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Abstract

This paper aims to study the impact of digitalization on energy efficiency in Europe, where institutions are committed to promoting both digital transformation and energy transition by implementing the European Twin Transition, ETT (European Commission, 2022; Muench et al., 2022). The paper starts by empirically analysing the state of play of the Twin Transition across European Member States (MS) by mapping the Digital Economy and Society Index (DESI), its sub-indices, and the energy productivity. Then, we assess the impact of the abovementioned digital indicators on energy productivity growth in 26 European MS during the period 2016-2020 by applying a system GMM model. The results show a significant and positive impact of digitalization on energy efficiency and relevant complementarities across diverse digitalization dimensions. This study contributes in an original manner to the literature by applying for the first time DESI and its sub-indices in a European twin transition analysis; moreover, empirical insights have important policy implications because all the variables considered are parts of the European policy targets.

Keywords: twin transition, digital transformation, energy efficiency, DESI

JEL Code: L86, O33, O44, Q43.

Highlights

- This paper explores the impact of digitalization on energy efficiency
- A statistical investigation of twin transition across European MS is carried out
- DESI and its sub-indices have a positive and significant impact on energy productivity growth
- Potential complementarities exist among DESI sub-indices with respect to their impact on energy productivity growth

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1. Introduction

Energy is central to both the 2030 Agenda for Sustainable Development and the Paris Agreement and is also a prerequisite for the realization of human rights for billions of people. However, CO2 emissions from energy use are a major contributor to global warming and account for some 75% of all human-made greenhouse gas emissions in the European Union (European Commission, 2018). EU strategies aimed at empowering businesses and people in a human-centred, sustainable and more prosperous digital future rely on the concept of "decoupling," which consists in promoting economic growth while reducing energy consumption and GHG emissions. According to the European Environment Agency (EEA, 2018), over the period 2010-2020, almost all the members of the European Union decoupled as measured by a steady decline in energy intensity defined as the ratio between final energy consumption and gross domestic product (GDP).

Policies addressing climate change, efficient and renewable energy supply and use, and industrial emissions have been effective in lowering carbon-intensive energy supply over time. However, in 2021, when most of the COVID-19 containment measures were lifted by the EU Member States (MS), carbon dioxide (CO2) emissions from fossil fuel combustion in the EU (mainly oil and oil products, natural gas, coal and peat) increased by 6.3% compared with the previous year. In 2022, in response to the adversity and global energy market disruption caused by Russia's invasion of Ukraine, the European Commission (EC) presented the REPowerEU Plan for saving energy, producing clean energy and diversifying European energy supplies. In October 2022, in addition to the emergency interventions to tackle high energy prices, the EC adopted the "EU action plan on digitalising the energy system," a system-wide digitalisation energy action plan that aims to contribute to the European Green Deal and EU energy policy objectives by supporting the development of a sustainable, (cyber)secure, transparent and competitive market for digital energy services, ensuring data privacy and sovereignty, and supporting investment in digital energy infrastructure. This action plan illustrates the potentially very significant economic, environmental and social benefits of digitalisation in the energy sector. The EC is launching actions to boost data sharing, promote investments in digital electricity infrastructure, ensure benefits for consumers and strengthen cybersecurity. Digital technologies have the potential to boost more inclusive and sustainable growth by spurring innovation, generating efficiencies and improving services (OECD, 2021). The EC "Path to Digital Decade" plan aims to address the areas of digital skills, digital infrastructures, digitalisation of businesses and public services.

The digital progress of the MS has constantly been monitored through the well-known Digital Economy and Society Index (DESI), introduced in 2014 and originally composed of five core indicators. In 2021 DESI's cardinal points were aligned with the objectives of the 2030 Digital Agenda and had four core dimensions: human capital, connectivity, integration of digital technology and digital public services, thus matching the four points of Digital Compass (EC, 2021a and EC2021b). In this perspective, digital transformation represents an important driver of smart, inclusive and sustainable growth by enabling people and firms to build an inclusive and sustainable digital society (EC2021b). With reference to the ecological transition, the use and implementation of digital technologies increase the availability of information instrumental both for more sustainable choices by customers and for a more sustainable management for firms (EC2021b).

By considering the abovementioned twin transition policy challenges, we aim to jointly examine digital transformation and energy productivity across the EU MS. In order to achieve this objective, we analyse the impact of the Digital Economy and Society Index and its sub-indices on the energy productivity growth rate in 26 European MS during the period 2016-2020 by applying an econometric dynamic panel model. Our research contributes to the existing knowledge about the relationship between digitalization and energy productivity in several ways. To the authors' knowledge, until now the assessment of the relationship between the values of digitalization dimensions and the energy productivity growth rate in the EU MS has not been explored in literature. Moreover, these variables have a high policy value because they are expressions both of the European Digital Transition Strategy (EC, 2022) and of the European Energy Transition Strategy; thus our study analyses in depth the European Twin Transition (Muench et al., 2022). Finally, we originally indicate the multidimensionality of digitalization and the multifaceted impact on energy efficiency by considering the DESI sub-indices and the interactions among them.

The remainder of the paper is organized as follows. In Section 2 we review the literature on digitalization and energy transition. In Section 3 we assess the progress of the twin transition in Europe by considering the 4 Dimensions of the DESI index and the energy productivity of the European Union. Section 4 reports the econometric model and the estimation strategy. Section 5 presents the results and finally, Section 6 concludes the paper by highlighting the main implications of our findings.

2. Literature Review

Digitalization refers to a series of economic activities that use information and knowledge as key production factors and the effective use of information and communication technology (ICT) as an important driving factor for improving efficiency and optimizing the economic structure (Alhassan and Adam, 2020). In the background of the increasingly prominent impact of digitalization on environment and energy, researchers have developed a strong interest in the field of environmental and energy economy.

The impact of digitalization on energy transition is complex. According to the conceptual framework of Lange et al. (2020), digitalization can have different effects on energy consumption: on the one hand, the production, usage and disposal of information and communication technologies tend to directly increase the energy consumption as well as indirectly through their positive influence on the drivers of economic growth; on the other hand, ICT services favour energy savings and digitalization has a positive impact on energy efficiency.

With reference to the impact of digitalization on energy efficiency, Berkhout and Hertin (2001) stress five elements that favour this relationship: (i) digital simulation of production processes; (ii) intelligent design and operation of products and services; (iii) intelligent distribution and logistics by providing new form of distribution structures and the supply chain efficiency; (iv) changing seller-buyer relationships with e-commerce; (v) work organization, such as smart working. Bauer et al. (2021), evaluating the EU plans for twin transition, underline that digitalization can help improve the efficient use of energy resources, facilitate the integration of renewables into the grid, and save costs for EU consumers and energy companies.

Xu et al. (2022) investigate the impact of digitalization on energy and its mechanisms from an international perspective. The authors demonstrated that digitalization reduces energy consumption, decreases energy intensity and optimizes energy structure by pointing out the heterogeneity between high- and low-income countries. Husaini and Lean (2022) verify the impact of digitalization on both total and disaggregated energy consumption by using a balance panel dataset that covers 1990-2018 in five major Asean countries. Their results indicate that digitalization brings down energy consumption levels in total and in all disaggregated sources, thus concluding that more investment in increasing and enhancing the digital infrastructure is recommended for achieving energy sustainability strategic objectives. Bianchini et al. (2022) explore the nexus between digital and green transformations in European Regions in an effort to identify the impact of digital and environmental technologies on the greenhouse gas emissions originating from industrial production. Results show that the local development of environmental technologies reduces GHG emissions, while the local development of digital technologies increases them.

