)	(0.318)	(0.363)	(0.364)	(0.415)	(0.395)	(0.418)	(0.381)	(0.334)	(0.333)
L.INDUS	6.14***	7.03***	5.53***	8.20***	5.46***	5.01***	−1.56***	−0.19	−1.67***	3.76***	−3.66***	−3.86***
	(1.366)	(1.421)	(1.437)	(1.425)	(1.430)	(1.415)	(0.481)	(0.572)	(0.474)	(0.713)	(0.570)	(0.467)
L.DEMO	−3.03***	−2.27***	−2.93***	−3.02***	−2.94***	−2.88***	−1.05***	−0.33	−1.02***	−1.21***	−1.19***	−0.82**
	(0.628)	(0.592)	(0.612)	(0.553)	(0.617)	(0.610)	(0.358)	(0.315)	(0.323)	(0.276)	(0.395)	(0.340)
L.CORR	−0.14***	−0.15***	−0.13***	−0.10***	−0.13***	−0.13***	0.04*	0.02	0.06**	0.12***	0.04	0.05**
	(0.045)	(0.041)	(0.045)	(0.037)	(0.045)	(0.044)	(0.026)	(0.020)	(0.027)	(0.027)	(0.027)	(0.024)
Observations	108	108	108	108	108	108	108	108	108	108	108	108
R-squared	0.504	0.532	0.500	0.520	0.500	0.503	0.258	0.307	0.265	0.384	0.311	0.333
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ES1	ES2	ES3	ES4	ES5	ES6
	DESI					
Panel B: The FGLS estimates						
L.ES	1.79*	0.06***	0.00	0.12***	5.13***	0.14***
	(1.022)	(0.012)	(0.061)	(0.034)	(1.572)	(0.028)
L.Y	0.02	0.02*	0.02*	0.03***	0.01	0.01
	(0.012)	(0.011)	(0.012)	(0.012)	(0.012)	(0.011)
L.TRADE	0.04	−0.54**	−0.15	−0.47*	0.41	0.44

Table 6 (continued)

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	ES1	ES2	ES3	ES4	ES5	ES6
	DESI					
	(0.288)	(0.263)	(0.276)	(0.275)	(0.312)	(0.273)
L.FDI	−0.05	−0.28	−0.01	0.11	−0.04	−0.08
	(0.323)	(0.304)	(0.326)	(0.312)	(0.312)	(0.295)
L.INDUS	−1.14	1.36	−0.36	2.59	−1.88	−2.39
	(2.302)	(2.122)	(2.291)	(2.337)	(2.234)	(2.105)
L.DEMO	−1.58***	−0.94**	−1.70***	−1.80***	−1.84***	−1.51***
	(0.452)	(0.445)	(0.453)	(0.431)	(0.434)	(0.410)
L.CORR	0.09**	0.06	0.08*	0.12***	0.07*	0.08**
	(0.041)	(0.038)	(0.042)	(0.041)	(0.039)	(0.037)
Observations	108	108	108	108	108	108
Number of countries	27	27	27	27	27	27

Variables	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
	ES1	ES2	ES3	ES4	ES5	ES6	ES1	ES2	ES3	ES4	ES5	ES6
	Digital business						Digital public services					
L.ES	−1.36	0.05***	−0.01	0.11**	0.28	0.04	−0.40	0.05***	0.09	0.22***	6.52***	0.15***
	(1.437)	(0.018)	(0.085)	(0.049)	(2.294)	(0.043)	(1.475)	(0.018)	(0.086)	(0.046)	(2.260)	(0.042)
L.Y	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.03*	−0.01	−0.00
	(0.017)	(0.016)	(0.017)	(0.017)	(0.018)	(0.017)	(0.017)	(0.017)	(0.018)	(0.016)	(0.018)	(0.017)
L.TRADE	−0.03	−0.23	0.12	−0.18	0.14	0.26	−0.57	−0.88**	−0.59	−1.13***	0.18	0.09
	(0.405)	(0.387)	(0.384)	(0.395)	(0.455)	(0.420)	(0.416)	(0.396)	(0.391)	(0.376)	(0.448)	(0.408)
L.FDI	−0.55	−0.82*	−0.58	−0.47	−0.58	−0.60	0.19	−0.07	0.20	0.40	0.14	0.10
	(0.454)	(0.448)	(0.454)	(0.447)	(0.454)	(0.453)	(0.466)	(0.458)	(0.462)	(0.426)	(0.448)	(0.441)
L.INDUS	6.14*	7.03**	5.53*	8.20**	5.46*	5.01	−1.56	−0.19	−1.67	3.76	−3.66	−3.86
	(3.236)	(3.130)	(3.189)	(3.355)	(3.259)	(3.239)	(3.322)	(3.198)	(3.245)	(3.193)	(3.211)	(3.149)

Table 6 (continued)

Variables	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
	ES1	ES2	ES3	ES4	ES5	ES6	ES1	ES2	ES3	ES4	ES5	ES6
	Digital business						Digital public services					
L.DEMO	−3.03***	−2.27***	−2.93***	−3.02***	−2.94***	−2.88***	−1.05	−0.33	−1.02	−1.21**	−1.19*	−0.82
	(0.636)	(0.656)	(0.631)	(0.619)	(0.634)	(0.631)	(0.653)	(0.670)	(0.642)	(0.589)	(0.624)	(0.614)
L.CORR	−0.14**	−0.15***	−0.13**	−0.10	−0.13**	−0.13**	0.04	0.02	0.06	0.12**	0.04	0.05
	(0.057)	(0.056)	(0.058)	(0.059)	(0.057)	(0.057)	(0.059)	(0.057)	(0.059)	(0.056)	(0.056)	(0.055)
Observations	108	108	108	108	108	108	108	108	108	108	108	108
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Standard errors in parentheses

DESI is the DESI overall index. Desi1 is connectivity calculated based on the weighted average of the following dimensions: fixed broadband take-up, fixed broadband coverage, mobile broadband, and broadband price index. Desi2 is human capital calculated based on the weighted average of the following dimensions: the internet user skills and advanced skills and development. Desi3 is online transactions. Desi4 is the integration of digital technology services calculated based on the weighted average of the following dimensions: business digitization and e-commerce. Finally, Desi5 is digital public services calculated by taking the score for e-Government.

Table 7 Digitalization and energy security: short-run and long-run effects

Variables	(1)	(3)	(1)	(3)	(9)	(11)
	Non-fossil energy consumption		CO2 emissions		Renewable energy consumption	
Short-run effects						
EC term	−1.22***	−1.23***	−0.87***	−0.85***	−1.21***	−1.26***
	(0.110)	(0.118)	(0.121)	(0.128)	(0.110)	(0.118)
D.DESI	0.01		−0.08		0.01	
	(0.010)		(0.160)		(0.009)	
D.Desi1		0.01		0.00		0.01
		(0.006)		(0.088)		(0.005)
D.Desi3		−0.02		0.07		−0.02*
		(0.010)		(0.151)		(0.009)
D.Desi4		0.00		0.02		−0.00
		(0.005)		(0.082)		(0.005)
D.Desi5		0.00		−0.08		0.01
		(0.006)		(0.091)		(0.005)
D.Desi2		0.01*		−0.15		0.01
		(0.006)		(0.093)		(0.006)
Long-run effects						
DESI	0.01**		−0.25***		0.01***	
	(0.002)		(0.048)		(0.002)	
Desi1		−0.01		0.01		−0.01
		(0.005)		(0.106)		(0.004)
Desi3		0.02**		−0.34*		0.01*
		(0.009)		(0.203)		(0.008)
Desi4		0.00		−0.02		0.01*
		(0.004)		(0.095)		(0.004)
Desi5		0.00		0.03		0.00
		(0.004)		(0.082)		(0.003)
Desi2		−0.00		−0.05		−0.00
		(0.005)		(0.120)		(0.005)

***$p<0.01$, **$p<0.05$, *$p<0.1$

Standard errors in parentheses

is transmitted through the improvement of human capital (Ferro, 2011; Haini, 2019), the trade-related R&D spillovers (Ahmedov, 2020; OECD, 2019; Shyla, 2020), and the behavior of firms (Busenitz et al., 2000; Tebaldi & Elmslie, 2013; Varsakelis, 2006) and individuals (Galeotti et al., 2008; Lee & Lee, 2009; Martínez-Zarzoso & Maruotti, 2011) that take time to change and demonstrate a significant contribution to the energy security. Our finding confirms that digitalization plays a vital role in promoting countries to achieve sustainable economic development, especially in the long term.

