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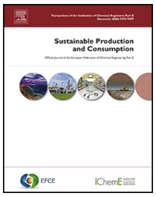

Research article

Digitalization, innovation and environmental policies aimed at achieving sustainable production

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ABSTRACT

Humanity is running out of time to curb climate change, and its effects are becoming ever more intense and harmful to humankind. A change in habits and production methods is required in order to slow the advance of this scourge. This research seeks to provide quantitative information on the nexus between digitalization and sustainable production (SP). The analysis focuses exclusively on the 27 EU member states (2015–2019), all of which are characterized by a proactive stance towards environmental degradation. First, a synthetic index is constructed using cross-efficiency, in order to assess Europe's position in terms of SP. This index is then taken as the dependent variable in an estimation of the effects of the different aspects of digitalization measured in the Digital Economy and Society Index, as well as the environmental and innovation policies adopted in the EU. The generalized method of moments is used to examine the effect of the trend in SP. Results reveal that the level of income per capita does not determine SP and that it is more a matter of society's commitment to implementing practices that foster SP. Furthermore, the evidence found indicates that Europe has not yet been able to break the negative link between GDP and sustainability, despite the positive impact of all facets of digitalization, innovation and environmental policies.

1. Introduction

Human beings are facing major challenges that require an active stance from all parties involved; companies, public administrations and the general population. Climate change and the scarcity of natural resources call for a new growth paradigm, wherein economic and social progress guarantee sustainable development (SD). The World Commission on Environment and Development defined SD as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). SD centres on the protection of nature, economic well-being and social inclusion, while respecting planetary boundaries (Hummels and Argyrou, 2021; Méndez-Picazo et al., 2021; Marinakis and White, 2022).

SD has been the basis for the adoption of the 2030 Agenda, which sets the global goal of ensuring people's well-being while protecting the planet (UN, 2015). A total of 17 Sustainable Development Goals (SDGs) were established, divided into 169 economic, social and environmental targets, all of which are aimed at addressing the major challenges of the 21st century and ensuring a better life without compromising the balance of ecosystems. The 17 SDGs are closely interconnected and cannot be tackled in isolation (Weitz et al., 2018; van Soest et al., 2019). For example, there is a strong connection between Responsible Consumption and Production (SDG 12), Zero Hunger (SDG 2) and No Poverty (SDG 1); that is, better production and consumption systems contribute to the eradication of hunger and poverty (Principato et al., 2019).

Responsible Consumption and Production is one of the most cross-cutting and relevant SDGs for developed countries (Gasper et al., 2019). It calls for production models that ensure the efficient use of natural resources, reducing waste generation while properly managing polluting products. Environmental regulations mean that many industrial sectors are having to explore innovative investments in alternative ways to ensure compliance in order to internalize environmental externalities without hindering competitiveness (Romero-Castro et al., 2022). Companies must direct their innovative processes towards the implementation of sustainable practices that avoid environmental impacts (Haldar and Sethi, 2022); in this respect, the digital revolution should be examined from a dual perspective. On the one hand, due to its recent emergence and rapid development, it has become a major focus of energy demand, significantly increasing greenhouse gas (GHG) emissions (Fagas et al., 2017; Joyce et al., 2019). However, the massive presence

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of digital practices in all economic sectors makes it an opportunity for the introduction of environmentally-friendly solutions in all socio-economic structures (Abdollahpouri, 2017; Dabbous and Tarhini, 2021). Sustainable production (SP) and digitalization are, at first glance, two very disparate concepts, but they are becoming increasingly interconnected and can be seen to pursue a common goal (Saura, 2021).

SP was originally defined by the Lowell Center for Sustainable Production (LCSP, 1998) as the creation of goods and services through processes that are non-polluting, conserving of energy and natural resources, economically viable, and safe, healthy and rewarding for employees and consumers. Grounded on this notion are the principles of SP, which take six aspects into consideration: resources; the environment; economic performance; community development and social justice; workers and products (Khanzode et al., 2021). In turn, digitalization is the transformation of all types of interactions, communications, business functions and business models into a digital model, fostering the automation and boosting the speed of almost all tasks. It is a complex concept due to the multitude of associated facets, affecting organizations at different levels and in different ways (Broekhuizen et al., 2021; Tiago et al., 2021). *E*-commerce is just one of its manifestations; this technology can be found in all levels of society and the business environment, from the use of email to smartphones, and has changed the way most day-to-day activities are done (Branca et al., 2020).