Few articles analyse the dynamics of DESI and its sub-dimensions in Europe. Some papers focus on digital convergence: Borowiecki et a. 2021 show a convergence process in the period 2015-2020 in all dimensions of DESI with the exception of "Integration of Digital Technology" that presents an increasing polarization; Kovács et al. 2022 find a beta and sigma convergence and the potential influence of COVID-19 in the dynamic of DESI. Başol (2021) verifies for the year 2018 a positive impact of DESI on labour market indicators such as employment, personal earnings, and labour market security. Esses et al. (2021) provide a descriptive overview of the significant links between DESI - and its sub-indices- and Sustainable Development Goals of UN Agenda 2030, with reference to the Visegrad Group Countries, namely Czech Republic, Hungary, Poland and Slovakia. Thanh et al. (2022) study the interaction between digital transformation and environmental sustainability goals strategies; specifically, they show that DESI indicators have a positive impact on renewable energy consumption per capita and a negative impact on CO2 emissions per capita and on the CO2/GDP ratio. Thus, according to our knowledge, there do not exist contributions that use DESI and sub-indices to study the impact of digitalization on energy efficiency and specifically through an econometric analysis with digital complementarities. To fill this gap in the literature, we focus on DESI and its four dimensions (Human capital, Connectivity, integration of business technologies and digital public services) by providing an empirical analysis at EU level for the years 2016-2020, showing trends and heterogeneity across EU MS to assess the level of information and communication technologies development in the European economies. The analysis of the four can be interesting for the energy transition. The "Human Capital" dimension reveals the fact that digitalization can sustain energy efficiency through three human capital channels (Alfaro Navarro et al., 2017): the acceleration of human capital accumulation thanks to enlargement of the capacity to acquire, classify and store external knowledge; the improvement of the efficient allocation of human capital by removing human barriers to energy transformation; the amplification of channels and scopes of knowledge dissemination. The "Connectivity" and "integration of business technologies" dimensions can approximate the digital impact of energy efficiency through the technological channels (Xu et al., 2022): digitalization per se is a result of innovations and technical progress useful also for energy efficiency; digitalization creates technological and regional spillovers, accelerating the general innovation capacity (Rawte, 2017; Buuse and Kolk, 2019); digitalization optimizes the energy structure and production; digitalization can provide and diffuse information about the necessary energy transition, making the institutional and financial context more inclined to support energy efficiency initiatives. Finally, the "digital public services" dimension could indicate the utility of digitalization to improve the governance of energy transition initiatives in terms of availability, production and usage of data for setting, implementing, monitoring, and evaluating green policies as in the cases of SDGs initiatives (Del Rio Castro et al., 2022).

2. The Twin-Transition: Digital Economy and Society Index and Energy productivity across EU MS

To monitor the transition toward a sustainable economy, the Digital Economy and Society Index (DESI) and the energy efficiency measure have been analysed using data collected from Eurostat across the 26 EU MS over the period 2016-2020.

The DESI is a composite index based on OECD guidelines (EC, 2020). It summarises relevant indicators on Europe's digital performance and tracks the evolution of EU MS towards digital transition. The four DESI dimensions address the principal policy areas of the 2030 Digital Compass (EC, 2021b): Human capital, Connectivity, Integration of digital technology and Digital public services. Each dimension includes sub-dimensions and indicators, for a total of 32 indicators. Indicators expressed in different units are normalised according to the min-max method.

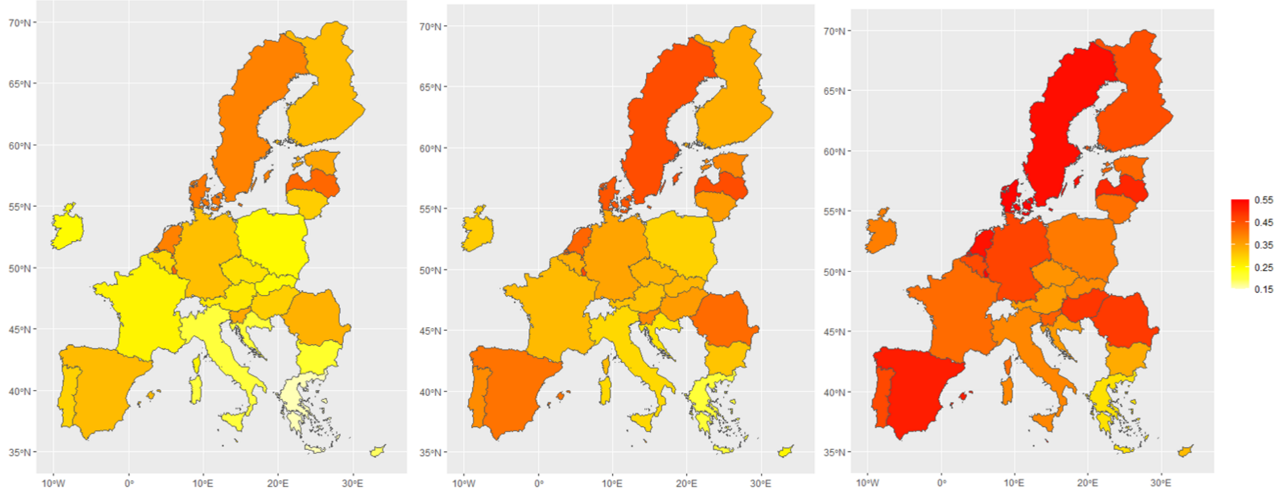
A weight is assigned to each indicator and sub-dimension. The aggregation process is performed from the bottom up using simple weighted arithmetic averages. Individual indicators included in each sub-dimension of the DESI are reported in Table A.1 of the appendix.

The connectivity (CONNECT) dimension, which is a European prerequisite for a society in which every business and citizen can fully participate, covers both the supply and demand side of connectivity. It includes 4 sub-dimensions for a total of 10 indicators, each of which has a specific weight: fixed and mobile broadband connection coverage (weighs equal to 25%), availability and use of high-speed Internet connections (weight equal to 40%) and the affordability of having broadband Internet connection (weight equal to 10%). The Connectivity dimension for MS *i* is computed as follows:

$$CONNECT_i = 0.25 \cdot FIXEDcoverage_i + 0.25 \cdot MOBILEcoverage + 0.40 \cdot HIGHSPEEDconnection_i + 0.10 \cdot BROADBANDprices_i$$

According to Figure 1, Luxemburg is the frontrunner in the EU (values respectively equal to 0.4297 in 2016 and 0.5485 in 2020) in term of the CONNECT dimension, while Greece is lags behind (values respectively equal to 0.1534 in 2016 and 0.2762 in 2020). Spain is the MS with the highest growth in the Connectivity dimension between the period 2016 and 2020: the value in 2016 was equal to 0.321 while in 2020 it reaches 0.519.

Figure 1: DESI- CONNECT, years 2016 (left), 2018 (middle) and 2020(right)



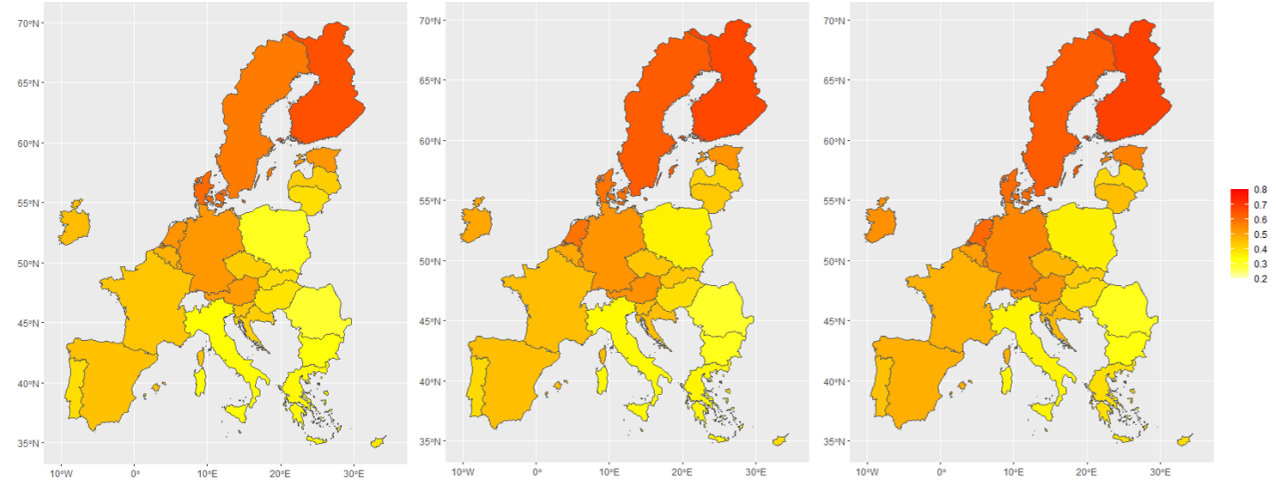
Source: Author's elaboration from Eurostat data

To pursue digital policies that empower people and businesses to seize a human-centred, sustainable and more prosperous digital future, the *Human capital* (HUM_CAP) dimension measures the appropriate skills to take advantage of the Internet and of the myriad of possibilities offered by a digital society. This dimension considers two sub-dimensions for a total of seven indicators: the percentage of individuals with basic usage skills that enable individuals to take part in the digital society and consume digital goods and services, and the percentage of individuals with advanced skills that empower the workforce to develop new digital goods and services and to take advantage of technology for enhanced productivity and economic growth. Equal weights have been attributed to the Human Capital sub-dimensions. The Human Capital dimension for MS *i* is computed as follows:

$$\mathrm{HUM\_CAP}_i = 0.50 \cdot FIXEDcoverage_i + 0.50 \cdot MOBILEcoverage_i$$

As reported in Figure 2, the highest values in the HUM_CAP dimension, which plays a key role for explaining the phenomena of digital inclusion and exclusion, are reported in Finlandia (with values respectively equal to 0.655 in 2016 and 0.685 in 2020). On the contrary, the lowest values are reported in Romania (with values respectively equal to 0.295 in 2016 and 0.316 in 2020). Over the last five years, Bulgaria, Romania, Italy, Malta and Latvia have been scoring the lowest progress in terms of the Human Capital dimension. On the contrary, the evolution of human capital digital skills shows an improving trend between 2016 and 2020, especially for Luxembourg, with a growth rate equal to 0.067.

