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DIGITALIZATION AND ENERGY EFFICIENCY: A BIVARIATE ANALYSIS OF DESI AND SDG7 ENERGY INDICATORS

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Abstract. *This study examines the relationship between digitalization and energy performance in European countries by analyzing the Digital Economy and Society Index (DESI) with Sustainable Development Goal 7 (SDG7) indicators. Applying bivariate mapping and correlation analysis, spatial patterns from 2017 to 2022 are assessed. The findings reveal a positive correlation between digital advancement and the integration of renewable energy while simultaneously highlighting issues with energy poverty and digital inclusion. Most countries showed improvements in digitalization and energy efficiency between 2017 and 2022; yet progress remained uneven across regions. Regional disparities persist. Thus, Nordic nations illustrate the success of holistic policies while Southern and Eastern European countries face enduring challenges. The findings highlight the need for cohesive digital and energy policies, expansion of digital infrastructure and targeted support to marginalized areas.*

Key words: *Digitalization, DESI, Bivariate mapping, Energy efficiency*

1. INTRODUCTION

The Fourth Industrial Revolution and the transition to Industry 4.0 open up opportunities and pitfalls for the sustainable development path. This industrial transformation, as noted [1], increased resource and energy intensity, which in turn contributed to environmental degradation, climate change and biodiversity loss. Here, the integration of Digital Technologies (DT) and Renewable Energy Sources (RES) is regarded as a means to achieve, if not maximize, the Sustainable Development Goals (SDGs)—SDG7. SDG7 focuses on three fundamental dimensions of the energy sector: 1) universal access to energy services that considers access to energy for all (i.e., households, educational institutions, healthcare facilities, urban and rural communities, etc.); 2) the increase of RES in total energy production; and 3) the increase in energy efficiency for decreasing energy consumption and GHG.

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The focus of this section covers how digitalization ties to energy efficiency and recent literature uncovering how the digital transformation contributes to sustainable development and renewable energy sources. Advancement towards SDG7 includes addressing a sustainable energy future, ensuring access to affordable, reliable, sustainable and modern energy for all.

1.1. Digitalization and energy efficiency

A growing body of literature agrees that digitalization for energy efficiency is a function of the sector, scale and region. Empirical studies about the correlation between digital transformation and the reduction of energy intensity or improvement in efficiency-related outcomes demonstrate a clear positive relationship. For instance, [2] shows that regional digitalization contributes significantly to improved energy efficiency in China's industrial sector, especially when it is supported along with innovation policies. Similarly, [3] shows that digitalization increases clean energy efficiency by 5.4% thanks to technological innovation and energy consumption. Evidence from firm-level studies also supports these arguments; according to [4], digital transformation improves energy efficiency in enterprises through cost savings and improved productivity and innovation. Urban government-led digital transformation in China is crucial for boosting green total factor energy efficiency, particularly in resource-dependent areas [5].

Digital technologies will transform energy infrastructures and smart systems as well. The cloud-edge computing and digital twin technologies mentioned in [6] increase liquid cascade refrigeration systems by 7.2% in energy efficiency. The digital economy, at the city level, propels urban energy efficiency with a long-run perspective, conditioned on supportive factors such as industrial upgrading and financial backing [7]. The analysis validates the positive effects of digitalization on energy productivity in Europe, evaluated in [8], confirming the effectiveness of the European Twin Transition strategy. Systematic reviews like [9] highlight digital technologies' importance in predictive control, real-time monitoring and distributed energy management, which are the backbone of energy integration and efficiency in smart cities.

The evidence in these varied studies affirms the fact that the enabling environment of suitable technology, economic policy and governance structures allows digitalization to function in enhancing energy efficiency and fosters a transition toward sustainable energy systems. These interactions define the level of consideration given to increased energy efficiency accrual, as illustrated in the interactions of digital technology with institutional mechanisms [2, 3, 5, 8]. Simultaneously, careful design of policy is required so that possible rebound effects [10] are suppressed while efficiency gains remain balanced from an equity and regional perspective [11].