The rise of digitalization in businesses, households and financial sectors is making it difficult to separate out the direct and indirect effects of Information and Communication Technology (ICT) on the environment (Danish et al., 2018; Avom et al., 2020), and globalization is undoubtedly a driver of the adoption of digital technology (Skare and Soriano, 2021). This situation has sparked the interest of the scientific community, and a large body of literature has recently emerged, focusing on this new way of doing things. For example, Ahmed et al. (2021) provide evidence of the positive impact of ICT and globalization on CO_2 emissions, while at the same time growth and urbanization degrade the various layers of the biosphere. Traditional goods and services are being replaced by virtual practices that reduce energy use and emissions. *E*-commerce, e-banking, virtual meetings and online education render people's physical presence unnecessary, reducing travel and the associated pollution (Adeleye et al., 2021; Ulucak and Danish, 2020). New evidence has been reported on the effects of robotization, digitalization and innovation on productivity and employment in companies (Ballestar et al., 2021). Digital transformation at all levels will ensure sustainable production and consumption, as well as business continuity in any scenario, including pandemic situations (Al-Omoush et al., 2020; Bai et al., 2021; Guaita et al., 2022; Klimant et al., 2021) provide evidence of the advances implemented in manufacturing processes, yielding more efficient work teams and use of resources.

The present research involves a detailed analysis of the nexus between the different areas of digitalization and SP, as well as the role of environmental policies and innovation (Marti and Puertas, 2022). In order to use a homogenous setting for the analysis, the study focuses on the 27 EU member states, which show a proactive attitude towards climate change mitigation, as made clear by the recent European Green Deal. A five-year period (2015–2019) is analysed in order to ensure the robustness of the results, which will allow us to answer two research questions:

Q1. Which countries are most committed to developing and introducing SP in their economies?

As part of this study, a Synthetic Index (SI) is constructed to reveal the relative position of each country, with SP evaluated in terms of resources and the natural environment. A variant of Data Envelopment Analysis (DEA)—intertemporal cross-efficiency (CE)—will be used to produce a ranking that can provide an answer to this question.

Q2. What aspects of digitalization are strengthened by the policies adopted in countries' pursuit of SP?

This question will be answered by estimating the parameters of a panel data model using the Generalized Method of Moments (GMM). The different pillars of the Digital Economy and Society Index (DESI) will be analysed individually, along with variables that shed light on the environmental position and ICT innovation policies of the analysed countries.

This research aims to fill the related gap in the literature by providing valuable evidence on as yet understudied aspects: (1) digitalization is analysed with a focus on all its facets (*human capital, connectivity, integration of digital technology, and digital public services*) in order to identify possible differences among them; (2) the SI assesses different aspects of SP, so that the ranking is not based on a single variable; (3) the length of the period analysed guarantees the quality of the results obtained, ensuring that isolated events do not distort the conclusions; (4) the use of up-to-date statistical information means that the conclusions drawn can immediately be put into effect in policies that contribute to the arduous task of achieving SP.

The rest of the paper is structured as follows. Section 2 presents a review of the literature on the advances made relating to digitalization and SP. Section 3 describes the methods and the sample used. Section 4 analyses the results obtained in the research. Lastly, the conclusions, contributions of the study and limitations are summarized in Section 5.

2. Theoretical framework: progress made in digitalization and sustainable production

Business objectives are changing in response to the degradation of the biosphere; many industries are beginning to prioritize the reduction of environmental impact over profit, promoting digitalized manufacturing, known as Industry 4.0. This transformation has erupted into all levels of society, with physical information being converted into languages read using information technology practices. The increase in productivity has been amply demonstrated, from its adaptation in socio-economic uses to environmental issues (Mondejar et al., 2021; Lioutas et al., 2021). This transformation is also providing the data needed for optimal decision-making, facilitating the efficient use of available resources and services (Dubey et al., 2019; Appio et al., 2021).