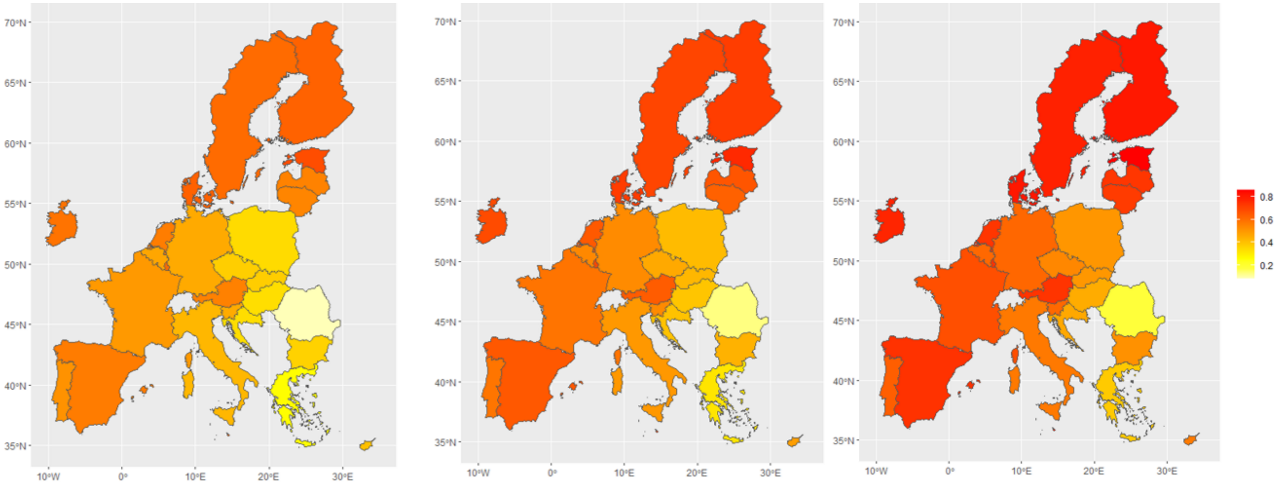
Figure 2: DESI- HUM_CAP, years 2016 (left), 2018 (middle) and 2020 (right)



Source: Author's elaboration from Eurostat data

The *Digital public services* (DIG_PUB_SERV) domain aims at providing holistic and easy access to public services, measuring the digital public services, and at introducing or improving the e-government solutions that figure prominently across the Recovery and Resilience Plans. Improving the performance of this dimension will also contribute to stimulating productivity gains by European businesses thanks to more efficient services that are digital by default (EC,2021b). This dimension includes 1 sub-dimension, namely e-Government (with weight equal to 100%) and 5 individual indicators. The improvements of the use of DIG_PUB_SERV are reported in Figure 3. The top performer is Luxembourg (its values respectively equal to 0.679 in 2016 and 0.859 in 2020), while Romania reported the weakest performance (values respectively equal to 0.085 in 2016 and 0.179 in 2020). The evolution of DIG_PUB_SERV shows an improving trend between 2016 and 2021 for all counties, especially for Austria, with a growth rate equal to 0.186.

Figure 3: DESI DIG_PUB_SERV, years 2016 (left), 2018 (middle) and 2020 (right)



Source: Author's elaboration from Eurostat data

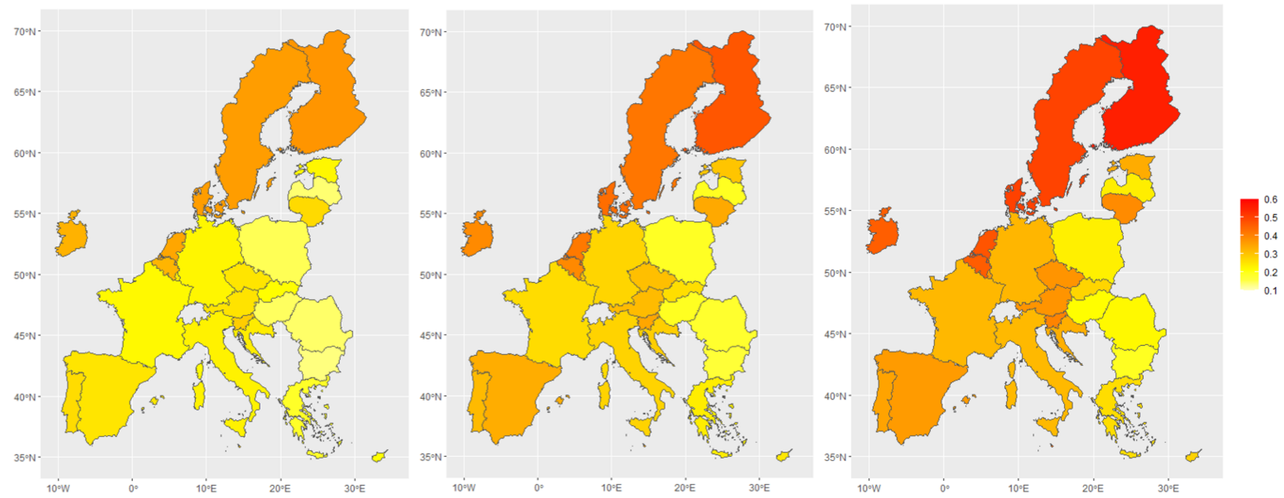
With respect to business, the *Integration of digital technology* (INT_DIG_TECH) dimension enables businesses to gain a competitive advantage, improve their services and products and expand their markets. The integration of digital technology will enable businesses to adopt digital technologies with a lower environmental footprint and higher energy and material efficiency (EC, 2021b).

This dimension includes 3 sub-dimensions, each of which has a specific weight, namely: Digital intensity (weight equal to 15%), business digitalization (weight equal to 70%) and e-commerce (weight equal to 15%) for a total number of 11 individual indicators. The Integration of digital technology dimension for MS *i* is computed as follows:

$$\mathrm{INT\_DIG\_TECH}=0.15\cdot DIGITALintensity_i+0.70\cdot BUSINESSdigitalization_i+0.15\cdot E\text{-}COMMERCE_i$$

Figure 4 shows the distribution of the INT_DIG_TECH dimension across EU MS. This dimension is one of the main contributors to competitive advantage and growth for businesses. As reported in Figure 4, Finlandia scored highest (with values respectively equal to 0.373 in 2016 and 0.556 in 2020) while Bulgaria scored lowest (with values respectively equal to 0.132 in 2016 and 0.168 in 2020). The highest growth rate in the period 2016-2020 is observed in Malta with a value equal to 0.187.