1.2. Digitalization and sustainable development

Digital technologies have become an event for the thriving economies of the present by promoting efficiency, reducing resource consumption and inspiring innovation [1]. A very encouraging profile is emerging with a good number of papers showing an intersection between DT adoption and economic sustainability or environmental quality. For instance, [12] shows that digital transformation has significantly enhanced the sustainability of China's marine equipment manufacturing sector, while [13] urges OECD countries to prioritize next-generation digital infrastructure, such as 5G, in promoting green growth. [14], in turn, argues that digital-induced innovation in Asia-Pacific economies brings about resource efficiency and emissions reduction, which in turn fosters the green economic transformation. Advanced technologies such as AI, geospatial analytics, IoT, blockchain and 3D printing are increasingly perceived to be enabling technologies that allow smarter and more sustainable production systems [15]. Such technologies not only optimize their own processes but also support supply chains that are increasingly transparent, efficient and low-impact.

Renewable energy sources are critical for reducing fossil fuel dependency while facilitating ecologically sustainable development [16]. The convergence between data technologies and renewable energy systems is critical because digitalization allows for real-time monitoring and predictive maintenance of energy systems [17], significantly enhancing the performance and efficiency of RES infrastructure.

Digital innovations enable clean energy access through virtual power plants and microgrids, built on Industry 4.0 technologies [18]. The empirical studies within the OECD confirm that digitalization in conjunction with RES and green innovations is reducing environmental degradation through dematerialization and decarbonization [19]. Another empirical study done in China finally corroborates that data technology can improve energy efficiency, minimize losses in energy supply chains and mitigate pollution [20].

Moreover, investments in digital infrastructure for the integration and management of renewable energy systems are pitfalls [21], leaving DT as not just a helper of energy transitions but rather a passive catalyst for broader transformative change within the energy market.

1.3. Digitalization and Policy Dimensions

SDG7 is built on the three key pillars: universal access to energy, higher shares of RES in the energy mix and higher energy efficiency. Digital technologies actively engage in all three [22, 23]. The synergy between the twin transitions of digital and sustainable development has been brought to light by the European Commission [24].

The impact of digitalization on SDG7 varies across geographies. Several authors note that the deployment of digital infrastructure in underdeveloped regions is essential [25-28]. The digital divide remains one of the greatest impediments to equitable progress, especially in rural and low-income communities. According to example [20], a digitalization index of China's energy sector was devised and states that advanced digital instruments mitigate energy-related losses and environmental pollution. Likewise, [29] states that enhancing individuals' digital skills will enable them to leverage the positive influence of DT on sustainability outcomes to greater effect.

ICT applications for urban contexts also spur environmental monitoring and smart city initiatives that contribute to the establishment of intelligent and sustainable communities [30].

Despite the potential benefits of digitalization, regional disparities and unequal access to digital infrastructure remain. The digital divide worsens energy poverty in less-developed regions, serving to hinder the achievement of SDG7 [31]. Research studies such as [26, 27, 28] urge both national and international policymakers to adopt inclusive strategies to bridge digital inequality.

The European Commission developed the Digital Economy and Society Index to keep track of the digital transformation. The DESI provides an analysis of digital maturity with a multidimensional approach concerning four areas of competence: 1) Training of the people: digital skills across the population, 2) Connectivity: broadband coverage and access, 3) Integration of DT: digital adoption by enterprises; and 4) Digital public services: access to e-government, e-health, and open data services. These dimensions provide academics and policymakers with the ability to monitor the benchmark of digital readiness and sustainable energy objectives.

Although literature acknowledges strong individual impacts of both digitalization and renewable energy on sustainability, the research is fractured when addressing their combined, context-specific impacts with the core context of SDG7. Most studies presently address national samples or sectoral impacts without integrating spatial, technological and energy dimensions.

There is a marked lack of investigations documenting the overlap of digital development (such as captured by DESI) with energy parameters, particularly using spatial analytical tools. Bivariate or integrated analyses of digitalization and energy efficiency across regional contexts in the EU are critical for the purposes of targeted policymaking and resource allocation. However, such analyses are limited.

In line with the above mentioned, the objective of this research is to examine spatial patterns and synergies between digitalization levels (by means of DESI) and energy-related sustainability metrics (by means of SDG7 indicators). The primary goal in this study is to explore spatial relations and visualize co-occurrence patterns through bivariate spatial analysis, supported by Pearson correlation analysis for making an initial assessment of linear relationships among DESI and SDG7 indicators. This methodological synthesis is widely standard in spatial studies at the exploratory phase.