However, despite the fact that its implementation yields higher levels of efficiency and productivity while using fewer resources, it is a fiercely debated issue in the literature, giving rise to opposing positions. Jabbour et al. (2018) argue that there are synergies between Industry 4.0 and environmentally-sustainable manufacturing, considering the former as a means of developing green products and processes that will enable changes to patterns of production and consumption. Langley et al. (2021) claim that this new approach is associated with a wide margin of uncertainty, forcing companies to introduce organizational changes and to consider multiple interrelationships in decision-making processes.

The scientific community has shown great interest in these two fields of knowledge, but has sometimes overlooked the possible intersection between them. Maffei et al. (2019) point to the inherent difficulty in jointly analysing digitalization and sustainability. While the latter requires a long-term commitment to changing the underlying structures of industries, digitalization can be treated as a trend towards technological advancement independent of sustainability. The adoption of sustainable business models is now beginning to be seen as an opportunity. Zarte et al. (2019) claim that industrial evolution is focused on digitalization as a means to ensure SP, with the positive relationship between these two notions recently being confirmed (Bag et al., 2021; Svarc et al., 2021). According to Sharma et al. (2020) this emerging technology is posing a major environmental challenge worldwide. Authors such as Kamble et al. (2018) consider Industry 4.0 as a paradigm shift in manufacturing, merging new technologies aimed at ensuring maximum performance with the efficient use of resources. Table 1 presents in more detail some of the research carried out.

Similarly, there has been a rapid rise in recent years in the number of studies focusing on the digitalization of specific production processes as a way to curb pollution. Gružauskas et al. (2018) analyze the effect of

Table 1
Literature review: sustainable-digitalization.

Authors	Objetive	Methodology	Conclusions
Jovanović et al. (2018)	Examine the relationship between digitalization and sustainable development	Correlations of DESI and other composite indices.	Digital performance of EU affects main sustainable development components: economic, social, and environmental
Bürgin (2020)	Analyze how recent advances in the use of digital technology contributed to better data	Semistructured interviews	There are positive effects of digitalization on the institutional capacity of key stakeholders, and it can narrow the implementation gap in EU environmental law
Ciliberto et al. (2021)	Examine the relationships among sustainable production, lean production, and Industry 4.0	Lean production theory	The principles on which the pillars of a competitive and sustainable enterprise rest are set out.
Denicolai et al. (2021)	Investigate the internationalization, digitalization, and sustainability are growth paths for firms	Tobit regression	Digitalization and sustainability are positively related and they turn to be competing growth paths when the firm internationalizes.
Švarc et al., 2021	Investigate the association of intellectual capital with the EU digital transformation readiness	Multiple linear regression	Social capital and working skills can detect certain elements of digital divide between EU member states.
Del Río Castro et al. (2021)	Categorize the main SDGs research gaps and exploration exploration of the potential contribution of digital paradigms	Review and synthesis of relevant literature	Digitalization should be responsibly harnessed by mitigating negative impacts and ensuring genuine sustainability
Toktaş-Palut (2022)	Analyze the effects of Industry 4.0 technologies and coordination on the sustainability of supply chains	Nash bargaining based revenue-sharing contracts	When a supply chain uses the advantages of Industry 4.0 technologies in conjunction with coordination, this chain leads the market in terms of overall sustainability

implementing Industry 4.0 in the supply chain through the use of autonomous vehicles, in order to determine whether competitive advantages can be maintained in the long run. The authors find that issues such as legislation and available infrastructure can be a constraint. Karki and Porras (2021) review the literature on Industry 4.0 in maintenance services, demonstrating the positive effect in terms of sustainability. Annosi et al. (2021) research the effect of this new paradigm in the food supply chain as a means of preventing waste generation.

In light of this new approach, and although it should be clarified that the ecosystems analysed may have varying degrees of digitalization, innovation and environmental policies, innovation is an essential element for the replacement of traditional management systems, facilitating the adjustments needed to successfully bring together digitalization and SP. Many different resources are required, and management must play an appropriate role in integrating the two concepts. Some of the resources analysed in the literature include information processing capability, product and process traceability, design for the environment and for remanufacture, green human resources and IT resources (Bag and Pretorius, 2020; Li et al., 2019; Saidani et al., 2017; Telukdarie et al., 2018). For example, digital platforms facilitate mass production, meaning demand can be met without the need for overproduction; this helps ensure energy savings, giving companies an advantage over their competitors. Mittal et al. (2018) argue that companies opposed to adapting to this new operational approach have little chance of survival. According to Hecklau et al. (2017) industry must move towards SP by incorporating eco-design for a cleaner atmosphere. Geissdoerfer et al. (2017) claim that this is an emergent, more environmentally-friendly way of manufacturing, where proper resource management is assured and recycling helps to prevent undesirable waste.