Figure 4: DESI INT_DIG_TECH, years 2016 (left), 2018 (middle) and 2020 (right)



Source: Author's elaboration from Eurostat data

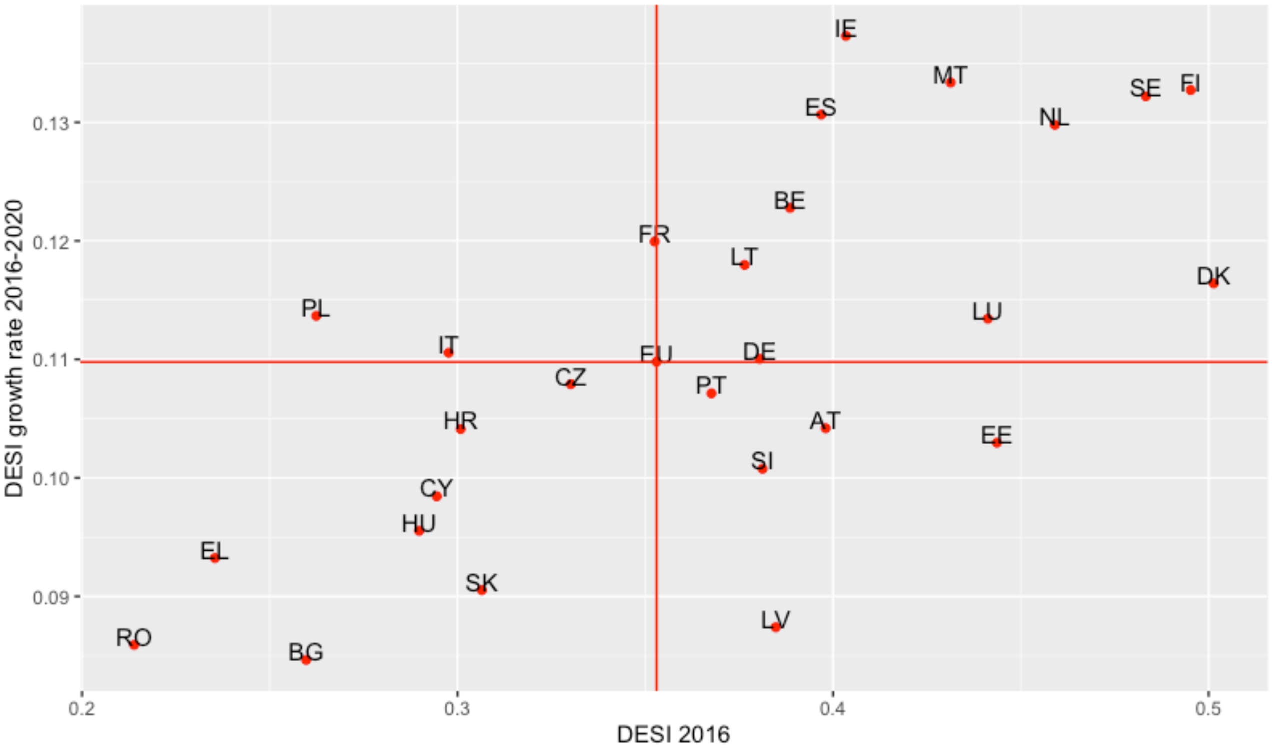
The four dimensions of the DESI are of equal importance, which is reflected in the equal weights of each dimension. The top-level DESI score for MS *i* is calculated using the formula:

$$DESI_i = 0.25\cdot HUM\_CAP+0.25\cdot CONNECT + 0.25\cdot DIG\_PUB\_SERV+0.25\cdot INT\_DIG\_TEC$$

Turning to the top-level DESI composite indicator, Figure 5 shows high heterogeneity across EU MS. Overall, northern countries report higher values for the DESI indicator when compared to the EU-27 average; in particular, Finland, Denmark, Netherlands and Sweden are the EU frontrunners. There is an overall positive convergence trend: almost all the EU MS are improving their level of digitalization. Over the period 2016-2020, Romania, Bulgaria and Greece lag behind all other EU MS, according to the DESI growth rate. Although the observed level of DESI index in 2016 for Italy and Poland is above the EU 27 average, those countries are catching up and, looking at the progress of their DESI score over the past five years, they are advancing at a remarkable pace.

Over the period 2016-2020 we observe significant relative dispersion, measured by σ-convergence,[2] only for the CONNECT dimension, for which the standard deviation values move from 0.25 to 0.17 (p-value: 0.04). On the contrary, β-convergence[3] is significant for the CONNECT DIG_PUB_SERV and INT_DIG_TECH dimensions, with values respectively equal to -0.10, -0.056 and -0.02 (p-values equal to 0). Thus, the results partially confirm the previous studies of DESI convergence (Borowiecki et a. 2021; Kovács et al. 2022); the non-significance of σ-convergence also puts in evidence the difficulty to study DESI convergence with a robust analysis due to the overly short time series.

Figure 5: DESI MS' progress, 2016-2020



Source: Author's elaboration from Eurostat data

In line with the EU Strategic Priorities, the digitalization process can accelerate the transition toward a Net-Zero Greenhouse Gas Emissions economy (EC, 2022b).

Despite the considerable debate about the contribution of energy efficiency policies in enhancing energy security and helping reduce emissions from the use of energy, there is no one clear and accepted definition of

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[2] σ-convergence means the harmonization of regional output over time. It evaluates the relationship between the standard deviation and the mean value of a series for different groups and uses the ensuing trend in such a relationship to determine the pattern of convergence or divergence. A decreasing trend in the standard deviation or coefficient of variation calculated from 2016 to 2020 is an indication of convergence, while an increasing trend suggests divergence.

[3] β-convergence means a decline of dispersion because poor regions have stronger growth than rich regions.

energy efficiency. According to Bhattacharyya (2011), most definitions are based on the simple ratio of "useful output of a process/energy input into a process". Several indicators have been suggested for measuring and comparing energy efficiency levels across countries, regions, and firms, including economic indicators, where output and input are measured purely in terms of monetary values and economic–thermodynamic indicators, where output is measured in monetary values and the energy input is measured in thermodynamic units (Patterson, 1996). The indicator "energy intensity," measured by energy consumption per unit of gross domestic product (GDP), is widely used to represent a country's energy performance. From an econometrics point of view, in this paper we follow the first approach described by Filippini and Hunt (2015), thus using an econometric method to investigate the reducing or increasing effects of energy intensity (Xu et al 2022). To measure energy intensity we consider the Eurostat "Energy productivity indicator" (EPROD), which refers to the amount of economic output that is produced per unit of gross available energy: with this choice we consider a European policy indicator.

The gross available energy (GAE) includes the overall supply of energy for all activities on the territory of the country and it represents the quantity of energy products necessary to satisfy the total demand of entities in the geographical area under consideration. The GAE includes energy needs for energy transformation, support operations of the energy sector itself, transmission and distribution losses, final energy consumption (industry, transport, households, services, agriculture), the use of fossil fuel products for non-energy purposes (e.g. in the chemical industry) and the fuel purchased within the country that is used elsewhere (e.g. international aviation, international maritime bunkers and, in the case of road transport, "fuel tourism"). This aggregate is calculated according to the following formula:

GAE = Primary production + Recovered & Recycled products + Imports – Export + Stock changes.

For the economic output, Eurostat uses the GDP either in the unit of million euro in chain-linked volumes to reference year 2010 (at 2010 exchange rates) or in the unit million purchasing power standards[4] (PPS). The former is used to observe the evolution over time for a specific region while the latter helps compare Member States in a given year.

Energy Productivity is an indicator included in the Resource Efficiency Scoreboard of the EC, used to monitor progress towards an efficient resource of an individual MS and the European Union as a whole, complementing the lead indicator on the area of carbon. It belongs to the set of the EU Sustainable Development Goals indicators. The Energy Productivity indicator results from the division of the gross domestic product (GDP) by the gross available energy for a given calendar year. It measures the productivity of energy consumption and provides a picture of the degree of decoupling of energy use from growth in GDP.

As reported in Figure 6, Ireland scored the highest values in EPROD (with values respectively equal to 15.58 in 2016 and 24.42 in 2020), while Estonia scored lowest in 2016 (its value equal to 4.55) and Malta scored lowest in 2018 and 2020 (with values respectively equal to 4.90 in 2018 and 5.05 in 2020). The highest growth rate is observed in Ireland: 6.8 in the period 2016-2020.