2. Methods and Data

2.1. Data

In this research, data for the 27 European states were collected to analyze the relationship between DESI and selected SDG7 indicators in Europe (Belgium, Spain, Luxembourg, Romania, Bulgaria, France, Hungary, Slovenia, Czech Republic, Croatia, Malta, Slovakia, Denmark, Italy, Netherlands, Finland, Germany, Cyprus, Austria, Sweden, Estonia, Latvia, Poland, Greece, Lithuania and Portugal).

Data were gathered for the years 2017 and 2022, since for those years, DESI is continuously reported for all selected states. Data for DESI are collected from the EC Digital Decade platform.

For the analysis of the relationship with SDG7, we used two sets of indicators: UN and Eurostat. The UN defines SDG7 through four main indicators: CO_2 emissions from fuel combustion per total electricity output (CO_2), population with access to electricity (PAE), population with access to clean fuels and technology for cooking (PCF), renewable energy share in total final energy consumption (RES).

EC, through Eurostat, measures SDG7 progress by additional indicators: population unable to keep home adequately warm by poverty status (AFR), primary energy consumption (PEC), final energy consumption (FEC), final energy consumption in households per capita (FECp) and energy import dependency by products (EID). The descriptive statistics of the selected indicators for 2017 and 2022 for the selected EU countries are presented in Table 1 and discussed in detail in the following text.

Table 1 Summarized descriptive statistics for the selected indicators for 2017 and 2022

	Year	Minimum	Maximum	Mean	Std. Deviation	Variance
DESI	2017	19.40	67.10	36.45	9.87	97.35
	2022	30.58	69.60	53.30	9.94	98.82
RES	2017	6.19	70.04	23.06	15.06	226.87
	2022	13.07	75.88	27.96	15.89	252.45
AFR	2017	0.80	36.50	9.17	9.49	90.09
	2022	1.40	22.50	8.44	6.38	40.67
FECp	2017	0.00	81.36	38.15	19.32	373.17
	2022	0.00	78.84	34.00	17.38	301.98
CO_2	2017	0.26	23.30	2.08	4.30	18.49
	2022	0.22	9.86	1.55	1.83	3.35
PEC	2017	0.00	99.73	17.02	24.49	599.72
	2022	0.00	99.65	17.64	24.63	606.66
FEC	2017	0.00	99.73	16.63	23.39	547.21
	2022	0.00	99.66	17.07	23.54	554.28
EID	2017	0.00	99.95	52.75	26.05	678.68
	2022	0.00	99.91	59.00	25.50	650.04

The descriptive statistics of the DESI indicator show that the minimum value (30.58) and average value (53.30) in 2022 have notably increased compared to 2017 (19.40; 36.45), indicating the development of the digital economy and society. The leaders according to the DESI ranking in both observed years are the Scandinavian countries Finland, Sweden, Norway and Northern European countries such as Denmark and the Netherlands. Southern European countries are lagging behind. A classic example is Romania, which is at the bottom of the list for both years. With the minimal growth of the standard deviation (+0.07) and variance (+1.47), it can be said that the order of advancement among the countries has become uniform. Norway was the only country to report a decline. The largest progression was noted in developed nations such as Denmark, the Netherlands, Finland, Ireland, Italy and Spain. Countries like Romania, Latvia, Bulgaria, Belgium, Estonia, Hungary and Greece showed modest development.

According to the average value of RES in 2022 (27.96), a slight increase in the share of renewable energy sources is noted. The best results in RES are achieved by Scandinavian countries, while the lowest results are recorded in the Netherlands, Malta and Luxembourg. The simultaneous rise in the minimum and maximum values suggests that all countries have progressed, but the value of the variance that has increased (+25.58) indicates a disparity in growth dynamics between them. Leaders in increasing RES are northern countries such as Sweden, Estonia, Cyprus, the Netherlands, Luxembourg and Denmark. Countries struggling in the process of RES increase with weaker growth are Bulgaria, Italy, Austria and Hungary, while Romania is the only country with a recorded decrease.