In short, the ultimate goal of all these technological processes must be the introduction of new developments that foster SP. Technological innovation plays a crucial role in economic prosperity by fostering competitiveness, green innovation and SD (OECD, 2015). Nevertheless, despite all the progress that has been made, the link between economic growth and pollution has not yet been broken (Safi et al., 2021; Su et al., 2022). In this context, green innovations contribute to the reduction of carbon emissions (Khattak et al., 2022), while ensuring companies' competitiveness (Le and Ikram, 2022).

3. Methods and materials

The empirical analysis of this research was carried out using a sample of EU member states for the period between 2015 and 2019. The motivation for choosing these countries was to identify patterns of behaviour in the nations most committed to climate change issues. Intertemporal CE is used to produce an SI that combines in a single variable the different facets of one of the main indicators of SP, resources, along with GHG emissions. Additionally, the parameters that determine the nexus between the different aspects of digitalization and SP are estimated using GMM, and countries' commitment in terms of innovation and climate change is analysed.

3.1. Stage 1: cross-efficiency and variables used in the SI

DEA is a non-parametric linear programming method used to determine the level of efficiency of decision-making units (DMUs). It involves constructing a production frontier based on the optimal combination of the inputs and outputs that define the problem under study. Originally, Charnes et al. (1978) built the model in a setting of constant returns to scale (CRS), which did not account for the size of the DMUs; they all operated at an optimal scale. In response to this limitation, Banker et al. (1984) proposed the introduction of variable returns to scale (VRS), such that inputs and outputs would not have to vary proportionally. The flexibility of the DEA model also allows different orientations to be established, as appropriate: thus, outputs can be maximized with the available resources (output orientation, *oo*); or, conversely, inputs can be minimized while producing the highest possible level of output (input orientation, *io*). Under either orientation, the optimal level of efficiency takes the value of 1. In the case of *oo*, the excess over 1 indicates how much the outputs should increase by, using the available resources, to achieve maximum efficiency. As for *io*, the efficiency level ranges between 0 and 1, and the distance to 1 represents the reduction in inputs needed to achieve a score of 1. For *oo*, the efficiency score is calculated as the inverse of the value obtained. The literature includes a notable body of scientific output that supports the use of this method with issues related to sustainability, energy (Chu et al., 2021), carbon emissions (Sun et al., 2021), green tourism (Martín and Salinas, 2022; Zhang et al., 2022), water security (de Castro-Pardo et al., 2022) and even in the SP of foods such as corn (Mwambo et al., 2021).

Despite the great popularity of this method, it also has some disadvantages that must be taken into account to ensure that the correct interpretation is drawn from the conclusions (Cooper et al., 2006): the results are highly dependent on the choice of inputs and outputs, and it is not possible to validate their selection; the presence of outliers can seriously influence the results; only quantitative data can be used; and it is not possible to distinguish between efficient observations, as they are all assigned the value of 1 without necessarily being equivalent. Intertemporal CE overcomes some of these limitations by enabling a complete ranking of all the observations in the sample. Moreover, in order to avoid the influence of possible outliers, the observations corresponding to the 5 years of the sample are taken as a comprehensive set, with the construction of a single production frontier. Thus, the efficiency level of the DMUs is the mean obtained in each year (Puertas et al., 2020a; Carracedo and Puertas, 2021; Bresciani et al., 2021).

The CE matrix provides an evaluation of the performance of each DMU using the optimal input and output weights of the other DMUs in the sample, with its final value being the average of all the efficiencies obtained. This variant of DEA was originally proposed by Sexton et al. (1986), who developed an evaluation matrix to facilitate the production of rankings, thus allowing the researcher to order all the observations. This method involves calculating the efficiency score of each DMU n times to produce a CE matrix. The elements of the matrix are calculated using the following equation:

$$E_{kj} = \frac{\sum_{r=1}^{s} u_{rk} y_{rj}}{\sum_{i=1}^{m} v_{ik} x_{ij}} \; j = 1, \dots, n; k = 1, \dots, n \tag{1}$$

where u_{rk} and v_{ik} are the optimal multipliers determined through DEA for the corresponding DMU, x_{ij} and y_{rj} represent the inputs and outputs consumed and produced by each j-th unit. The CE score for DMU j is the average of its corresponding efficiency scores obtained in the matrix, E_{kj}.