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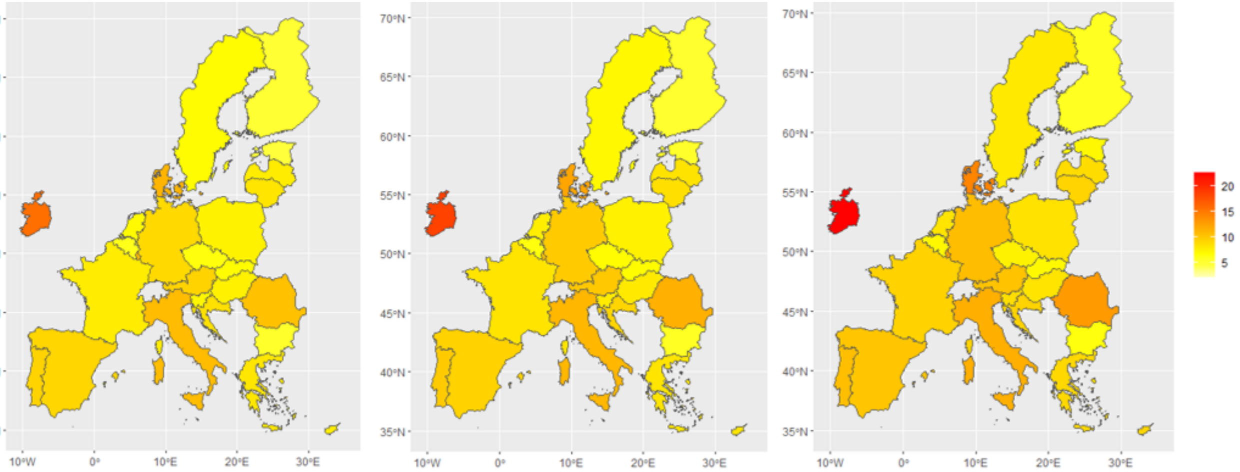
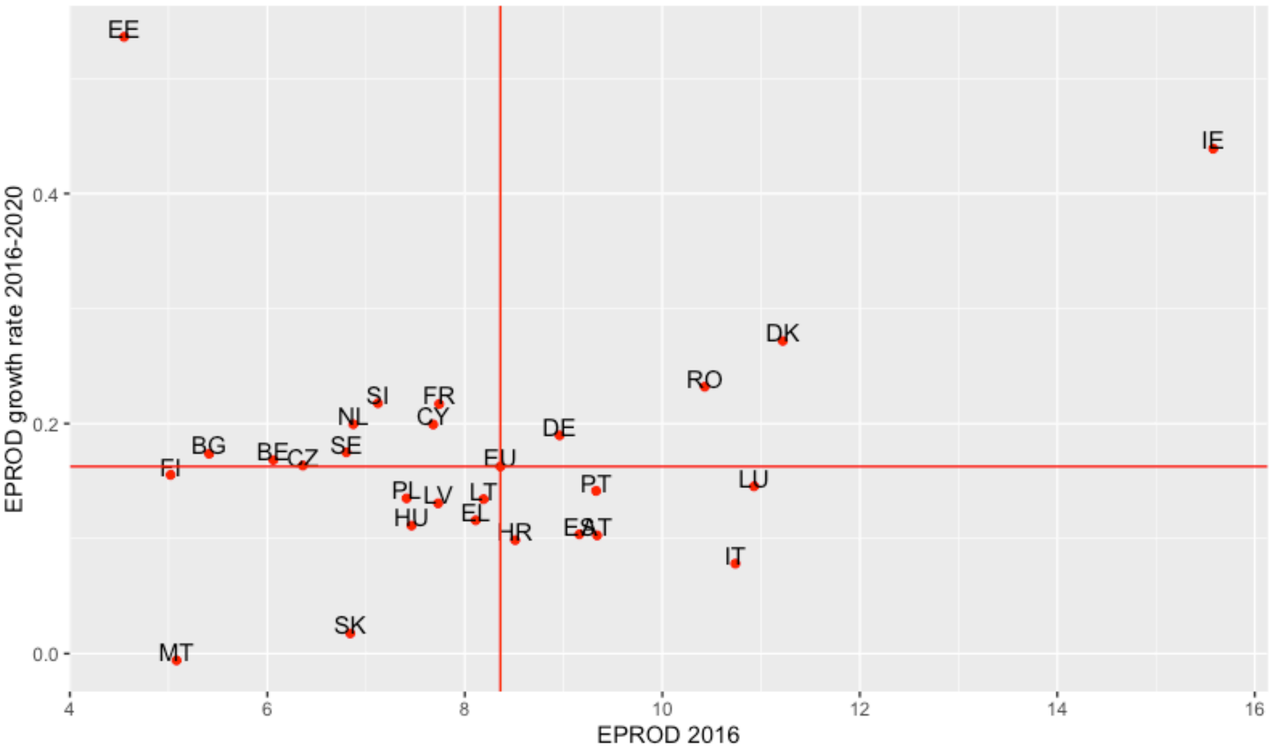
[4] PPS is an artificial currency unit. PPS is a common currency that eliminates the differences in price levels between countries allowing meaningful volume comparisons of GDP between countries.

Figure 6: Energy Productivity, years 2016 (left), 2018 (middle) and 2020 (right)



Source: Author's elaboration from Eurostat data

Figure 7: Energy productivity dynamic, 2016-2020



According to Figure 7, during the period 2016-2020 countries with the highest EPROD tend to increase it at the highest rates, and countries with the lowest EPROD tend to have lower rates of change, even if σ-convergence and β-convergence are not significant.

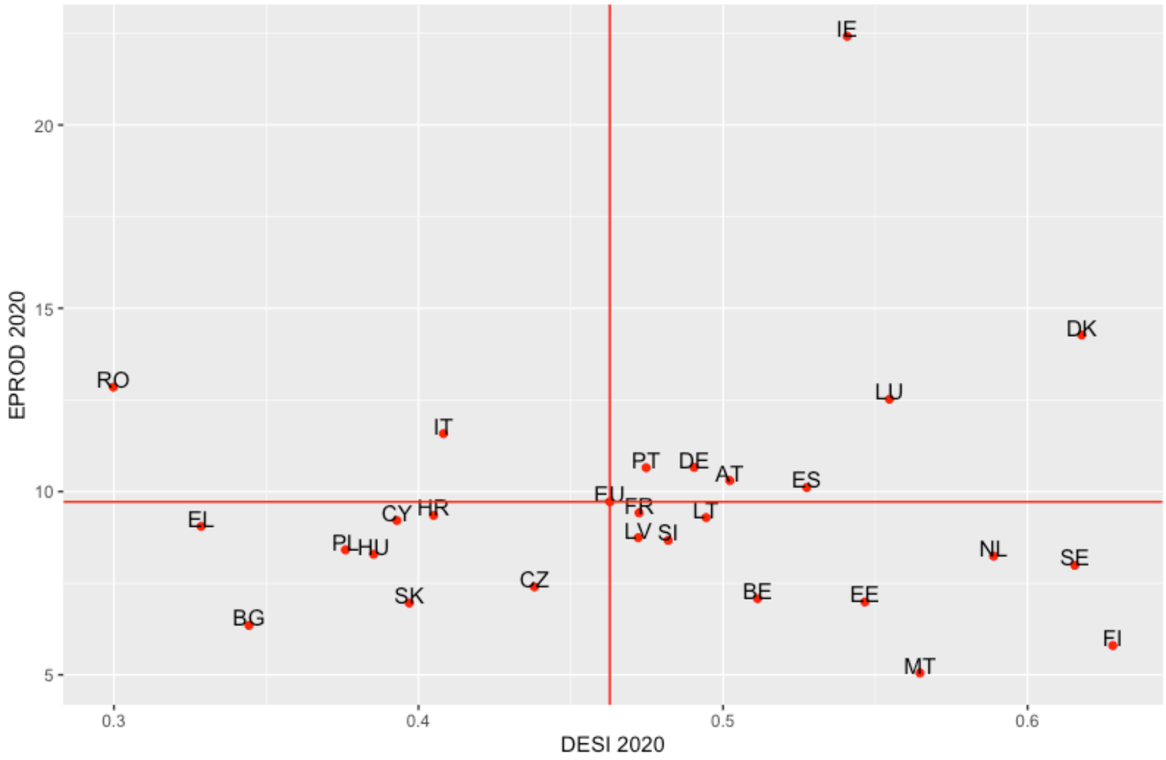
Most of the Central and Eastern European countries (e.g. Polonia, Hungaria, Latvia, Lithuania) have lagged behind in terms of the EPROD and EPROD growth rate. Ireland, Denmark, Romania and Germany are the best performing countries in terms of the EPROD growth rate.