On the other side, we also examine the short- and long-term influences of ES on digitalization. The results described in Table 8 show no relationship both in the long run and in the short run between ES and DESI. However, we find evidence on the effects of ES on digitalization in the business sector. Particularly, setting energy security goals

Table 8 Energy security and digitalization: Short-run and long-run effects

Variables	(1) ES1 DESI	(3) ES2	(5) ES3	(7) ES4	(9) ES5	(11) ES6
	Short-run effects					
EC term	0.02	0.05	0.01	0.04	0.02	0.03
	(0.034)	(0.036)	(0.044)	(0.037)	(0.035)	(0.037)
D.ES	0.01	0.02	−0.01	−0.04	0.00	0.02
	(0.014)	(0.019)	(0.009)	(0.059)	(0.014)	(0.038)
	Long-run effects					
ES	−1.03	0.65	1.00	−0.64	−0.77	−0.28
	(2.461)	(0.578)	(6.189)	(1.681)	(1.906)	(2.547)
	Digital business					
	Short-run effects					
EC term	−0.29***	−0.24***	−0.35***	−0.30***	−0.30***	−0.32***
	(0.046)	(0.049)	(0.056)	(0.049)	(0.047)	(0.048)
D.ES	−0.04*	0.01	0.04**	0.17*	−0.05*	−0.13**
	(0.024)	(0.033)	(0.015)	(0.099)	(0.025)	(0.064)
	Long-run effects					
ES	0.29**	0.18	−0.15***	−0.78*	0.32***	1.05***
	(0.124)	(0.179)	(0.043)	(0.409)	(0.121)	(0.305)
	YES	YES	YES	YES	YES	YES
	YES	YES	YES	YES	YES	YES
	Digital public services					
	Short-run effects					
EC term	−0.04	−0.04	−0.09	−0.04	−0.06	−0.07
	(0.046)	(0.048)	(0.054)	(0.049)	(0.046)	(0.047)
D.ES	−0.00	−0.01	0.01	0.05	−0.02	−0.09
	(0.024)	(0.032)	(0.016)	(0.102)	(0.025)	(0.065)
	Long-run effects					
ES	0.53	0.57	−0.35*	−0.26	1.07	2.96
	(0.859)	(1.039)	(0.190)	(2.996)	(0.928)	(1.957)

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Standard errors in parentheses

toward reducing energy consumption and pollution emission promotes the digital transformation process in the business sector of countries in the short run, whilst the promotion of renewable energy consumption can help countries to accelerate the digitalization process in the long run.

4.2 Nonlinear effects of online transactions and digital public services toward sustainable development

This section examines whether there are nonlinear impacts of digital activities, such as online transactions and digital public services, on energy securities. We focus on these two sectors since digitalization in these sectors adversely influences the sustainable development of the economy, as shown in Table 5. However, we argue that sustainable development requires digital transformation implementation to be achieved at a certain level and scale; thus, the negative impacts of digitalization on ES no longer exist. We believe that online transactions and digital public services have nonlinear effects on energy security. According to the estimations in Table 9, there is a nonlinear relationship between online transactions and ES1, ES3, ES5, and ES6 as revealed by significant and adverse effects of digitalization and significant and positive impacts of its squared term. The results imply that the initial rise in the digitalization index in online transactions negatively influences energy security. Still, those effects will turn out to be positive when online transactions increase to a certain extent. Likewise, the digital public services variable has the same effect on ES as the online transaction variable in terms of impact variables and direction of impact. In general, there is a nonlinear relationship between online transactions, digital public services, and energy security in the shape of the U curve. We use predictive margins analysis to display our conclusion in Fig. 1. ES decreases slightly concerning a given amount of increase in online transactions or digital public services as displayed in Panel A and Panel B, respectively. The acceptability, develop-ability, and sustainability of ES then increase when digitalization reaches a certain level. The negative impact of digitalization on energy security in the initial phase is consistent with our expectation about the "rebound effects" of digitalization. Specifically, the settings and usage of digital-based business and governance models, the expanding production and consumption activities as facilitated by digital technologies, and the production and application of green technologies may increase energy demand and worsen environmental deterioration (Font Vivanco et al., 2014; Jenkins et al., 2011; Kemp-Benedict, 2014; Lange et al., 2020). Nevertheless, the favorable impacts of digitalization on energy security could prevail in the latter stage due to two primary reasons. First, the "rebound effects" of digitalization may be offset by significant positive externalities of green technologies to energy efficiency and environmental quality in the long run. Second, digitalization needs to reach a sufficiently high level to create substantial changes on mediating factors such as human capital, innovation systems, trade openness, and institutional quality that could foster the growth and bioenergy industries (Abdulwakil et al., 2020; Alsaleh & Abdul-Rahim, 2018; Alsaleh et al., 2017, 2020a, 2020b). In this regard, our findings confirm the argument of Loock (2020) that digitalization-based business model innovation helps resolve the bottlenecks regarding the development and application of sustainable energy technologies and, therefore, drives forward sustainable energy transitions. Our empirical evidence aligns with Alsaleh and Abdul-Rahim (2021) that ICT development, as a dimension of digitalization, could foster bioenergy growth in EU economies and Moyer and Hughes (2012) regarding the positive influence of digitalization on renewable energy production and consumption in the long run.

4.3 Nonlinear effects of sustainability of energy security on digitalization

On the other side of the coin, we concentrate on investigating the impacts of ES on digitization in this section. The results presented in Panel A in Table 10 describe the effect of ES on DESI. Non-fossil energy consumption and CO2 emissions have a statistically significant impact on DESI. Non-fossil and renewable energy consumption initially reduce DESI; however, when this indicator reaches a specific value, it will drive DESI up. The findings suggest that the impact of non-fossil and renewable energy consumption follows the U-shaped curve. Panel A also suggests the nonlinear inverted U-shaped effects of energy

Table 9 Nonlinear effects of online transactions and digital public services on energy securities

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(13)	(14)	(15)	(16)	(17)	(18)
	Online transactions						Digital public services					
	ES1	ES2	ES3	ES4	ES5	ES6	ES1	ES2	ES3	ES4	ES5	ES6
L.DESI	−0.06***	0.00***	−1.08***	0.43	−0.05***	−0.00***	−0.03**	−0.00	−0.34**	0.51	−0.04***	−0.00***
	(0.014)	(0.000)	(0.251)	(0.488)	(0.008)	(0.000)	(0.011)	(0.000)	(0.166)	(0.369)	(0.014)	(0.000)
L.DESI^2	0.01***	0.00	0.08***	0.02	0.00***	0.00***	0.00**	0.00	0.03**	0.01	0.00***	0.00***
	(0.001)	(0.000)	(0.017)	(0.026)	(0.001)	(0.000)	(0.001)	(0.000)	(0.012)	(0.022)	(0.001)	(0.000)
L.Y	0.00	0.00	−0.05***	−0.08**	0.00***	0.00***	0.00***	0.00	−0.05***	−0.08***	0.00***	0.00***
	(0.000)	(0.000)	(0.006)	(0.033)	(0.000)	(0.000)	(0.000)	(0.000)	(0.005)	(0.030)	(0.000)	(0.000)
L.TRADE	−0.09***	0.00***	0.83***	2.34***	−0.10***	−0.00***	−0.10***	0.00***	0.74***	3.00***	−0.10***	−0.00***
	(0.007)	(0.000)	(0.116)	(0.567)	(0.005)	(0.000)	(0.006)	(0.000)	(0.078)	(0.430)	(0.005)	(0.000)
L.FDI	0.02*	0.00**	−0.12	−0.91*	0.00	0.00	0.02*	0.00**	−0.12	−1.10**	0.00	0.00
	(0.012)	(0.000)	(0.136)	(0.518)	(0.012)	(0.000)	(0.011)	(0.000)	(0.213)	(0.523)	(0.006)	(0.000)
L.INDUS	0.53***	−0.00*	−0.51	−19.63***	0.38***	0.00***	0.44***	−0.00***	−0.29	−23.03***	0.32***	0.00***
	(0.033)	(0.000)	(0.768)	(3.606)	(0.034)	(0.000)	(0.026)	(0.000)	(0.567)	(2.746)	(0.022)	(0.000)
L.DEMO	−0.06***	−0.00***	0.04	2.11	0.04***	0.00	−0.07***	−0.00***	0.30	1.72	0.04***	−0.00*
	(0.019)	(0.000)	(0.317)	(1.748)	(0.013)	(0.000)	(0.016)	(0.000)	(0.238)	(1.399)	(0.014)	(0.000)
L.CORR	−0.01***	0.00**	−0.16***	−0.38***	−0.00	−0.00***	−0.00***	0.00**	−0.16***	−0.39***	0.00	−0.00***
	(0.001)	(0.000)	(0.020)	(0.062)	(0.001)	(0.000)	(0.001)	(0.000)	(0.014)	(0.062)	(0.001)	(0.000)
Observations	108	108	108	108	108	108	108	108	108	108	108	108
R-squared	0.348	0.634	0.244	0.414	0.461	0.521	0.323	0.616	0.250	0.489	0.489	0.510
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Standard errors in parentheses