$$CE_j = \frac{1}{n} \sum_{k \neq j} E_{kj} \tag{2}$$

Through the use of CE, DMUs that are not efficient, but are close to being so, can achieve a good position in the ranking. This method corrects the possible disproportion between the number of outputs and the scale of the activity of the group they represent. It has been widely used in the literature for SI construction (Marti and Puertas, 2020; Fernández-Macho et al., 2020; Puertas et al., 2020b).

In this study, an SI is constructed to determine the relative position of European countries in terms of SP. The inputs and outputs used were first treated to ensure that different units of measurement do not result in erroneous rankings (OECD, 2008; Cherchye et al., 2008). Before calculating the level of efficiency, all variables were transformed into natural logarithms and then rescaled to values ranging between 1 and 2. Finally, since there was no clear correspondence between the variables used and their assignation as inputs or outputs, the inputs were transformed into “variables to be improved” so as to yield an appropriate production function (Martí et al., 2017).

Two inputs (domestic material consumption and final energy consumption of industry) and three outputs (renewable energy, recycling and industrial GHG emissions) have been used in the construction of the SI. All of these have previously been used as indicators of SP in the literature (Veleva and Ellenbecker, 2001; Krajnc and Glavič, 2003; Elhuni and Ahmad, 2017). Given the aim of this research and the variables used, it was decided to estimate a CE model under VRS and *oo*, using DeaR software (Coll-Serrano et al., 2018). Table 2 presents the variables, indicating the role they play, the units of measurement and their corresponding sources.

Table 2
Variables used in the construction of the SI.

Variable	Role	Unit	Source
Domestic material consumption	Input	Tonnes per capita	Eurostat
Industrial energy consumption	Input	Tonnes per capita	Odyssee
Renewable energy	Output	Percentage	Eurostat
Recycling	Output	Kg per capita	Eurostat
Industrial GHG emissions	Undesirable output	Tonnes per capita	Eurostat

Table 3
Descriptive statistics for inputs and outputs (2015–2019).

	Mean	SD	Max	Min
Domestic material consumption	3.52	2.07	12.47	1.02
Industrial energy consumption	0.62	0.40	2.12	0.15
Renewable energy	21.13	11.77	56.39	4.99
Recycling	126.28	63.10	309.00	14.00
Industrial GHG emissions	0.90	0.43	1.95	0.32

Since GHG emissions constitute an undesirable output, this variable has been transformed (1/GHG) so that it can be maximized along with the rest of the proposed variables (Koçak et al., 2021; Carracedo et al., 2021). Table 3 shows the main descriptive statistics for all the variables.

An analysis of the values in Table 3 shows that there is no pattern in the behaviour of these indicators. While Estonia and Finland consume the most material and energy per capita, respectively, Sweden and Germany are the most advanced countries in terms of renewable energy and recycling. At the opposite end of the scale are Latvia and Malta in terms of inputs, and Luxembourg and Romania in terms of outputs. Regarding emissions, Austria is the country with the highest level of GHG per capita and Denmark is the least polluting. These results reflect the countries' commitment to tackling climate change and the efforts made in certain sectors.

3.2. Stage 2: GMM and variables used

Answering the second research question requires a panel data analysis. A dynamic panel data model has been chosen in order to incorporate an endogenous structure into the model, accounting for causal relationships in the estimation. This approach, originally proposed by Arellano and Bond (1991), involves treating endogeneity through differences of the lags. Other estimators were developed to deal with small panels, where lags in the levels of the variables are used as instruments. Given the characteristics of the sample, this paper uses the variant developed by Roodman (2006), where the instruments are incorporated in levels, reducing information loss.