The AFR indicator with a decline in the mean value (-0.73) in 2022, shows a decrease in the share of the population unable to keep home adequately warm due to poverty status. Most of the countries of Western and Northern Europe achieve the best AFR values, while the countries of Southern Europe indicate an existing problem with AFR. The drastic decline in variance from 90.09 to 40.67 shows a reduction in differences between countries when looking at this indicator. Bulgaria, Lithuania, Greece and Italy have taken significant steps in addressing the problem. While in Spain and France this problem has gained importance and is recognized as a growing challenge.

FECp describes a similar tendency to AFR. Finland and Sweden are leaders in FECp, while industrially less developed countries such as Malta, Portugal and Spain are smaller energy consumers. These countries are characterized by an area with a warmer climate without the pronounced need for district heating as in the Scandinavian countries. A decrease in the mean value (-4.15) is observed, along with a decrease in the standard deviation (-1.94) and variance (-71.19). Developed central and northern countries such as Luxembourg, Denmark, Belgium, Sweden and the Netherlands have significantly reduced FECp values. Poland and Romania are the only ones in the observed sample that do not show a clear strategy for reducing FECp.

The drastic reduction of the maximum CO_2 values (-13.44) confirms the reduction of carbon dioxide emissions in the observed period as well, which is confirmed by the decreasing trends of the standard deviation (-2.47) and variance (-15.14). The lowest CO_2 emissions are recorded in Scandinavian countries, while the maximum values are recorded in Luxembourg, Lithuania and Poland. The leader in reducing CO_2 is Luxembourg, while other countries such as Lithuania, the Netherlands and Croatia are far behind. Some of the countries like Latvia, Romania and Slovenia stand out with the increased trend of CO_2 emissions.

PEC and FEC did not undergo significant changes given the minor changes in minimum, maximum and mean values, but differences between countries remained visible with a slight increase in variance for PEC (+6.94) and FEC (+7.07). The lowest PEC and FEC are achieved by smaller countries such as Cyprus, Malta, Estonia and Luxembourg. The highest recorded values were convincingly found in Germany and France, which are also the industrial leaders in Europe, with a large population. Italy and Poland are recognized for the highest growth of both PEC and FEC, while France and Norway report the highest decrease in PEC and the Netherlands in FEC. Industrially developed countries such as Germany and France show a downward trend in PEC and FEC.

The EID descriptive statistics reflected an increase in reliance on energy imports according to an increase in the mean value (+6.25) alongside a decrease in the standard deviation (-0.55) and variance (-28.64). Norway and Estonia show the lowest EID values, while over 90% of EIDs are Malta, Luxembourg and Cyprus because they do not produce their own energy. EID trends indicate that some countries manage to reduce their dependence on energy imports, but a certain group of countries failed to do so. Northern countries such as the Netherlands, Denmark and Ireland are becoming more dependent, while Latvia, Portugal and Finland have effective strategies for lowering the dependence on energy imports.

2.2. Spatial analysis

In this research, bivariate mapping is applied for the analysis of the spatial relationship between DESI and selected SDG7 indicators. Bivariate maps illustrate two phenomena and have the capacity to reveal relationships and patterns between two types of data more effectively than showing patterns related to a single dataset. They allow us to compare and contrast multiple datasets simultaneously, identifying clusters, outliers and correlations that wouldn't be visible otherwise.

For the purpose of this study, free and open access and open-source Geographic Information System software QGIS3.4 is used.

To conduct meaningful bivariate mapping, two variables must be correlated. A Pearson correlation was performed between the DESI index and SDG7 indicators (RES, AFR, FECp, CO2, PEC, FEC, EID) to assess their linear associations. Furthermore, all the indicators that were not given in percentage scale form 0–100 are normalized in order to have a comparable data set. After initial analysis of the UN SDG7 indicators: population with access to electricity and population with access to clean fuels and technology for cooking are omitted from correlation analysis since they have the same values for each state (100% of the population) and would not yield meaningful results.

3. Results and Discussion

3.1. Correlation analysis

In order to determine which energy-related indicators have a significant relationship with digital development levels among European countries, Pearson's correlation analysis was performed on SDG7-related indicators with the DESI. This analysis aims at identifying which variables are statistically related to DESI because only such variables serve as possible candidates for later bivariate spatial analysis. In this way, subsequent bivariate mapping considers only those variables that are both relevant and appropriate to revealing meaningful spatial patterns.