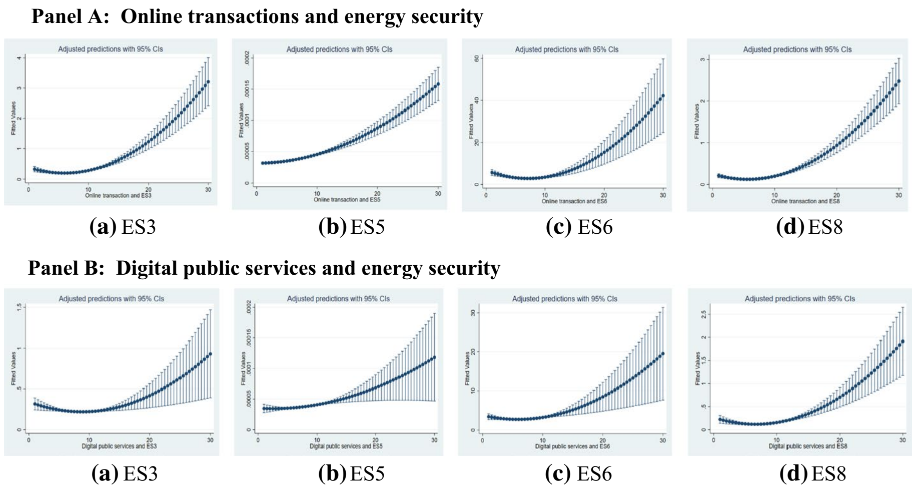

Fig. 1 Predictive margin of digitalization on energy security. **a** Online transactions and energy security and **b** Digital public services and energy security

consumption and CO2 emissions on digitalization. Given that the digital transformation requires sufficient infrastructure, human capital, and a favorable institutional environment (Dasgupta et al., 1999; Khalifa, 2016; Wang & Feeney, 2014), this finding is in line with the "feedback hypothesis" about a bidirectional causality between energy consumption and economic growth (Apergis & Tang, 2013; Ozturk, 2010; Payne, 2010). In this regard, the supply and consumption of non-fossil and primary energy that fuels economic growth (Le & Nguyen, 2019) become a condition for digitalization. However, the significant change in the level of digitalization is only attained when the economic contribution of the energy system reaches a sufficiently high threshold.

In the subsequent analysis, the study examines the nonlinear influence of ES on each dimension of digitalization. We focus on specific digital activities, including online transactions digitalization in the business and public sectors. The first thing worth noting is that the four elements of ES all have a nonlinear effect on online transactions. Non-fossil energy consumption and renewable energy consumption act in a U shape, while primary energy consumption and CO2 emissions affect in an inverted U shape. For the digital business, there is only one variable with the nonlinear influence, which is non-fossil energy consumption, and this effect is positive after non-fossil energy consumption reaches a particular value. The remaining ES variables show the nonlinear relationship as expected, but some variables are not statistically significant. Three factors that affect digital public services nonlinearly consist of non-fossil energy consumption, primary energy consumption, and CO_2 emissions. While the non-fossil energy consumption has a positive effect after reaching a particular value, the remaining two variables have an inverted U shape. All the above results are illustrated through Panels A, B, C, and D in Fig. 2. This finding provides a different perspective about the impact of energy security on digitalization. Specifically, the rising energy consumption and carbon dioxide emissions, at sufficiently high levels, may constitute an alert or motivation that is strong enough for businesses and governments to go digital (Liu et al., 2019; Renner et al., 2020).

Table 10 Nonlinear effects of energy security on digitalization

Variables	(1) Non-fossil energy consumption	(2) Primary energy consumption/population	(3) CO2 emissions	(4) Renewable energy consumption
	DESI			
Panel A				
L.ES	−7.85***	0.07***	0.56***	−0.23
	(0.481)	(0.024)	(0.044)	(0.203)
L.ES^2	15.24***	−0.00	−0.02***	0.18***
	(0.692)	(0.000)	(0.003)	(0.045)
L.Y	0.02***	0.02***	0.05***	0.01
	(0.007)	(0.005)	(0.006)	(0.008)
L.TRADE	−0.18**	−0.53***	−0.99***	0.22*
	(0.089)	(0.088)	(0.099)	(0.130)
L.FDI	−0.07	−0.28*	0.17	−0.03
	(0.140)	(0.169)	(0.131)	(0.093)
L.INDUS	0.65	1.20*	2.52***	−1.17*
	(0.585)	(0.670)	(0.365)	(0.646)
L.DEMO	−1.37***	−0.92***	−1.55***	−1.71***
	(0.235)	(0.211)	(0.219)	(0.288)
L.CORR	0.12***	0.06***	0.13***	0.08***
	(0.013)	(0.016)	(0.014)	(0.015)
Observations	108	108	108	108
R-squared	0.623	0.633	0.651	0.608
Number of countries	27	27	27	27

Table 10 (continued)

Variables	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
	ES1	ES3	ES4	ES6	ES1	ES3	ES4	ES6	ES1	ES3	ES4	ES6
	Online transactions				Digital business				Digital public services			
Panel B												
LES	− 8.34***	0.10***	0.36***	− 0.87***	− 7.84***	0.08***	0.22**	− 0.35	− 12.10***	0.20***	0.84***	0.26
	(0.836)	(0.021)	(0.038)	(0.232)	(1.027)	(0.029)	(0.087)	(0.239)	(1.510)	(0.038)	(0.080)	(0.188)
LES^2	14.60***	− 0.00***	− 0.01***	0.28***	10.24***	− 0.00	− 0.01	0.09*	18.49***	− 0.00***	− 0.03***	0.10***
	(1.156)	(0.000)	(0.002)	(0.054)	(1.365)	(0.000)	(0.005)	(0.054)	(2.065)	(0.000)	(0.003)	(0.035)
L.Y	0.00	0.00	0.02***	− 0.00	0.01	0.01	0.02*	0.01	0.02**	0.01**	0.05***	− 0.00
	(0.005)	(0.005)	(0.005)	(0.006)	(0.013)	(0.011)	(0.014)	(0.014)	(0.007)	(0.006)	(0.006)	(0.008)
L.TRADE	0.16*	0.09	− 0.29***	0.31***	− 0.18	− 0.18	− 0.32	0.04	− 0.83***	− 0.64***	− 1.87***	0.08
	(0.099)	(0.073)	(0.088)	(0.117)	(0.254)	(0.248)	(0.285)	(0.313)	(0.186)	(0.153)	(0.276)	(0.174)
L.FDI	− 0.21**	− 0.35**	− 0.05	− 0.18**	− 0.56	− 0.80*	− 0.46	− 0.57	0.17	0.01	0.48	0.15
	(0.101)	(0.154)	(0.078)	(0.087)	(0.362)	(0.451)	(0.312)	(0.365)	(0.426)	(0.408)	(0.387)	(0.337)
L.INDUS	− 5.15***	− 6.32***	− 4.18***	− 6.28***	7.34***	6.42***	8.18***	5.82***	0.62	− 2.88***	3.66***	− 3.28***
	(0.848)	(0.699)	(0.548)	(0.744)	(1.288)	(1.395)	(1.434)	(1.430)	(0.536)	(0.706)	(0.819)	(0.618)
L.DEMO	− 1.62***	− 1.23***	− 1.81***	− 1.75***	− 2.89***	− 2.22***	− 2.96***	− 2.87***	− 0.80***	− 0.14	− 0.85***	− 1.12***
	(0.204)	(0.203)	(0.181)	(0.216)	(0.604)	(0.601)	(0.560)	(0.610)	(0.282)	(0.314)	(0.218)	(0.375)
L.CORR	0.08***	0.04**	0.08***	0.05***	− 0.11***	− 0.15***	− 0.09**	− 0.13***	0.09***	0.06***	0.14***	0.04
	(0.017)	(0.018)	(0.015)	(0.017)	(0.043)	(0.040)	(0.038)	(0.043)	(0.025)	(0.023)	(0.030)	(0.025)
Observations	108	108	108	108	108	108	108	108	108	108	108	108
R-squared	0.583	0.573	0.575	0.566	0.517	0.533	0.522	0.501	0.322	0.321	0.463	0.313
Number of countries	27	27	27	27	27	27	27	27	27	27	27	27