The fact that the different aspects of digitalization are correlated means they have to be analysed individually, thus requiring five estimations (one per pillar and another for the overall index). In addition, we analyze the degree of the impact of environmental and innovation policies on SP. Therefore, 10 models in total have to be estimated, the general structure of which is given as follows:

$$\begin{aligned} \ln SI\_PS_{it} = {} & \beta_0 + \beta_1 lnSI_{it-1} + \beta_2 lnVA\_DESI_{it} + \beta_3 \ln X_{it-1} + \beta_4 lnZ_{it} \\ & + \beta_5 lnGDP_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

$i = 1,2, \dots, 27$ countries and $t = 2015, \dots, 2019$.

where SI_PS represents the SP index; VA_DESI is industrial value added for each pillar of the DESI analysed (Kopp and Lange, 2019); X and Z are variables introduced to account for innovation (environmental patents and government budget allocations for ICT R&D) and environmental commitment (business expenditure on environmental protection and environmental taxes); lastly, GDP captures the level of production of the countries analysed.

The European Commission publishes the DESI annually to monitor the progress made in EU countries in terms of digital competitiveness. It covers four distinct dimensions: *human capital* (HC), *connectivity* (C), *integration of digital technology* (IDT), and *digital public service* (DPS). All of them are defined by sub-dimensions and indicators that yield a value for each pillar and for the total digitalization index. The DESI for 2021 reflects statistical information from the previous year; thus, this study uses the DESIs published in the period 2016–2020, which provide data for the period 2015–2019. Table 4 provides definitions of the independent variables for each of the models.

Table 4
Description of determinants in the SI.

Common variables		
Human Capital[a]	Internet user skills and advanced skills and development	%
Connectivity[a]	Fixed broadband take-up, fixed broadband coverage, mobile broadband and broadband prices	%
Integration of digital technology[a]	Digital intensity, digital technologies for businesses and e-commerce	%
Digital public service[a]	E-government	%
DESI[a]	Total index	%
GDP	Gross domestic product	Millions of euros

Variables	Definition	Unit
Model 1: innovation policies		
Patents	Patents developed in environment-related technologies	Number
ICT GBARD	Government budget allocations for ICT R&D	Millions of euros
Model 2: Environmental policies		
National expenditure on environmental protection by corporations (NEPE)	Transactions related to the prevention, reduction, and elimination of pollution and any other degradation of the environment.	Millions of euros
Environmental taxes (ET)	Total tax revenue by category of environmental taxes: energy taxes, transport taxes and the sum of pollution and resource taxes	Millions of euros

[a] All DESI components have been multiplied by VA to account for the possibility that the effect of one variable may depend on the state of another; that is, the effect of digitalization on SP may differ depending on the industrial VA.

These variables enable an analysis of the nexus between SP and digitalization, as well as the importance of the environmental and innovation policies adopted in European countries. Table 5 shows the descriptive statistics for all the variables.

These variables have been ln-transformed in order to smooth the variability, make the data more homogenous and help ensure the robustness of the estimates (Puertas and Marti, 2021). Table 5 reveals very disparate behaviour of the variables. Regarding digitalization, while we ~~do not~~ observe a low degree of dispersion in the sample, the standard deviation is well above the corresponding average. This may be due to the disparity in the size and economic level of the countries analysed. The overall DESI reveals that the EU still has a long way to go to improve digitalization, with the maximum (63%) being recorded by Finland in 2019. Countries' economic situation might be expected to be closely related to the DESI; however, a country such as Italy, which has a high level of economic capacity (measured in terms of GDP), has a level of digital development similar to Croatia, Cyprus and Slovakia, and lies behind other countries such as Slovenia, Portugal, Latvia, Lithuania, Estonia and Czechia.

Table 5
Descriptive statistics of independent variables (2015–2019).

	Mean	SD	Max	Min
HC	0.12	0.02	0.17	0.07
C	0.09	0.02	0.14	0.04
IDT	0.08	0.02	0.14	0.03
DPS	0.14	0.04	0.21	0.02
DESI	0.42	0.09	0.63	0.21
GDP	703,221.62	1,028,202.80	4,481,173.47	17,733.19
Patents_{t-1}[a]	4410.34	10,618.09	55,643.79	25.03
ICT GBARD	209.21	329.74	1769.06	0.15
NEPE_{t-1}[a]	5154.74	9069.74	48,383.00	31.10
ET	11,714.17	17,117.58	61,111.00	269.90

[a] These two variables have been lagged one year due to the unavailability of statistical information for 2019. Sometime, however, the research must reflect the time lag needed to obtain the corresponding results.