The Pearson's correlation analysis showed for both observed periods a statistically significant and positive relationship between DESI and RES and DESI and households per capita FECp, and a statistically significant and negative relationship between DESI and AFR. For the rest of the indicators considered, there is no statistically significant correlation with DESI (Table 2). Thus, for bivariate spatial analysis, only those pairs that show statistically significant correlation are considered. In the following text, the presented results of the correlations are discussed in detail.

Table 2 Pearson's correlation of DESI and SDG7 indicators

Variable 1	Variable 2	*r*	*p-value*
2017			
DESI	Renewable energy share in total final energy consumption (RES)	**0.566**	**.0017**
	Population unable to keep their home adequately warm by poverty status (AFR)	**-0.514**	**.0050**
	Final energy consumption in households per capita (FECp)	**0.528**	**.0038**
	CO_2 emissions from fuel combustion per total electricity output	-0.208	.2906
	Primary energy consumption	-0.121	.5430
	Final energy consumption	-0.116	.5601
	Energy import dependency by products	-0.286	.1401
2022			
DESI	Renewable energy share in total final energy consumption (RES)	**0.421**	**.0260**
	Population unable to keep their home adequately warm by poverty status (AFR)	**-0.490**	**.0500**
	Final energy consumption in households per capita (FECp)	**0.406**	**.0320**
	CO_2 emissions from fuel combustion per total electricity output	-0.116	.5601
	Primary energy consumption	-0.026	.8915
	Final energy consumption	0.001	.9992
	Energy import dependency by products	-0.028	.9195

*Correlation is significant at the level of 0.05 (2-tailed).

The Pearson's correlation coefficient analysis of DESI and a few SDG7-related energy indicators reveals both stable and fluctuating correlations over the period 2017-2022.

Beginning with the RES there is a statistically significant, though moderate, positive correlation between the two years. For the year 2017, the correlation coefficient was $r = 0.566$ ($p = .0017$), and for the year 2022, it slightly dropped to $r = 0.421$ ($p = .0260$). This consistent positive relationship suggests that those countries with more developed digital advancement are likely to have a higher share of renewable energy in their energy mix.

Similarly, the relationship between DESI and the AFR is also constant. In 2017, it was $r = -0.514$ (.0050) and in 2022, it remained negative but just significant at $r = -0.490$ (.0500). These results indicate that comparatively more advanced countries in the digital context possess a lower incidence of energy poverty.

In the case of FECp, data also demonstrate a statistically significant moderate positive correlation with DESI for both years: $r = 0.528$ ($p = .0038$) in 2017 and $r = 0.406$ ($p = .0320$) in 2022. The results of these findings are that the countries with more advanced digital development have greater household energy consumption per capita.

On the other hand, the correlation between DESI and CO_2 is weak and statistically insignificant in both years. In 2017, the coefficient was $r = -0.208$ ($p = .2906$) and in 2022, it fell to $r = -0.116$ ($p = .5601$). These results indicate that the degree of digitalization in a country is not a stable predictor of the carbon intensity of electricity generation. A lack of statistically significant relationship was found between DESI and PEC with coefficients of $r = -0.121$ ($p = .5430$) for 2017 and $r = -0.026$ ($p = .8915$) for 2022. The correlation between DESI and FEC also proved to be insignificant, showing $r = -0.116$ ($p = .5601$) for 2017 and $r = 0.001$ ($p = .9992$) for 2022. These findings suggest that overall national energy consumption, both at primary and final levels, lack association with the level of digital development.

Lastly, the correlation between DESI and EID was not significant in either year, though the direction of the relationship changed slightly. In 2017, the coefficient was $r = -0.286$ ($p = .1401$), which showed a weak negative trend, while in 2022 it nearly disappeared with $r = -0.028$ ($p = .9195$). This means that, in contrast to expectations, there is no firm evidence that digitally more advanced countries are less dependent on imported energy. In summary, the evidence shows that DESI is positively and strongly correlated with the RES and FECp and negatively correlated with AFR. Such linkages are consistent across both study years. Thus, these relations are considered for further analysis. No statistically significant association, however, exists with DESI and indicators such as aggregate or primary energy consumption, electricity CO_2 emissions or import dependence of energy. This would suggest that, although digitalization may have the effect of making certain things in energy sustainability better, it is limited or has an indirect influence on broader system-level trends for energy.