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

Standard errors in parentheses

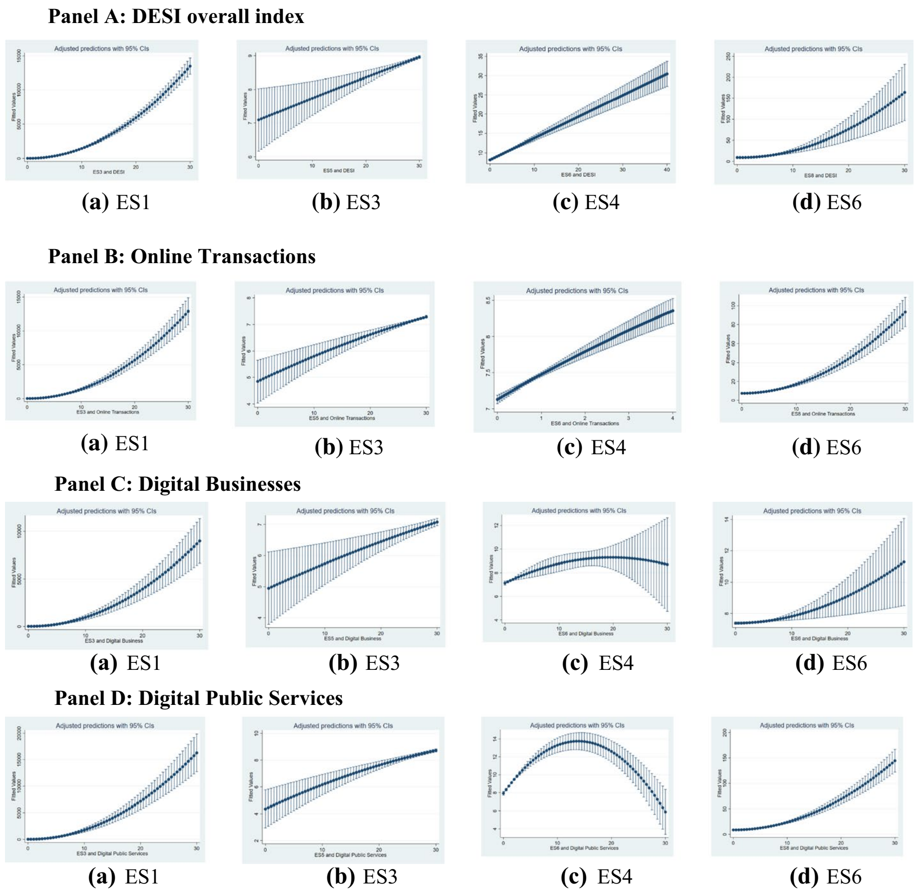

Fig. 2 Predictive margin of energy security on digitalization. **a** DESI overall index, **b** online transactions, **c** digital businesses, and **d** digital public services

5 Conclusion and policy implications

We are the first to empirically analyze the nexus of digital transformation and energy security. By using the international sample of 27 European countries over the period from 2015 to 2019, we reveal interesting findings. *First*, a promotion in digital transformation causes a significantly positive effect on the acceptability and sustainability of energy security but a negative impact on develop-ability (ES4) of energy security. Notably, digitalization is beneficial for sustainable economic development, reflected by a positive effect on energy security reflected by a rise in non-fossil and renewable energy consumption and a decrease in CO2 emission. *Second,* ES has a positive impact on the digital transformation, especially the digital transformation in the business and public sectors. *Third,* setting energy security goals toward reducing energy consumption and pollution emission promotes the digital transformation process in the business sector of countries in the short run, while the promotion of renewable energy consumption can help countries to accelerate the digitalization process in the long run. *Fourth*, online transactions and digital public services have nonlinear effects on the acceptability, develop-ability, and sustainability of energy security. Similarly, the acceptability, develop-ability, and sustainability of ES have a nonlinear impact on digitalization.

This paper contributes new theoretical and empirical justifications about the influence of digitalization on energy security. While previous studies examine the linkage between digitalization and energy security based on insufficient proxies of the two constructs, our paper provides a more reliable answer based on more comprehensive measurements and updated international data. Specifically, digitalization may cause different impacts on different aspects of energy security. Those relationships also vary when the focus is given to different dimensions of digitalization. Moreover, the nonlinear effects of online transactions and digital public services, as two crucial dimensions of digitalization on the acceptability, develop-ability, and sustainability of energy security, as found in this research, help further explain the contradicting arguments and empirical evidence about the digitalization–energy security nexus (Ha, 2022a; Lange et al., 2020; Loock, 2020; Moyer & Hughes, 2012; Ren et al., 2021; Wen et al., 2021). Specifically, while digital connectivity, human capital with digital skills, and the use of the Internet help foster sustainable energy development, only the use of the Internet is found to reduce energy consumption. Those impacts occur immediately and become persistent in the long run. Nevertheless, it is noble that there is a time lag to witness the positive externalities of business digitalization and digital public services on energy security. In other words, it takes time to leverage the positive impacts of the digital transformation in business and government sectors on human capital, innovation, and institutional environment before favorable changes in renewable energy production and consumption could be witnessed. Moreover, it also needs time for sufficient energy efficiency to be achieved to offset the "rebound effects" of technological innovation in a digital world. The second novelty of this paper is to confirm the two-way interaction between digitalization and energy security by pointing out the existence of a nonlinear relationship between them. This provides insights into the nature of the digitalization–energy security nexus for the construction of more comprehensive management policies over the energy system.

Our findings suggest that managing the digital world could be a crucial tool to maintain energy security on the policy front. Despite that business digitalization and the launch of digital public services during their initial phases, the acquirement of digital skills and accelerating digital connectivity may endanger energy security in some aspects. The scale-up of digitalization could reduce the amount of carbon dioxide emission and foster the sustainable development of the energy system in the long run. Therefore, continuous investment in digital transformation across sectors is deemed to be beneficial to energy security. However, since energy consumption and carbon dioxide emissions may rise steeply and endanger energy security during the first phase of digitalization, the policies aiming at fostering digitalization among societies, businesses, and government sectors should accompany strict environmental regulations. In addition, the positive externalities of digitalization on the sustainable energy transitions could be witnessed sooner if the government provides a suitable enabling environment for the rapid enhancement of human capital, capital accumulation, and institutional quality that accelerates the bioenergy industry development and the diffusion of green technologies. On the other hand, our findings indicate that maintaining good energy security also fosters digitalization. In this regard, digitalization and energy security are complementary to each other. Combining strategies that encourage green R&D activities and renewable energy production and consumption while accelerating the digital transformation would constitute a win–win solution for overall sustainable development in the long term.

The findings of this study could be interpreted in light of limitations. First, we utilized archival data accumulated only for the European Union area. It is essential to consider the role of digitalization in enhancing the security of the energy system in developing countries, where there have been warnings about environmental degradation and energy overconsumption (Ha et al., 2021). However, surveys following stringent guidelines to collect information about the digital transformation process in developing economies are not available (Ha, 2022a). Second, there may be further channels through which digitalization affects energy security. It is necessary to consider levels of economic development and economic complexity performance, and the effectiveness of government policies. A study taking these channels into account is expected to provide insights for economists and policymakers in designing policy to promote digital transformation and energy security performance. Future research may explore the data sources to collect more information about digitalization in developing countries and examine the role of digitalization in this area.

Appendix

See Table 11.

Table 11 Countries in the sample

EU countries		
Austria	Hungary	Portugal
Belgium	Iceland	Slovak Republic
Bulgaria	Ireland	Slovenia
Czech Republic	Italy	Sweden
Denmark	Lithuania	
Spain	Luxembourg	
Estonia	Latvia	
UK	Malta	
Greece	Netherlands	
Croatia	Poland	

Data availability Data available on request due to privacy/ethical restrictions.