Turning to the twin transition, Figure 8 shows a positive, even if not significant, relationship between the green and digital transitions during 2020 across EU MS. Overall, Ireland,[5] Luxemburg and Denmark report higher values for both indicators when compared to the EU-27 average; on the contrary, most of the Mediterranean countries score low values in both indicators with the exception of Italy and Romania, where the level of EPROD is above the EU-27 average thanks to the political, economic and social measures they have adopted in the transition to a climate neutral economy (Firoiu, 2022).

Comparing the DESI MS's progress illustrated in Figure 5 with the Energy productivity dynamic illustrated in Figure 7, the trends of these two measures appears positive and it seems that these two indicators are moving in the same direction. Almost all the central and northern EU MSs are improving their levels of digitalization and energy efficiency over the period 2016-2020 thanks to sustained investment in new digital technologies and the adopted policies aimed at providing the green and digital transitions (Firoiu, 2022).

On the contrary, some eastern EU MS such as Bulgaria, Latvia, Slovakia, Greece and Hungary are lagging behind. These countries need strong support in order to facilitate the green-digital transition process.

Figure 8: Energy and digital transition across EU countries, 2020



Source: Author's elaboration from Eurostat data

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[5] In Ireland, ambitious energy efficiency targets have been established in national policies and programmes starting in 2009 in all sectors (Department of the Environment, Climate and Communications, 2009).

3. The econometric model and estimation strategy: digitalization and energy efficiency

We carry out an econometric analysis to evaluate whether and to what extent the digitalization indicators influence energy efficiency. We adopt a dynamic panel analysis with an econometric model based on the system GMM estimation method (Roodman, 2009). Compared to the traditional measurement model, this model takes the lagged terms of the explained variables into account as explanatory variables (Uddin et al., 2017). Meanwhile, this method considers the measurement error and the lag of the core explanatory variable and solves the problem of fixed effects. Second, it takes into account the potential endogeneity problem mainly caused by the simultaneity between dependent and independent variables (Roodman, 2009). Observations refer to the 26 European countries during the period 2016-2020.

We specified five models, as described below. The models differ for a specific variable, which is added to consider the corresponding digitalization dimension.

(1) $\mathrm{dEPROD}_{it} = \alpha_0 + \alpha_1 \mathrm{dEPROD}_{it-1} + \alpha_2 \mathrm{EPROD\_GAP}_{it} + \alpha_3 \mathrm{dPROD}_{it} + \alpha_4 \mathrm{DESI}_{it} + \sum_{c=1}^{t} \mu_t \rho_t + \varphi_{it}$

(2) $\mathrm{dEPROD}_{it} = \beta_0 + \beta_1 \mathrm{dEPROD}_{it-1} + \beta_2 \mathrm{EPROD\_GAP}_{it} + \beta_3 \mathrm{dPROD}_{it} + \beta_4 \mathrm{CONNECT}_{it} + \sum_{c=1}^{t} \mu_t \rho_t + \varphi_{it}$

(3) $\mathrm{dEPROD}_{it} = \gamma_0 + \gamma_1 \mathrm{dEPROD}_{it-1} + \gamma_2 \mathrm{EPROD\_GAP}_{it} + \gamma_3 \mathrm{dPROD}_{it} + \gamma_4 \mathrm{DIG\_PUB\_SERV}_{it} + \sum_{c=1}^{t} \mu_t \rho_t + \varphi_{it}$

(4) $\mathrm{dEPROD}_{it} = \delta_0 + \delta_1 \mathrm{dEPROD}_{it-1} + \delta_2 \mathrm{EPROD\_GAP}_{it} + \delta_3 \mathrm{dPROD}_{it} + \delta_4 \mathrm{HUM\_CAP}_{it} + \sum_{c=1}^{t} \mu_t \rho_t + \varphi_{it}$

(5) $\mathrm{dEPROD}_{it} = \theta_0 + \theta_1 \mathrm{dEPROD}_{it-1} + \theta_2 \mathrm{EPROD\_GAP}_{it} + \theta_3 \mathrm{dPROD}_{it} + \theta_4 \mathrm{INT\_DIG\_TECH}_{it} + \sum_{c=1}^{t} \mu_t \rho_t + \varphi_{it}$

Variable dEPROD represents the growth rate of energy productivity. Variable EPROD_GAP indicates the natural logarithm of the level of the energy productivity gap, measured by the ratio between the yearly maximum European value and the value of the country considered. This variable can capture the potential divergence or convergence processes concerning energy productivity depending on whether the coefficient is negative or positive, respectively. Variable dPROD stands for the growth rate of labour productivity. Labour productivity is an indicator included in the Eurostat's Labour Productivity Indicators (LPIs), which are of interest to EU policy makers and researchers for analysing trends at national level. These indicators are disseminated by EUROSTAT annually and are based on national accounts data that MS send to Eurostat under the new European System of National and Regional Accounts transmission programme for data. Labour productivity indicators are built on the basis of data on different measures of labour input: persons employed (employees and self-employed) and hours worked. We use the labour productivity per person employed in the economy, measured as a ratio of GDP-chain-linked volumes (reference year 2010 in PPS) per person employed over a given time period t calculated by dividing GDP in current prices by employed persons. In Appendix we use the labour productivity per hour (see Table A.3 and Table A.4 in Appendix).

The variables DESI, CONNECT, DIG_PUB_SERV, HUM_CAP, INT_DIG_TECH stand for the natural logarithms of "Digital Economy and Society Index" and its sub-indices "Connectivity", "Digital Public Services", "Human Capital" and "Integration of digital technology". Parameters ρ and φ indicate the time dummy from year 2016 to year 2020 and the error term that consists of both unobserved country-specific effects and observation-specific errors. Table A.2 in the Appendix shows the descriptive statistics of all the abovementioned variables.

This econometric model analyses the impact of digitalization on energy productivity by taking into account other important drivers of standard and green technological progress studied in literature.

With reference to the dependent variable and control variables, the growth rate of energy productivity represents the energy efficiency and could capture green innovations and technological progress; in addition, as usual, dPROD can be a proxy for standard innovations and technological progress. The energy productivity gap can approximate the national distance from the European green technological frontier. Specifically, the coefficient of EPROD_GAP, if positive, could represent a process of green technological catching-up (Guarini, 2015; Hein and Tarassow, 2010). Finally, when the coefficient of labour productivity is positive, it can capture the potential complementarity between standard and green technological progress. This phenomenon can be generated in different ways: green and standard innovations create positive technological spillovers by producing new knowledge that is a public good; they can also create economies of scale in terms of learning by doing, networking, learning by using and scale effects of digital economy. Finally, green and standard innovations can generate economies of scope: the most performant equipment can correspond to the most energy efficient one (Guarini, 2015).

The focus variables concern digitalization and its impact on energy efficiency. As argued in the previous section, many contributions underline how digitalization can have a positive influence on it. Digitalization can improve general efficiency and energy efficiency of production system with reference to both the horizontal division of labour, by increasing the weight of high technology and high knowledge intensive sectors, and the vertical division of labour by reorganizing the production processes by changing tasks, roles, and equipment. Moreover, the DESI subindices can specify the aspects of the twin transition concerning the digital human capital (HUM_CAP), the digital technologies and infrastructures (CONNECT and INT_DIG_TECH), and the digital capacity of public sector (DIG_PUB_SERV).

4. Estimation Results

Table 2 shows the estimations of equations (1), (2), (3), (4), (5). All coefficients of control variables are highly significant – almost significant at 1%-: the coefficient of the lagged dependent variable is negative and that could represent an unstable dynamic of energy productivity; even the coefficient of the energy productivity gap is negative, showing an absence of energy catching-up processes; finally, the coefficient of dPROD is positive, which is consistent with the hypothesis of complementarity between green and standard technological progress. Concerning the core explanatory variables, the results appear to confirm a positive role of digitalization for energy efficiency. Indeed, the coefficients of DESI and its sub-indices are significant and positive, except for the coefficient of sub-index CONNECT that is negative and not significant. The significance of the DESI Index, with coefficient equal to 0.030 and significant at 1%, confirms the potential complementarity between digitalization and environmental/energy transition (Isensee et al., 2020; Mondejar, 2021) and the relevance of energy digitalization to face the energy transition challenges. In particular, the relevance of this empirical result is based on the fact that energy efficiency measures are expected to be the most important strategy for achieving a successful decoupling (Moreau and Vuille, 2018, Bertoldi, 2020) and digitalization could play a key role in achieving climate neutrality, reducing pollution and restoring biodiversity (Lange et al., 2020). Thus, this empirical insight confirms the potentiality of the twin transition. The statistical relevance of variable INT_DIG_TECH, with a coefficient equaling 0.020 and significant at 10%, could reflect the instrumental role of digital technologies, such as smart grids, for producing and consuming renewable energies, which are more efficient than fossil energies (Baidya et al., 2021). This result confirms the role of digital technologies in the governance of the energy transition thanks to the provision of data and information useful for energy efficiency improvements (OECD, 2021; EC, 2021b). The positive significance of HUM_CAP, with a coefficient equaling 0.046 and significant at 5%, could indicate how digital competencies and skills are necessary to set dynamic firm capabilities and how new business models can adapt to the energy transition (Idries et al. 2022). Moreover, its impact appears to be the highest, given the highest coefficient among all digitalization variables. Finally, the statistical robustness of the DIG_PUB_SERV variable, with a coefficient equaling 0.014 and significant at 5%, could concern the positive impact of digitalization on quality and efficiency of institutions that favour the governance of the energy transition (Thanh et al., 2022).