3.2. Spatial analysis

3.2.1. DESI and RES

Both DESI and RES are important environmental factors since both are critical sustainability metrics. While DESI measures the integration of digital technologies, digital infrastructure, and skills development, the share of RES indicates the transition to cleaner energy sources.

A higher DESI value reflects an advanced stage of the digitalization process and can induce the application of RES and energy efficiency. For instance, deployment of IoT and smart grids enables optimized consumption of energy, while various digital tools can aid planning and management of RES through improved prediction, monitoring and automatization, which consequently decrease the use of fossil fuels. On the other hand, integration of RES can positively enhance DT development, ensuring that growth of the digital economy does not exacerbate CO_2 emissions.

As results show, in 2017 countries like Poland, Slovakia, the Czech Republic, Hungary and Cyprus had low DESI and RES, reflecting underperforming energy systems and digitalization processes (Fig. 1). Low DESI and moderate RES are in Bulgaria, Romania, Greece and Italy, while only Croatia achieved high RES in this group. In the second group, Belgium and Ireland achieved moderate DESI while RES remained low-scoring. On the other hand, Latvia, Portugal and Austria scored moderate DESI and high RES. In group three, Malta, Netherlands and Luxembourg scored high on the DESI but remain with low RES. On the other extreme, the best performers are noted in the Scandinavian region and Estonia, which achieved high scores for both indicators in 2017.

By 2022, most countries showed improvement in both metrics: 32% on average for DESI and 21% for RES. This reflects continuous advancement looking at the region as a whole, maintained stable, albeit incremental, progress. However, only Ireland moved from the first group to the second, reflecting a significant improvement in digitalization (DESI change from 41 to 63) and a slight increase in renewable energy share. Bulgaria and Romania achieved zero progress in RES, while Norway recorded a negative DESI trend.

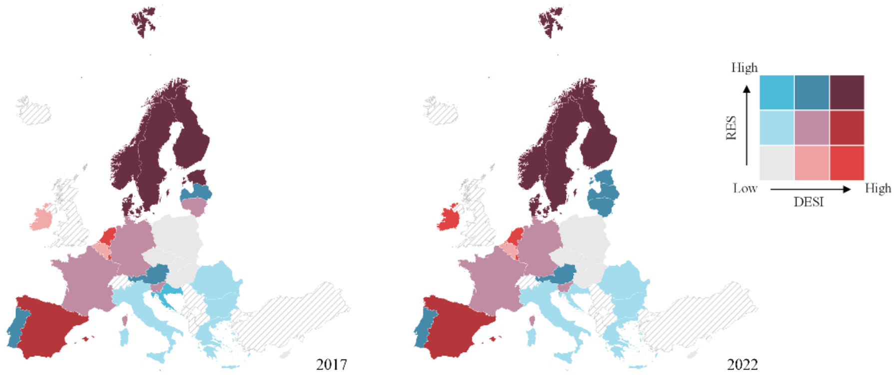

Fig. 1 Bivariate map of Digital Economy and Society Index (DESI) and the share of renewable energy in total final energy consumption (RES) for the years 2017 and 2022

3.2.2. DESI and AFR

Digital technologies like smart energy meters or residential energy management systems can help residents to optimize energy use and ensure thermal comfort. Furthermore, digitalization can help raise awareness and access to energy efficiency subsidies, which is essential for low-income households. On the other hand, impoverished populations often face challenges to digital inclusion, limiting their access to energy-saving technologies and information. Such a digital divide can further enhance energy poverty.

Analysis of data for 2017 for DESI and AFR showed two prominent spatial clusters (Fig. 2). The first cluster includes Cyprus, Greece, Bulgaria, Romania and Italy, countries with low scores for DESI and high scores for AFR, reflecting challenges in the digitalization process and energy-related poverty. On the contrary, the second cluster consists of Scandinavian countries, Lithuania and the Netherlands with high DESI scores and low AFR scores, reflecting the advanced digitalization process and advanced status when it comes to energy poverty. Besides these clusters, among countries with the highest DESI scores, Spain has the highest percentage of the population that is unable to keep their homes adequately warm.