References

Abdulwakil, M. M., Abdul-Rahim, A. S., & Alsaleh, M. (2020). Bioenergy efficiency change and its determinants in EU-28 region: Evidence using Least Square Dummy Variable corrected estimation. *Biomass and Bioenergy, 137*, 105569. https://doi.org/10.1016/j.biombioe.2020.105569

Acheampong, A. O. (2019). Modelling for insight: Does financial development improve environmental quality? *Energy Economics, 83*, 156–179. https://doi.org/10.1016/j.eneco.2019.06.025

Adam, I. O. (2020). Examining E-Government development effects on corruption in Africa: The mediating effects of ICT development and institutional quality. *Technology in Society, 61*, 101245. https://doi.org/10.1016/j.techsoc.2020.101245

Ahmedov, I. (2020). The Impact of digital economy on international trade. *European Journal of Business and Management Research, 5*(4), https://doi.org/10.24018/ejbmr.2020.5.4.389

Airehrour, D., Gutiérrez, J., & Ray, S. K. (2016). *Greening and optimizing energy consumption of sensor nodes in the internet of things through energy harvesting: challenges and approaches*. International Conference on Information Resources Management (Conf-IRM 2016), Cape Town, South Africa
Ali, M., Raza, S. A., Puah, C. H., & Arsalan, T. (2022). Does e-government control corruption? Evidence from South Asian countries. *Journal of Financial Crime, 29*(1), 258–271. https://doi.org/10.1108/JFC-01-2021-0003
Ali, U., Li, Y., Yánez Morales, V. P., & Hussain, B. (2021). Dynamics of international trade, technology innovation and environmental sustainability: Evidence from Asia by accounting for cross-sectional dependence. *Journal of Environmental Planning and Management, 64*(10), 1864–1885. https://doi.org/10.1080/09640568.2020.1846507
Alsaleh, M., & Abdul-Rahim, A. S. (2018). Determinants of cost efficiency of bioenergy industry: Evidence from EU28 countries. *Renewable Energy, 127*, 746–762. https://doi.org/10.1016/j.renene.2018.04.085
Alsaleh, M., & Abdul-Rahim, A. S. (2021). The pathway toward bioenergy growth: Does information and communication technology development make a difference in EU economies? *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-021-01933-9
Alsaleh, M., Abdul-Rahim, A. S., & Mohd-Shahwahid, H. O. (2017). Determinants of technical efficiency in the bioenergy industry in the EU28 region. *Renewable and Sustainable Energy Reviews, 78*, 1331–1349. https://doi.org/10.1016/j.rser.2017.04.049
Alsaleh, M., Zubair, A. O., & Abdul-Rahim, A. S. (2020a). Productivity growth and its determinants of the bioenergy industry in the EU28 region: Empirical evidence using Malmquist productivity index. *Business Strategy & Development, 3*(4), 531–542. https://doi.org/10.1002/bsd2.115
Alsaleh, M., Zubair, A. O., & Abdul-Rahim, A. S. (2020b). The impact of global competitiveness on the growth of bioenergy industry in EU-28 region. *Sustainable Development, 28*(5), 1304–1316. https://doi.org/10.1002/sd.2085
Amable, B. (2000). International specialisation and growth. *Structural Change and Economic Dynamics, 11*(4), 413–431. https://doi.org/10.1016/S0954-349X(00)00026-6
Antoci, A., Galeotti, M., & Sordi, S. (2018). Environmental pollution as engine of industrialization. *Communications in Nonlinear Science and Numerical Simulation, 58*, 262–273. https://doi.org/10.1016/j.cnsns.2017.06.016
APERC (2007). *Quest for energy security in the 21st century: Resources and constraints.* Asia Pacific Energy Research Centre
Apergis, N., & Payne, J. E. (2009). Energy consumption and economic growth in Central America: Evidence from a panel cointegration and error correction model. *Energy Economics, 31*(2), 211–216. https://doi.org/10.1016/j.eneco.2008.09.002
Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy, 38*(1), 656–660. https://doi.org/10.1016/j.enpol.2009.09.002
Apergis, N., & Payne, J. E. (2012). Renewable and non-renewable energy consumption-growth nexus: Evidence from a panel error correction model. *Energy Economics, 34*(3), 733–738. https://doi.org/10.1016/j.eneco.2011.04.007
Apergis, N., & Tang, C. F. (2013). Is the energy-led growth hypothesis valid? New evidence from a sample of 85 countries. *Energy Economics, 38*, 24–31. https://doi.org/10.1016/j.eneco.2013.02.007
Apergis, N., Can, M., Gozgor, G., & Lau, C. K. M. (2018). Effects of export concentration on CO2 emissions in developed countries: An empirical analysis. *Environmental Science and Pollution Research, 25*(14), 14106–14116. https://doi.org/10.1007/s11356-018-1634-x
Azzuni, A., & Breyer, C. (2018). Definitions and dimensions of energy security: A literature review. *Wiley Interdisciplinary Reviews: Energy and Environment, 7*(1), e268. https://doi.org/10.1002/wene.268
Bakhsh, K., Rose, S., Ali, M. F., Ahmad, N., & Shahbaz, M. (2017). Economic growth, CO2 emissions, renewable waste and FDI relation in Pakistan: New evidences from 3SLS. *Journal of Environmental Management, 196*, 627–632. https://doi.org/10.1016/j.jenvman.2017.03.029
Baldwin, D. A. (1997). The concept of security. *Review of International Studies, 23*(1), S0260210597000053. https://doi.org/10.1017/S0260210597000053
Basu, S., & Fernald, J. (2007). Information and communications technology as a general-purpose technology: Evidence from US industry data. *German Economic Review, 8*(2), 146–173. https://doi.org/10.1111/j.1468-0475.2007.00402.x
Beck, N., & Katz, J. N. (1995). What to do (and not to do) with time-series cross-section data. *The American Political Science Review, 89*(3), 634–647. https://doi.org/10.2307/2082979
Berkhout, F., Hertin, J. (2001). I*mpacts of ICT on environmental sustainability: Speculations and evidence.* Report to the OECD, Brighton.

Bernstein, R., & Madlener, R. (2010). Impact of disaggregated ICT capital on electricity intensity in European manufacturing. *Applied Economics Letters, 17*(17), 1691–1695. https://doi.org/10.1080/13504850903120717

Bi, K., Huang, P., & Ye, H. (2015). Risk identification, evaluation and response of low-carbon technological innovation under the global value chain: A case of the Chinese manufacturing industry. *Technological Forecasting and Social Change, 100*, 238–248. https://doi.org/10.1016/j.techfore.2015.07.005

Blum, B., Hübner, J., Müller, S., & Neumarker, K. J. B. (2018). *Challenges for sustainable environmental policy: Influencing factors of the rebound effect in energy efficiency improvements*. Freiburg: University of Freiburg, Institute for Economic Research, Department of Economic Policy and Constitutional Economic Theory.

Blyth, W., Gross, R., Speirs, J., Sorrell, S., Nicholls, J., Dorgan, A., & Hughes, N. (2014). *Low carbon jobs: The evidence for net job creation from policy support for energy efficiency and renewable energy* [Reports and working papers]. UKERC. http://www.ukerc.ac.uk/publications/low-carbon-jobs-the-evidence-for-net-job-creation-from-policy-support-for-energy-efficiency-and-renewable-energy.html

Boutabba, M. A. (2014). The impact of financial development, income, energy and trade on carbon emissions: Evidence from the Indian economy. *Economic Modelling, 40*, 33–41. https://doi.org/10.1016/j.econmod.2014.03.005

Busenitz, L. W., Gómez, C., & Spencer, J. W. (2000). Country institutional profiles: Unlocking entrepreneurial phenomena. *Academy of Management Journal, 43*(5), 994–1003. https://doi.org/10.5465/1556423

Can, M., & Gozgor, G. (2017). The impact of economic complexity on carbon emissions: Evidence from France. *Environmental Science and Pollution Research, 24*(19), 16364–16370. https://doi.org/10.1007/s11356-017-9219-7

Canh, N. P., & Thanh, S. D. (2020). Financial development and the shadow economy: A multi-dimensional analysis. *Economic Analysis and Policy, 67*, 37–54. https://doi.org/10.1016/j.eap.2020.05.002

Ceccobelli, M., Gitto, S., & Mancuso, P. (2012). ICT capital and labour productivity growth: A non-parametric analysis of 14 OECD countries. *Telecommunications Policy, 36*(4), 282–292. https://doi.org/10.1016/j.telpol.2011.12.012

Cherp, A., & Jewell, J. (2014). The concept of energy security: Beyond the four as. *Energy Policy, 75*, 415–421. https://doi.org/10.1016/j.enpol.2014.09.005

Collard, F., Fève, P., & Portier, F. (2005). Electricity consumption and ICT in the French service sector. *Energy Economics, 27*(3), 541–550. https://doi.org/10.1016/j.eneco.2004.12.002

Costantini, V., & Crespi, F. (2008). Environmental regulation and the export dynamics of energy technologies. *Ecological Economics, 66*(2/3), 447–460. https://doi.org/10.1016/j.ecolecon.2007.10.008

Dasgupta, S., Agarwal, D., Ioannidis, A., & Gopalakrishnan, S. (1999). Determinants of information technology adoption. *Journal of Global Information Management, 7*(3), 30–40. https://doi.org/10.4018/jgim.1999070103

Dunnewijk, T., & Hultén, S. (2007). A brief history of mobile communication in Europe. *Telematics and Informatics, 24*(3), 164–179. https://doi.org/10.1016/j.tele.2007.01.013

El Bassam, N. (2021). Drivers for digitalization of energy. In *Distributed renewable energies for off-grid communities* (pp. 443–446). Elsevier. https://doi.org/10.1016/B978-0-12-821605-7.00003-9

Esfahani, A. N., Moghaddam, N. B., Maleki, A., & Nazemi, A. (2021). The knowledge map of energy security. *Energy Reports, 7*, 3570–3589. https://doi.org/10.1016/j.egyr.2021.06.001

European Commission (1999). *The EU's eco-industry's export potential*. Final report to DGXI of the European Commission.