4. Results and discussion

In the first stage of the research, the SI was calculated to establish the relative positions of European countries in terms of SP. Since they all belong to the EU, they show a fairly homogeneous pattern of behaviour in response to climate and environmental challenges. The European Green Pact signed in 2019 by the European Commission covers pollution control measures, social policies and actions against climate change, sustainability laws, emission reduction, energy efficiency, the circular economy and the green economy. The overarching aim is to preserve, maintain and improve the EU's natural capital, thereby enhancing the well-being of the population. Therefore, the proposed SI reveals which countries hold the best positions and, conversely, which countries need to take stronger action. Table 6 shows each country's efficiency score with the SI_PS, its ranking, and mean GDP per capita in purchasing power parity (PPP) constant prices.

The application of CE yielded a complete ranking, with Denmark, Finland, Sweden and Germany occupying the top positions, and others such as Slovakia, Cyprus, Malta and Romania at the bottom. The latter require more action on energy to foster the development of sustainable practices, recycling, renewable energies, and activities to reduce GHG emissions. Furthermore, it can be seen that a country's wealth does not determine its commitment to SP. For example, Malta, which has a GDP per capita higher than Slovenia, Estonia and Latvia, occupies the second to last position in the SI_PS, while the aforementioned countries are in fifth, sixth and eighth positions, respectively.

Bekun et al. (2019) confirm that economic growth and non-renewable energy consumption increase carbon emissions in Europe. Hence, countries need to intensify the use of renewable energy in all production systems. Despite the differences between the countries analysed, Wang et al. (2019) confirm that European countries play a clear leading role in terms of practices relating to sustainable production and consumption. For all countries, it is a slow process and difficult to implement, but it is particularly so for developing economies. In some circumstances, economic priorities still take precedence over environmental and social

Table 6
SI_PS of European Countries (2015–2019).

Country	SI_SP	Ranking	GDP per capita (PPP, constant)
Denmark	0.960	1	55,155
Finland	0.932	2	47,108
Sweden	0.917	3	51,882
Germany	0.906	4	52,705
Slovenia	0.887	5	36,418
Estonia	0.884	6	33,673
Austria	0.869	7	54,297
Latvia	0.838	8	28,775
Italy	0.819	9	41,484
Luxembourg	0.815	10	115,204
Bulgaria	0.808	11	21,534
Ireland	0.807	12	78,357
Lithuania	0.799	13	33,810
France	0.792	14	44,586
Czechia	0.790	15	38,584
Croatia	0.789	16	27,102
Netherlands	0.780	17	54,951
Portugal	0.776	18	32,999
Belgium	0.770	19	50,560
Spain	0.769	20	39,289
Hungary	0.766	21	29,785
Poland	0.754	22	30,281
Greece	0.748	23	28,789
Slovakia	0.721	24	26,913
Cyprus	0.711	25	37,767
Malta	0.685	26	42,058
Romania	0.660	27	26,913

Table 7
Two-step GMM estimation results (Digitalization + Innovation Policies).

	Digitalization + Innovation Policies				
	Model 1	Model 2	Model 3	Model 4	Model 5
ln SI_SP$_{t-1}$	0.032***	0.021	0.031***	0.025*	0.024**
ln VA_HC	0.101***				
ln VA_C		0.096***			
ln VA_IDT			0.068***		
ln VA_DPS				0.096***	
ln VA_DESI					0.118***
ln Patents$_{t-1}$	0.020	0.060***	0.051***	0.033	0.034*
ln ICT GBARD	0.044***	0.052***	0.047***	0.044***	0.047***
ln GDP	−0.144***	−0.186***	−0.144***	−0.153***	−0.178***
Hansen chi2(Prob>chi2)	5.81(0.21)	2.31(0.68)	3.82(0.43)	2.37(0.67)	2.30(0.68)
Abond AR(2) z(Prob>z)	0.96(0.33)	1.31(0.19)	1.11(0.26)	1.05(0.29)	1.15(0.25)
Wald chi2 (Prob>chi2)	1342.7(0.00)	1167.1(0.00)	1177.0(0.00)	1445.2(0.00)	1070.1(0.00)
Observations/groups	108/27	108/27	108/27	108/27	108/27
Instruments	10	10	10	10	10

***p-value <0.01, **p-value <0.05, *p-value <0.1.

ones, despite the ongoing and increasingly severe manifestations of climate change (Ramcilovic-Suominen and Pülzl, 2018).