By 2022, only limited progress was recorded when it comes to AFR, indicating persistent challenges in energy poverty in most of the countries. Advanced nations, like Finland, Denmark and Norway, kept their leadership position with high DESI and low AFR scores.

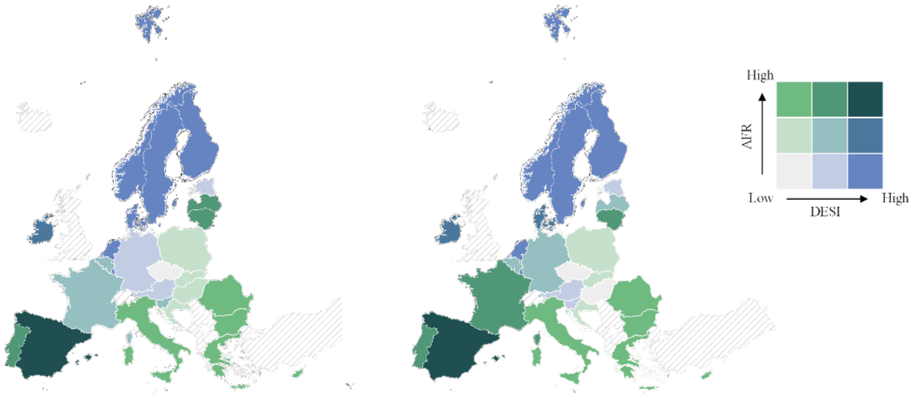

Fig. 2 Bivariate map of Digital Economy and Society Index (DESI) and the population unable to keep their homes adequately warm by poverty status (AFR) for the years 2017 and 2022

3.2.3. DESI and FECp

Since DESI indicates the level of digitalization in one state, it assumably reflects wider use of smart-home technologies like energy-efficient appliances, automated heating and cooling systems, smart meters, etc. Such technologies enable households to optimize energy consumption and lower energy use per capita. On the other extreme, increased digitalization may lead to increased use of energy per capita due to the proliferation of electronic devices in households. Analysis of the relationship between DESI and FECp can offer an understanding of whether digital advancement leads towards energy saving or goes against environmental goals.

The comparison result shown in Fig. 3 reveals a spatial cluster with low DESI values and moderate final energy consumption in households per capita (FECp): Slovakia, Cyprus, Greece, Romania and Bulgaria, reflecting slow progress in the digitalization process along with considerable energy consumption. In contrast, the Scandinavian countries, together with Denmark, Estonia and Lithuania, form a spatial cluster that stands out with high DESI and high FECp. Finally, on the other extreme is Malta, with a low DESI performance but also the lowest energy consumption per capita in households.

By 2022, as shown previously, most of the countries improved their DESI scores by 32.5% on average, but also most of them decreased the percentage of FECp. This points out improvement in both digitalization and energy efficiency, looking at the region as a whole. Looking at the single cases, the Netherlands joined Malta, with a significant improvement in digitalization (DESI change from 46 to 67) and improvements in household energy efficiency (FECp from 35 to 26).

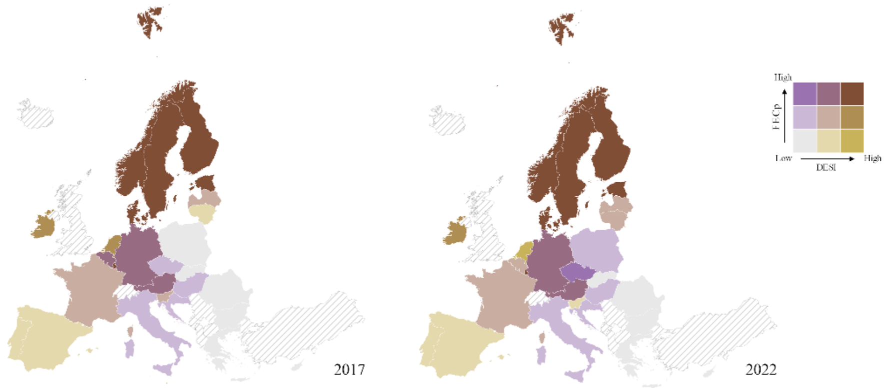

Fig. 3 Bivariate map of Digital Economy and Society Index (DESI) and Final energy consumption in households per capita (FECp) for the years 2017 and 2022

4. Concluding Remarks

The presented bivariate analysis of the DESI index and selected energy metrics revealed some valuable insights into the process of digitalization and integration of SDG7 in the European Union countries for the observed period. The results showed that a higher DESI might positively correlate with the integration of RES. Digital technologies enable optimized management of energy resources. However, exemptions exist where some countries, like Malta, scored high on DESI but kept low scores for RES. This fact points out that digitalization obviously is not the sole factor that contributes to the adoption of RES.