Table 3 shows estimations of equations (1), (2), (3), (4), (5) integrated with the interactions across digitalization variables. In these estimations, control variables have similar values maintaining high significance at 1%. Concerning the explanatory variables, all interactions are significant and positive showing relevant complementarities across digitalization dimensions and all indices are significant and positive. Specifically, the coefficient of interaction terms CONNECT*DIG_PUB_SERV, CONNECT*HUM_CAP and CONNECT*INT_DIG_TECH are equal to 0.179 and significant at 5%, 0.295 and significant at 5%, 0.167 and significant at 1%, respectively, while the coefficient of interaction terms DIG_PUB_SERV*HUM_CAP, DIG_PUB_SERV*INT_DIG_TECH and HUM_CAP*INT_DIG_TECH are equal to 0.228 and significant at 5%, 0.110 and significant at 1%, 0.262 and significant at 5%, respectively. Thus, the general strategy of Digital Compass (EC, 2021a, 2021b) that is facing the digital transformation with a comprehensive approach appears verified. In particular, the CONNECT in these estimations appears to be taking advantage of the interactions with all other indices because in Table 1 is not significant. The CONNECT sub-index mainly refers to the digital transformation of the production system and this interesting result could represent the difficulty of firms to implement processes of digitalization and energy efficiency without digital support from institutions (approximated by DIG_PUB_SERV), a digital reskilling of workers and consumers (approximated by HUM_CAP), and an upgrading of digital infrastructure (represented by INT_DIG_TECH). Finally, from the comparison of the two tables an interesting general result emerges: the coefficients of digitalization indices increase their values remarkably; this element reinforces the relevance of the multidimensionality of digitalization. Tests Wald chi2, AR(1), AR(2), and the Hansen test validate the robustness of all estimations. As a robustness analysis, we substitute labour productivity per worker with labour productivity per hour (see Table A.3 and A.4 in Appendix) and we obtain similar results.

Table 2 The Impact of European Digitalization Indices on Energy productivity

	System GMM				
	Dependent variable: dEPROD				
	(1)	(2)	(3)	(4)	(5)
dEPROD_1	-0.234***	-0.229***	-0.230***	-0.226***	-0.230***
	(0.031)	(0.027)	(0.281)	(0.038)	(0.026)
dEPROD_GAP	-0.036***	-0.031**	-0.039***	-0.028***	-0.034***
	(0.009)	(0.014)	(0.010)	(0.008)	(0.010)
dPROD	0.766***	0.789***	0.728***	0.747***	0.747***
	(0.144)	(0.173)	(0.131)	(0.134)	(0.136)
DESI	0.030***				
	(0.012)				
CONNECT		-0.024			
		(0.027)			
DIG_PUB_SERV			0.014**		
			(0.006)		
HUM_CAP				0.046**	
				(0.019)	
INT_DIG_TECH					0.020*
					(0.011)
Constant	YES	YES	YES	YES	YES
Temporal dummies	YES	YES	YES	YES	YES
Observations	130	130	130	130	130
Wald chi2	0.000	0.000	0.000	0.000	0.000
AR(1)	0.036	0.056	0.039	0.026	0.046
AR(2)	0.654	0.652	0.673	0.615	0.675
Hansen test	0.930	0.998	0.892	0.849	0.914

Notes: In regressions, robust standard errors are in parentheses; *p-value <0.10. **p-value < .05. ***p-value < .01. About tests are reported p-values.

Table 3 The Impact of European Digitalization Indices on energy productivity: the interactions across Indices

	System GMM					
	Dependent variable: dEPROD					
	1	2	3	4	5	6
dEPROD_1	-0.180***	-0.193***	-0.185***	-0.294***	-0.237***	-0.226***
	(0.031)	(0.053)	(0.025)	(0.061)	(0.034)	(0.035)
dEPROD_GAP	-0.038***	-0.031***	-0.043***	-0.048***	-0.038***	-0.031*
	(0.011)	(0.011)	(0.011)	(0.015)	(0.009)	(0.016)
dPROD	0.756***	0.827***	0.724***	0.514***	0.597***	0.537***
	(0.160)	(0.157)	(0.130)	(0.167)	(0.100)	(0.124)
CONNECT	0.106**	0.201**	0.206***			
	(0.043)	(0.097)	(0.063)			
DIG_PUB_SERV	0.179**			0.245**	0.180*	
	(0.076)			(0.109)	(0.100)	
HUM_CAP		0.343**		0.142*		0.395*
		(0.134)		(0.085)		(0.216)
INT_DIG_TECH			0.174***		0.060**	0.212**
			(0.048)		(0.028)	(0.100)
CONNECT* DIG_PUB_SERV	0.179**					
	(0.076)					
CONNECT* HUM_CAP		0.295**				
		(0.122)				
CONNECT* INT_DIG_TECH			0.167***			
			(0.050)			
DIG_PUB_SERV* HUM_CAP				0.228**		
				(0.109)		
DIG_PUB_SERV* INT_DIG_TECH					0.110*	
					(0.061)	0.262**
HUM_CAP* INT_DIG_TECH						(0.133)
Constant	YES	YES	YES	YES	YES	YES
Temporal dummies	YES	YES	YES	YES	YES	YES
Observations	130	130	130	130	130	130
Wald chi2	0.000	0.000	0.000	0.000	0.000	0.000
AR(1)	0.062	0.059	0.061	0.010	0.032	0.042
AR(2)	0.613	0.489	0.594	0.747	0.886	0.733
Hansen test	0.995	0.401	0.995	0.160	0.995	0.157

Notes: In regressions. robust standard errors are in parentheses; *p-value <0.10. **p-value < .05. ***p-value < .01. About tests are reported p-values.

5. Concluding remarks and policy implications

The main innovative aspect reported in this paper is related to the adoption of digitalization indices, which refers to the international framework established by the European Commission since 2014 to monitor MS progress toward digitalization and to analyse the role of digitalization for improving energy efficiency. Indeed, compared to the previous research perspective, which is mainly focused on specific countries or regions, we evaluated the impact of DESI and its sub-indices on energy transition for all EU MS. Moreover, monitoring the progress of EU MS through the DESI index analysis could also help to understand the progress towards green transition since the four dimensions of the DESI index may improve the general efficiency of the production system.

In this paper, by using the DESI index and its four main dimensions and energy productivity, we monitored the digitalization process and energy efficiency in the EU MS during the period 2016-2020 and we evaluated digitalization's impact on energy productivity by referring to a panel dataset obtained from the EUROSTAT database.

Among the EU MS, each DESI dimension hides high heterogeneity, even if this comparative analysis showed that most of the MS are making progress in their digital transformation. In particular Italy, Poland and Greece have improved their DESI scores, implementing investments with a reinforced political focus on digital aspects. Regarding energy productivity, countries with the highest energy productivity tend to increase it at the highest rates, and countries with the lowest EPROD tend to have lower rates of change, even if σ-convergence and β-convergence are not significant. Overall, the relationship between energy productivity and digitalization is positive, even if is not significant. Ireland, Luxemburg and Denmark are the frontrunners in the EU in terms of the twin transition.