Faisal, F., Tursoy, T., & Berk, N. (2018). Linear and non-linear impact of Internet usage and financial deepening on electricity consumption for Turkey: Empirical evidence from asymmetric causality. *Environmental Science and Pollution Research, 25*(12), 11536–11555. https://doi.org/10.1007/s11356-018-1341-7

Fang, D., Shi, S., & Yu, Q. (2018). Evaluation of sustainable energy security and an empirical analysis of China. *Sustainability, 10*(5), 1685. https://doi.org/10.3390/su10051685

Farhadi, M., Ismail, R., & Fooladi, M. (2012). ICT use and economic growth. *PLoS ONE, 7*(11), e48903. https://doi.org/10.1371/journal.pone.0048903

Ferro, E. (2011). *Signaling and technological marketing tools for exporters*. World Bank.

Florida, R. (1996). Lean and Green: The move to environmentally conscious manufacturing. *California Management Review, 39*(1), 80–105. https://doi.org/10.2307/41165877

Font Vivanco, D., Kemp, R., van der Voet, E., & Heijungs, R. (2014). Using LCA-based decomposition analysis to study the multidimensional contribution of technological innovation to environmental pressures. *Journal of Industrial Ecology, 18*(3), 380–392. https://doi.org/10.1111/jiec.12118

Forster, B. A. (1973). Optimal capital accumulation in a polluted environment. *Southern Economic Journal, 39*(4), 544. https://doi.org/10.2307/1056705

Franco, C., & Marin, G. (2015). The effect of within-sector, upstream and downstream environmental taxes on innovation and productivity. *Environmental and Resource Economics, 66*(2), 261–291. https://doi.org/10.1007/s10640-015-9948-3

Gala, P., Camargo, J., Magacho, G., & Rocha, I. (2018). Sophisticated jobs matter for economic complexity: An empirical analysis based on input-output matrices and employment data. *Structural Change and Economic Dynamics, 45*, 1–8. https://doi.org/10.1016/j.strueco.2017.11.005

Galeotti, M., Manera, M., & Lanza, A. (2008). On the robustness of robustness checks of the environmental Kuznets curve hypothesis. *Environmental and Resource Economics, 42*(4), 551–574. https://doi.org/10.1007/s10640-008-9224-x

Green, K. W., Zelbst, P. J., Meacham, J., & Bhadauria, V. S. (2012). Green supply chain management practices: Impact on performance. *Supply Chain Management: An International Journal, 17*(3), 290–305. https://doi.org/10.1108/13598541211227126

Ha, L. T. (2022a). Are digital business and digital public services a driver for better energy security? Evidence from a European sample. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-021-17843-2

Ha, L. T. (2022b). Effects of digitalization on financialization: Empirical evidence from European countries. *Technology in Society, 68*, 101851. https://doi.org/10.1016/j.techsoc.2021.101851

Ha, L. T. (2022c). Socioeconomic and resource efficiency impacts of digital public services. *Environmental Science and Pollution Research*. https://doi.org/10.1007/s11356-022-21408-2

Ha, L. T., & Thanh, T. T. (2022). Effects of digital public services on trades in green goods: Does institutional quality matter? *Journal of Innovation & Knowledge*, *7*(1), 100168. https://doi.org/10.1016/j.jik.2022.100168

Ha, L. T., Nam, P. X., & Thanh, T. T. (2021). Effects of bribery on firms' environmental innovation adoption in Vietnam: Mediating roles of firms' bargaining power and credit and institutional constraints. *Ecological Economics*, *185*, 107042. https://doi.org/10.1016/j.ecolecon.2021.107042

Haider Zaidi, S. A., Zafar, M. W., Shahbaz, M., & Hou, F. (2019). Dynamic linkages between globalization, financial development and carbon emissions: Evidence from Asia Pacific Economic Cooperation countries. *Journal of Cleaner Production, 228*, 533–543. https://doi.org/10.1016/j.jclepro.2019.04.210

Haini, H. (2019). Internet penetration, human capital and economic growth in the ASEAN economies: Evidence from a translog production function. *Applied Economics Letters, 26*(21), 1774–1778. https://doi.org/10.1080/13504851.2019.1597250

Hauknes, J., & Knell, M. (2009). Embodied knowledge and sectoral linkages: An input–output approach to the interaction of high- and low-tech industries. *Research Policy, 38*(3), 459–469. https://doi.org/10.1016/j.respol.2008.10.012

Huang, B. -N., Hwang, M. J., & Yang, C. W. (2008). Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. *Ecological Economics*, *67*(1), 41–54. https://doi.org/10.1016/j.ecolecon.2007.11.006

Huberty, M., Gao, H., Mandell, J., & Zysman, J. (2011). *Shaping the green growth economy: A review of the public debate and the prospects for green growth*. The Berkeley Roundtable on the International Economy.

Ibrahim, M., & Alagidede, P. (2018). Effect of financial development on economic growth in sub-Saharan Africa. *Journal of Policy Modeling, 40*(6), 1104–1125. https://doi.org/10.1016/j.jpolmod.2018.08.001

IEA (International Energy Agency) (2014). *Energy security*. IEA Energy Technology Systems Analysis Programme. Paris. http://www.iea.org/topics/energysecurity/

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics, 115*(1), 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7

International Trade Centre. (2001). The environmental services business: Big and growing. *International Trade Forum, 2*, 6–9.

Ishida, H. (2015). The effect of ICT development on economic growth and energy consumption in Japan. *Telematics and Informatics, 32*(1), 79–88. https://doi.org/10.1016/j.tele.2014.04.003

Jalas, M. (2009). Time-use rebound effects: An activity-based view of consumption. In: *Energy efficiency and sustainable consumption* (pp. 167–184). Palgrave Macmillan UK. https://doi.org/10.1057/9780230583108_8

Jenkins, J., Nordhaus, T., & Shellenberger, M. (2011). *Energy emergence: Rebound and backfire as emergent phenomena*. Breakthrough Institute.

Jiang, X., & Liu, Y. (2015). Global value chain, trade and carbon: Case of information and communication technology manufacturing sector. *Energy for Sustainable Development, 25*, 1–7. https://doi.org/10.1016/j.esd.2014.12.001

Kanellakis, M., Martinopoulos, G., & Zachariadis, T. (2013). European energy policy—A review. *Energy Policy, 62*, 1020–1030. https://doi.org/10.1016/j.enpol.2013.08.008

Kao, C. (1999). Spurious regression and residual-based tests for cointegration in panel data. *Journal of Econometrics, 90*(1), 1–44. https://doi.org/10.1016/S0304-4076(98)00023-2

Kemp-Benedict, E. (2014). *Shifting to a green economy: Lock-in, path dependence, and policy options* (p. 16, Rep.). Stockholm Environment Institute.

Kennett, M., & Steenblik, R. (2005). *Environmental goods and services: A synthesis of country studies*, Vol. 3. OECD Publishing.

Khalifa, A. B. (2016). Determinants of ICT adoption by Tunisian firms. *Journal of Innovation Economics & Management, 20*(2), 151–177.