Next, the relationship between DESI and AFR reveals potentially complex dynamics between digitalization and energy poverty. On one hand, digital technologies can bring an energy efficiency improvement, such as advanced systems for managing home energy. But energy poverty is not very straightforward. Access to digital technology by itself would require overcoming hurdles—lack of digital literacy or affordability or even a lack of infrastructure, as one of many examples. For example, in 2017, Bulgaria, Romania and Greece were characterized by both low DESI and high AFR, indicating a dual burden of digital and energy exclusion. Though improvements in DESI scores were evidenced by 2022, the coverage of energy poor declined minimally because digitalization, by itself, is not sufficient in making a direct pathway to access energy for the most disadvantaged sections of society.

The third aspect, the relationship between DESI and FECp, reveals the twofold effect of digitalization on energy efficiency. For instance, smart homes (houses) can decrease final energy consumption per household, but at the same time, increased digitalization might lead to higher energy consumption due to the increased use of digital and electronic devices. In 2017, Scandinavian countries recorded both high DESI and FECp scores, which suggests that digitalization does not necessarily lead to a reduction in energy consumption.

However, by 2022, average energy consumption per household decreased which suggests the potential effect of the digitalization process on energy efficiency.

Overall, these trends reveal persistent regional divides in digital and energy transitions, which adds to previous arguments presented in [16-18]. While Nordic nations illustrate the success of holistic and integrated policies, Southern and Eastern European countries face enduring challenges. That goes in line with [10] who argued that advancements in DT have positive effects on energy sustainability. This calls for targeted strategies to foster digital growth and align it with energy efficiency and sustainability goals.

The evidence suggests that digitalization, when taken up comprehensively by a sufficient policy framework, can become a driving agent in the energy transition. But this is not an automatic relationship and involves concerted effort. First, policy integration is required—energy and digital policy cannot be crafted independently from each other. Governments need to promote digital energy efficiency solutions (e.g., smart grids, real-time data monitoring, home energy management systems) and make the solutions accessible and affordable, especially in underdeveloped regions. Secondly, focused support to backtracking areas, especially in South and East European regions, must be provided to cope with the twofold challenge of digital poverty and energy poverty. Investments in digital infrastructure need to be matched with training schemes and investments to equip low-income communities and households with the skills to engage in the digital energy transition. Lastly, institute reinforced monitoring mechanisms, which will enable follow-through on both energy and digital fronts and ensure that any digital expansion is for the environment and society's good.

While the current analysis is useful, some limitations must be mentioned. First, there may be discrepancies in data or reporting patterns across countries, especially for energy indicators. Second, time-lag factors can influence observed relations—digitalization gains take years to affect energy structures and behavior. Third, while the DESI index is comprehensive in nature, it may not fully reflect qualitative aspects of digitalization, such as cultural readiness or policy implementation quality. These limitations suggest caution in extrapolating inferences across contexts or over time.

To build on current evidence, follow-up research would have to explore the micro-level impacts of digital technologies on energy behavior and consumption and the institutional and governance arrangements that enable the successful integration of digital and energy policy. Comparative case studies could help illustrate how specific policy interventions influence outcomes in different regional contexts. Longitudinal studies would also help establish causality and account for temporal lags. Furthermore, the analysis of specific digital technologies and their contribution to energy efficiency and adoption of RES in targeted countries and the analysis of socio-economic factors of digitalization, i.e., factors that influence digital inclusion and its relation to energy poverty, might be valuable to enhance understanding of this initial study. Suggested follow-up research can offer material for deeper geospatial modeling and insights into regional discrepancies. This and related research can contribute to an understanding of how the digitalization process can become a tool in the transition towards sustainable energy profiles of the countries while simultaneously reducing socio-economic inequalities in access to digital technologies and energy resources.

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