Moreover, in order to evaluate the impact of the digitalization indices on energy efficiency measured by the growth rate of energy productivity, we carried out a dynamic panel analysis with an econometric model based on the GMM system estimation method by referring to the 26 European MS during the period 2016-2020. Results from this paper provide the first international evidence on the impact of digitalization, measured with the DESI index, on energy efficiency. In particular, for the dimension of Connectivity, which is a precondition for digital transformation, an interesting result emerges: it increases their values remarkably when it interacts with the other DESI sub-dimensions; this element reinforces the relevance of the multidimensionality of digitalization. Fostering the dimension of connectivity can help to bridge the gaps in the digital divide. Some important progress could be done in the twin transition analysis in different areas, such as carrying out a cluster analysis in Europe regarding digitalization and energy indicators; suggesting a new index of twin transition to monitor this phenomenon; expanding the dataset with regional data on twin transition; and extending the analysis of digitalization's impact on ecological transition by considering other energy and environmental key variables. The pathways to green and digital transitions depend to a great extent on inclusive and well-thought-out policymaking: the implementation of more efficient production systems should be a part of policy design. Indeed, our findings suggest that, although the business digitalization dimension may enhance the positive effects of the twin transition, it is insufficient for completing the twin transition.

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Appendix

Table A.1: DESI Dimensions, Sub-Dimensions and Indicators

Dimensions	**Sub-dimensions**	**Indicators**
Human capital	Internet user skills	At least basic digital skills
		Above basic digital skills
		At least basic digital content creation skills
	Advanced skills and development	ITC specialists
		Female ITC specialists
		Enterprises providing ICT training
		ICT graduates
Connectivity	Fixed broadband take-uo	Overall fixed broadband take-up
		At least 100 Mbps fixed broadband take-up
		At least 1 Gbps take-up
	Fixed broadband coverage	Fast broadband coverage
		Fixed Very High Capacity network coverage
	Mobile broadband	5G spectrum
		5G coverage
		Mobile broadbank take up
	Broadband prices	Broadband price index
Integration of digital technology	Digital intensity	SMEs with at least a basic level of digital intensity
	Digital technologies for business	Electronic information sharing
		Social Media
		Big data
		Cloud
		AI
		ICT for environmental sustainability
		e-invoices
	e-Commerce	SMEs selling online
		e-Commerce turnover
		Selling online cross-border
Digital public services	e-Government	e-Government users
		pre-filled forms
		Digital public services for citizens
		Digital public services for business
		Open data

Table A.2

Variable		Mean	Std. Dev.	Min	Max	Observations
dEPROD	overall	0.0314631	0.0432455	-0.1657006	0.2393085	N = 130
	between		0.0165867	-0.0066218	0.0649884	n = 26
	within		0.0400448	-0.1869679	0.2180411	T = 5
dEPROD_1	overall	0.0311637	0.046803	-0.1657006	0.260083	N = 130
	between		0.0200639	-0.0045392	0.088069	n = 26
	within		0.0424316	-0.2135994	0.2031777	T = 5
dEPROD_GAP	overall	0.0117264	0.2885664	-0.8876064	0.6029587	N = 130
	between		0.2909643	-0.7842397	0.5295093	n = 26
	within		0.0351493	-0.1378765	0.1572369	T = 5
dPROD	overall	0.0034558	0.0266062	-0.0855961	0.1167245	N = 130
	between		0.0173118	-0.026263	0.0493507	n = 26
	within		0.0204325	-0.0639509	0.0920159	T = 5
DESI	overall	-0.8792448	0.2197749	-1.542265	-0.4652581	N = 130
	between		0.2011499	-1.374672	-0.5895302	n = 26
	within		0.0953642	-1.057827	-0.6978995	T = 5
CONNECT	overall	-1.029002	0.226662	-1.686839	-0.6005312	N = 130
	between		0.1740212	-1.399425	-0.7503183	n = 26
	within		0.1484294	-1.404167	-0.6978045	T = 5
DIG_PUB_SERV	overall	-0.6307966	0.3733909	-2.460147	-0.1514836	N = 130
	between		0.3611586	-2.085916	-0.2715213	n = 26
	within		0.1141481	-1.005027	-0.2599899	T = 5
HUM_CAP	overall	-0.7839286	0.1993605	-1.220421	-0.3779803	N = 130
	between		0.1990917	-1.197332	-0.4081805	n = 26
	within		0.0365534	-0.8875964	-0.6934022	T = 5
INT_DIG_TECH	overall	-1.232983	0.3202125	-2.027389	-0.5869247	N = 130
	between		0.2957663	-1.810503	-0.77418	n = 26
	within		0.1333073	-1.519189	-0.9731378	T = 5

Table A.3 The Impact of European Digitalization Indices on Energy productivity (considering labour productivity per hours, PRODH)

	System GMM				
	Dependent variable: dEPROD				
	1	2	3	4	5
dEPROD_1	-0.218***	-0.210***	-0.239***	-0.207***	-0.214***
	(-6.36)	(-7.55)	(-6.89)	(-5.36)	(-8.02)
dEPROD_GAP	-0.046***	-0.039***	-0.047***	-0.036***	-0.044***
	(-3.98)	(-2.77)	(-4.01)	(-3.81)	(-3.56)
dPRODH	0.687***	0.693***	0.688***	0.649***	0.646***
	(3.78)	(3.49)	(3.67)	(4.41)	(3.78)
DESI	0.0311*				
	(1.93)				
CONNECT		-0.017			
		(-0.66)			
DIG_PUB_SERV			0.0231*		
			(1.65)		
HUM_CAP				0.0289**	
				(2.00)	
INT_DIG_TECH					0.0234*
					(1.87)
Constant	YES	YES	YES	YES	YES
Temporal dummies	YES	YES	YES	YES	YES
Observations	130	130	130	130	130
Wald chi2	0.000	0.000	0.000	0.000	0.000
AR(1)	0.0555	0.0719	0.0883	0.0478	0.0669
AR(2)	0.779	0.775	0.836	0.758	0.808
Hansen test	0.937	0.925	0.721	0.874	0.96

Notes: In regressions. robust standard errors are in parentheses; *p-value <0.10. **p-value < .05. ***p-value < .01. About tests are reported p-values.

Table A.4 The Impact of European Digitalization Indices on energy productivity: the interactions across Indices (considering labour productivity per hour, PRODH)

	System GMM					
	Dependent variable: dEPROD					
	1	2	3	4	5	6
dEPROD_1	-0.171***	-0.169***	-0.164***	-0.277***	-0.225***	-0.205***
	(-5.18)	(-2.77)	(-4.29)	(-4.39)	(-7.24)	(-5.86)
dEPROD_GAP	-0.0443***	-0.0333***	-0.0370***	-0.0506***	-0.0456***	-0.0286*
	(-3.77)	(-3.04)	(-3.21)	(-3.25)	(-4.31)	(-1.87)
dPRODH	0.662***	0.797***	0.640***	0.649***	0.486***	0.585***
	(3.73)	(3.74)	(3.88)	(3.57)	(3.89)	(3.52)
CONNECT	0.0875*	0.197***	0.148**			
	(1.83)	(2.65)	(2.41)			
DIG_PUB_SERV	0.142*			0.242**	0.164*	
	(1.86)			(1.99)	(1.68)	
HUM_CAP		0.346***		0.101*		0.353*
		(2.86)		(1.69)		(1.76)
INT_DIG_TECH			0.146***		0.0628**	0.249***
			(3.29)		(2.37)	(2.89)
CONNECT*DIG_PUB_SERV	0.145*					
	(1.88)					
CONNECT*HUM_CAP		0.296***				
		(2.87)				
CONNECT*INT_DIG_TECH			0.132***			
			(2.79)			
DIG_PUB_SERV*HUM_CAP				0.216**		
				(1.99)		
DIG_PUB_SERV*INT_DIG_TECH					0.105*	
					-1.74	
HUM_CAP*INT_DIG_TECH						0.274**
						(2.28)
Constant	YES	YES	YES	YES	YES	YES
Temporal dummies	YES	YES	YES	YES	YES	YES
Observations	130	130	130	130	130	130
Wald chi2	0.000	0.000	0.000	0.000	0.000	0.000
AR(1)	0.0765	0.0736	0.0637	0.0302	0.0483	0.0718
AR(2)	0.741	0.601	0.717	0.943	0.973	0.770
Hansen test	0.996	0.152	0.991	0.398	0.934	0.0758

Notes: In regressions. robust standard errors are in parentheses; *p-value <0.10. **p-value < .05. ***p-value < .01. About tests are reported p-values.