Kruyt, B., van Vuuren, D. P., de Vries, H. J. M., & Groenenberg, H. (2009). Indicators for energy security. *Energy Policy, 37*(6), 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Lange, S., Pohl, J., & Santarius, T. (2020). Digitalization and energy consumption. Does ICT reduce energy demand? *Ecological Economics*, *176*, 106760. https://doi.org/10.1016/j.ecolecon.2020.106760

Lapatinas, A., Litina, A., & Sartzetakis, E. S. (2019). Environmental projects in the presence of corruption. *International Tax and Public Finance, 26*(1), 103–144. https://doi.org/10.1007/s10797-018-9503-6

Le, T.-H. (2016). Dynamics between energy, output, openness and financial development in sub-Saharan African countries. *Applied Economics, 48*(10), 914–933. https://doi.org/10.1080/00036846.2015.1090550

Le, T.-H., & Nguyen, C. P. (2019). Is energy security a driver for economic growth? Evidence from a global sample. *Energy Policy, 129*, 436–451. https://doi.org/10.1016/j.enpol.2019.02.038

Le, T.-H., & Park, D. (2021). What drives energy insecurity across the world? A panel data analysis. *Energy Research & Social Science, 77*, 102093. https://doi.org/10.1016/j.erss.2021.102093

Le, T.-H., & Tran-Nam, B. (2018). Trade liberalization, financial modernization and economic development: An empirical study of selected Asia-Pacific countries. *Research in Economics, 72*(2), 343–355. https://doi.org/10.1016/j.rie.2017.03.001

Le, T.-H., Chang, Y., & Park, D. (2016). Trade openness and environmental quality: International evidence. *Energy Policy, 92*, 45–55. https://doi.org/10.1016/j.enpol.2016.01.030

Le, T.-H., Chang, Y., Taghizadeh-Hesary, F., & Yoshino, N. (2019). Energy insecurity in Asia: A multidimensional analysis. *Economic Modelling, 83*, 84–95. https://doi.org/10.1016/j.econmod.2019.09.036

Lee, C.-C., & Lee, J.-D. (2009). Income and CO2 emissions: Evidence from panel unit root and cointegration tests. *Energy Policy, 37*(2), 413–423. https://doi.org/10.1016/j.enpol.2008.09.053

Lee, S., Yoon, B., & Shin, J. (2016). Effects of nuclear energy on sustainable development and energy security: Sodium-cooled fast reactor case. *Sustainability, 8*(10), 979. https://doi.org/10.3390/su8100979

Levin, A., Lin, C.-F., & James Chu, C.-S. (2002). Unit root tests in panel data: Asymptotic and finite-sample properties. *Journal of Econometrics, 108*(1), 1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Li, M., Li, L., & Strielkowski, W. (2019). The impact of urbanization and industrialization on energy security: A case study of China. *Energies, 12*(11), 2194. https://doi.org/10.3390/en12112194

Liu, R., Gailhofer, P., Gensch, C.-O., Köhler, A., & Wolff, F. (2019). *Impacts of the digital transformation on the environment and sustainability*. Issue Paper under Task 3 from the "Service contract on future EU environment policy", European Commission, Berlin. Available at https://ec.europa.eu/environment/enveco/resource_efficiency/pdf/studies/issue_paper_digital_transformation_20191220_final.pdf. Accessed 18 Aug 2021.

Longo, S. B., & York, R. (2015). How does information communication technology affect energy use? *Human Ecology Review, 22*(1), 55–72.

Loock, M. (2020). Unlocking the value of digitalization for the European energy transition: A typology of innovative business models. *Energy Research & Social Science, 69*, 101740. https://doi.org/10.1016/j.erss.2020.101740

Luzzini, D., Brandon-Jones, E., Brandon-Jones, A., & Spina, G. (2015). From sustainability commitment to performance: The role of intra- and inter-firm collaborative capabilities in the upstream supply chain. *International Journal of Production Economics, 165*, 51–63. https://doi.org/10.1016/j.ijpe.2015.03.004

Madlener, R., & Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? *Sustainable Cities and Society, 1*(1), 45–53. https://doi.org/10.1016/j.scs.2010.08.006

Martínez-Zarzoso, I., & Maruotti, A. (2011). The impact of urbanization on CO2 emissions: Evidence from developing countries. *Ecological Economics, 70*(7), 1344–1353. https://doi.org/10.1016/j.ecolecon.2011.02.009

Moyer, J. D., & Hughes, B. B. (2012). ICTs: Do they contribute to increased carbon emissions? *Technological Forecasting and Social Change, 79*(5), 919–931. https://doi.org/10.1016/j.techfore.2011.12.00

Myovella, G., Karacuka, M., & Haucap, J. (2020). Digitalization and economic growth: A comparative analysis of Sub-Saharan Africa and OECD economies. *Telecommunications Policy, 44*(2), 101856. https://doi.org/10.1016/j.telpol.2019.101856

Nguyen, C. P., Su, T. D., & Doytch, N. (2020). The drivers of financial development: Global evidence from internet and mobile usage. *Information Economics and Policy, 53*, 100892. https://doi.org/10.1016/j.infoecopol.2020.100892

Oberschelp, C., Pfister, S., Raptis, C. E., & Hellweg, S. (2019). Global emission hotspots of coal power generation. *Nature Sustainability, 2*(2), 113–121. https://doi.org/10.1038/s41893-019-0221-6

OECD (2019). *Trade in the digital era.* Available from https://www.oecd.org/going-digital/trade-in-the-digital-era.pdf. Accessed 18 Aug 2021

OECD (2020). *Digital transformation in the age of COVID-19: Building resilience and bridging divides. Digital Economy Outlook 2020 Supplement*. Available from https://www.oecd.org/digital/digital-economy-outlook-covid.pdf. Accessed 18 Aug 2021

Opoku, E. E. O., & Aluko, O. A. (2021). Heterogeneous effects of industrialization on the environment: Evidence from panel quantile regression. *Structural Change and Economic Dynamics, 59*, 174–184. https://doi.org/10.1016/j.strueco.2021.08.015

Opoku, E. E. O., & Boachie, M. K. (2020). The environmental impact of industrialization and foreign direct investment. *Energy Policy, 137*, 111178. https://doi.org/10.1016/j.enpol.2019.111178

Owusu-Agyei, S., Okafor, G., Chijoke-Mgbame, A. M., Ohalehi, P., & Hasan, F. (2020). Internet adoption and financial development in sub-Saharan Africa. *Technological Forecasting and Social Change, 161*, 120293. https://doi.org/10.1016/j.techfore.2020.1202

Ozturk, I. (2010). A literature survey on energy–growth nexus. *Energy Policy, 38*(1), 340–349. https://doi.org/10.1016/j.enpol.2009.09.024

Payne, J. E. (2010). Survey of the international evidence on the causal relationship between energy consumption and growth. *Journal of Economic Studies, 37*(1), 53–95. https://doi.org/10.1108/01443581011012261

Pedroni, P. (2004). Panel cointegration: Asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Econometric Theory, 20*(3), 597–625. https://doi.org/10.1017/S0266466604203073

Pesaran, M. H. (2021). General diagnostic tests for cross-sectional dependence in panels. *Empirical Economics, 60*(1), 13–50. https://doi.org/10.1007/s00181-020-01875-7

Pesaran, M. H., & Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of Econometrics, 68*(1), 79–113. https://doi.org/10.1016/0304-4076(94)01644-F

Polloni-Silva, E., Ferraz, D., Camioto, F. D. C., Rebelatto, D. A. D. N., & Moralles, H. F. (2021). Environmental Kuznets curve and the pollution-halo/haven hypotheses: An investigation in Brazilian municipalities. *Sustainability, 13*(8), 4114. https://doi.org/10.3390/su13084114

Qin, J., Liu, Y., & Grosvenor, R. (2017). *Data analytics for energy consumption of digital manufacturing systems using Internet of Things method. 2017 13th IEEE conference on automation science and engineering (CASE)*. https://doi.org/10.1109/coase.2017.8256150

Rafindadi, A. A. (2016). Does the need for economic growth influence energy consumption and CO2 emissions in Nigeria? Evidence from the innovation accounting test. *Renewable and Sustainable Energy Reviews, 62*, 1209–1225. https://doi.org/10.1016/j.rser.2016.05.028

Rafindadi, A. A., & Ozturk, I. (2015). Natural gas consumption and economic growth nexus: Is the 10th Malaysian plan attainable within the limits of its resource? *Renewable and Sustainable Energy Reviews, 49*, 1221–1232.

Rafindadi, A. A., & Ozturk, I. (2017). Dynamic effects of financial development, trade openness and economic growth on energy consumption: Evidence from South Africa. *International Journal of Energy Economics and Policy, 7*(3), 74–85.

Rafindadi, A. A., & Usman, O. (2020). Globalization, energy use, and environmental degradation in South Africa: Startling empirical evidence from the Maki-cointegration test. *Journal of Environmental Management, 244*, 265–275.

Rafindadi, A. A., Muye, I. M., & Kaita, R. A. (2018). The effects of FDI and energy consumption on environmental pollution in predominantly resource-based economies of the GCC. *Sustainable Energy Technologies and Assessments, 25*, 126–137.

Ren, S., Hao, Y., Xu, L., Wu, H., & Ba, N. (2021). Digitalization and energy: How does internet development affect China's energy consumption? *Energy Economics, 98*(98), 1–20. https://doi.org/10.1016/j.eneco.2021.105220

Renner, A., Cadillo-Benalcazar, J. J., Benini, L., & Giampietro, M. (2020). Environmental pressure of the European agricultural system: Anticipating the biophysical consequences of internalization. *Ecosystem Services, 46*, 101195. https://doi.org/10.1016/j.ecoser.2020.101195

Rivera-Batiz, L. A., & Romer, P. M. (1991). Economic integration and endogenous growth. *The Quarterly Journal of Economics, 106*(2), 531. https://doi.org/10.2307/2937946

Ruiz, J. L. (2018). Financial development, institutional investors, and economic growth. *International Review of Economics & Finance, 54*, 218–224. https://doi.org/10.1016/j.iref.2017.08.009

Sadorsky, P. (2012). Information communication technology and electricity consumption in emerging economies. *Energy Policy, 48*, 130–136. https://doi.org/10.1016/j.enpol.2012.04.064

Salahuddin, M., & Alam, K. (2016). ICT, electricity consumption and economic growth in OECD countries: A panel data analysis. *International Journal of Electrical Power & Energy Systems, 76*, 185–193. https://doi.org/10.1016/j.ijepes.2015.11.005

Salahuddin, M., & Gow, J. (2016). The effects of Internet usage, financial development and trade openness on economic growth in South Africa: A time series analysis. *Telematics and Informatics, 33*(4), 1141–1154. https://doi.org/10.1016/j.tele.2015.11.006

Salahuddin, M., Gow, J., & Ozturk, I. (2015). Is the long-run relationship between economic growth, electricity consumption, carbon dioxide emissions and financial development in Gulf Cooperation Council Countries robust? *Renewable & Sustainable Energy Reviews, 51*, 317–326.

Shahbaz, M., Khan, S., & Tahir, M. I. (2013). The dynamic links between energy consumption, economic growth, financial development and trade in China: Fresh evidence from multivariate framework analysis. *Energy Economics, 40*, 8–21. https://doi.org/10.1016/j.eneco.2013.06.006

Shyla, J. (2020). Effect of digitalization on import and export. *Emperor International Journal of Finance and Management Research, 5*(7), 1–12.

Simpson, A. (2007). The environment—Energy security nexus: Critical analysis of an energy 'love triangle' in Southeast Asia. *Third World Quarterly, 28*(3), 539–554. https://doi.org/10.1080/01436590701192710

Sinclair-Desgagné, B. (2008). The environmental goods and services industry. *International Review of Environmental and Resource Economics, 2*(1), 69–99.

Solomon, E. M., & van Klyton, A. (2020). The impact of digital technology usage on economic growth in Africa. *Utilities Policy, 67*, 101104. https://doi.org/10.1016/j.jup.2020.101104

Sorrell, S. (2007). *The rebound effect: An assessment of the evidence for economywide energy savings from improved energy efficiency*. UK Energy Research Centre London

Sovacool, B. K. (2011). Evaluating energy security in the Asia pacific: Towards a more comprehensive approach. *Energy Policy, 39*(11), 7472–7479. https://doi.org/10.1016/j.enpol.2010.10.008

Soytas, U., & Sari, R. (2003). Energy consumption and GDP: Causality relationship in G-7 countries and emerging markets. *Energy Economics, 25*(1), 33–37. https://doi.org/10.1016/S0140-9883(02)00009-9

Spiezia, V. (2011). Are ICT users more innovative?: An analysis of ICT-enabled innovation in OECD firms. *OECD Journal: Economic Studies, 2011*(1). https://doi.org/10.1787/eco_studies-2011-5kg2d2hkn6vg

Stares, B. P. (2000). *Rethinking energy security in East Asia* (p. 19). The Japan Center for International Exchange.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Development, 32*(8), 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Sweet, C., & Eterovic, D. (2019). Do patent rights matter? 40 years of innovation, complexity and productivity. *World Development, 115*, 78–93. https://doi.org/10.1016/j.worlddev.2018.10.009

Takase, K., & Murota, Y. (2004). The impact of IT investment on energy: Japan and US comparison in 2010. *Energy Policy, 32*(11), 1291–1301. https://doi.org/10.1016/s0301-4215(03)00097-1

Tamazian, A., Chousa, J. P., & Vadlamannati, K. C. (2009). Does higher economic and financial development lead to environmental degradation: Evidence from BRIC countries. *Energy Policy, 37*(1), 246–253. https://doi.org/10.1016/j.enpol.2008.08.025

Tayebi, S. K., & Younespour, S. (2012). The effect of trade openness on environmental quality: Evidence from Iran's trade relations with the selected countries of the different blocks. *Iranian Economic Review, 16*(32), 19–40.

Tebaldi, E., & Elmslie, B. (2013). Does institutional quality impact innovation? Evidence from cross-country patent grant data. *Applied Economics, 45*(7), 887–900. https://doi.org/10.1080/00036846.2011.613777

UNEP (United Nations Environment Program) (2019). The emissions gap report 2019. United Nations Environment Programme (UNEP): Nairobi, Kenya.

Varsakelis, N. C. (2006). Education, political institutions and innovative activity: A cross-country empirical investigation. *Research Policy, 35*(7), 1083–1090. https://doi.org/10.1016/j.respol.2006.06.002

Vassileva, I., Wallin, F., & Dahlquist, E. (2012). Understanding energy consumption behavior for future demand response strategy development. *Energy, 46*(1), 94–100. https://doi.org/10.1016/j.energy.2012.02.069

Verma, P., Savickas, R., Buettner, S. M., Strüker, J., Kjeldsen, O., & Wang, X. (2020). Digitalization: enabling the new phase of energy efficiency. Regulatory and policy dialogue addressing barriers to improve energy efficiency, 7th session, Geneva. Available from https://unece.org/sites/default/files/2020-12/GEEE-7.2020.INF_.3.pdf. Accessed 18 Aug 2021

Verspagen, B. (1997). Measuring intersectoral technology spillovers: Estimates from the European and US patent office databases. *Economic Systems Research, 9*(1), 47–65. https://doi.org/10.1080/09535319700000004

Visser, R. (2019). The effect of the internet on the margins of trade. *Information Economics and Policy, 46*, 41–54. https://doi.org/10.1016/j.infoecopol.2018.12.001

Wang, S., & Feeney, M. K. (2014). Determinants of ICT adoption in municipalities. *The American Review of Public Administration, 46*(3), 292–313. https://doi.org/10.1177/0275074014553462

Wang, S. S., Zhou, D. Q., Zhou, P., & Wang, Q. W. (2011). CO2 emissions, energy consumption and economic growth in China: A panel data analysis. *Energy Policy, 39*(9), 4870–4875. https://doi.org/10.1016/j.enpol.2011.06.032

Wen, H., Lee, C.-C., & Song, Z. (2021). Digitalization and environment: How does ICT affect enterprise environmental performance? *Environmental Science and Pollution Research, 28*(39), 54826–54841. https://doi.org/10.1007/s11356-021-14474-5

Westerlund, J. (2005). New simple tests for panel cointegration. *Econometric Reviews, 24*(3), 297–316. https://doi.org/10.1080/07474930500243019

Winzer, C. (2012). Conceptualizing energy security. *Energy Policy, 46*, 36–48. https://doi.org/10.1016/j.enpol.2012.02.067

Wolfers, A. (1952). "National Security" as an ambiguous symbol. *Political Science Quarterly, 67*(4), 481. https://doi.org/10.2307/2145138

Yang, L., & Li, Z. (2017). Technology advance and the carbon dioxide emission in China—Empirical research based on the rebound effect. *Energy Policy, 101*, 150–161. https://doi.org/10.1016/j.enpol.2016.11.020

Yu, C., Nataliia, D., Yoo, S.-J., & Hwang, Y.-S. (2019). Does trade openness convey a positive impact for the environmental quality? Evidence from a panel of CIS countries. *Eurasian Geography and Economics, 60*(3), 333–356. https://doi.org/10.1080/15387216.2019.1670087

Zaidi, S. A. H., Zafar, M. W., Shahbaz, M., & Hou, F. (2019). Dynamic linkages between globalization, financial development and carbon emissions: Evidence from Asia Pacific Economic Cooperation countries. *Journal of Cleaner Production, 228*, 533–543. https://doi.org/10.1016/j.jclepro.2019.04.210

Zakarya, G. Y., Mostefa, B., Abbes, S. M., & Seghir, G. M. (2015). Factors affecting CO2 emissions in the BRICS countries: A panel data analysis. *Procedia Economics and Finance, 26*, 114–125. https://doi.org/10.1016/S2212-5671(15)00890-4