European countries that are still lagging behind should promote the use of renewable energies in their production systems, while supporting recycling efforts. The combination of the two practices will lead to a reduction in the use of natural resources and will curtail emissions. According to Yu et al. (2016) industrialized economies should promote knowledge-intensive as a way to reduce energy consumption and carbon emissions.

In the second stage of this research, the SI_PS indicator is used as a dependent variable and a lagged independent variable in a panel data estimation incorporating the different components of digitalization. Table 7 shows the results of the five models estimated using two-step GMM, also including indicators of the innovation policies adopted by European countries. The coefficients have been standardized in order to compare the relative weight of each independent variable in terms of the effect on SP. Furthermore, a number of tests are conducted to confirm the adequacy of the results: the Hansen test confirms that the instruments used are valid and that there is no overidentification problem (Prob>chi2 greater than 0.05); the Arellano-Bond test confirms the absence of second-order serial correlation [AR(2)] (Prob>z greater than 0.05); the number of instruments is smaller than the number of groups (10 instruments and 27 groups); and the Wald test, with a Prob>chi2 of less than 0.05, confirms the correct specification and that the set of indicators explain the dependent variable.

All the models analysed indicate that it has still not been possible to break the link between GDP and sustainability, an issue that has attracted a great deal of debate in the literature (Azam et al., 2021). This strong association is typical of more economically advanced countries, as Alola et al. (2021) have shown for African countries that economic development and technological innovation drive SD.

Secondly, it is worth noting the importance of the different aspects of digitalization for SP, with a positive relationship found between the two concepts. This is valuable information for decision-makers, as the progress made in Industry 4.0 fosters the introduction of green manufacturing practices. Authors such as Demartini et al. (2019), Mondejar et al. (2021) confirm that these technological advances make a positive contribution to environmental sustainability, boosting resource and information efficiency, although it has not been possible to eliminate the negative burden associated with resource use and waste generation. Digitalization plays a role in addressing the serious challenges that humanity faces due to climate change.

Thirdly, it can be seen that innovation has made it possible to overcome the cyclical effects caused by SP. The coefficient for ICT GBARD was found to be positive and significant in all the models analysed, yielding a higher value for SP than in the preceding period. Additionally, patents show similar behaviour in three of the five estimations. The literature confirms that eco-innovation is a key factor in cutting carbon emissions (Ding et al., 2021). Countries seeking to bolster SP should foster innovation policies that encourage the introduction of new, more planet-friendly means of production (Birkie, 2018).

The results obtained when analysing environmental policies are shown below (Table 8). Again, the coefficients have been standardized in order to be able to determine which variable carries the greatest weight when it comes to SP, and all the tests carried out confirm the adequacy of the results.

Table 8
Two-step GMM estimation results (Digitalization + Environmental Policies).

	Digitalization + Environmental Policies				
	Model 1	Model 2	Model 3	Model 4	Model 5
ln SI_SP$_{t-1}$	0.066***	0.062***	0.063***	0.060***	0.062***
ln VA_HC	0.118***				
ln VA_C		0.045***			
ln VA_IDT			0.035***		
ln VA_DPS				0.045***	
ln VA_DESI					0.048***
ln NEPE$_{t-1}$	0.008	0.016***	0.013***	0.010*	0.012**
ln ET	0.023**	0.032**	0.024**	0.028**	0.025**
ln GDP	−0.075***	−0.091***	−0.070***	−0.080***	−0.082***
Hansen chi2(Prob>chi2)	11.79(0.22)	13.62(0.13)	12.32(0.19)	10.85(0.28)	11.68(0.23)
Abond AR(2) z(Prob>z)	0.9(0.36)	0.92(0.36)	0.88(0.38)	0.90(0.36)	0.91(0.36)
Wald chi2 (Prob>chi2)	18,959.29(0.00)	15,277.2(0.00)	16,631.7(0.00)	15,237.3(0.00)	15,510.5(0.00)
Observations/groups	108/27	108/27	108/27	108/27	108/27
Instruments	15	15	15	15	15

***p-value <0.01, **p-value <0.05, *p-value <0.1.

Once again, a country's level of production turns out to be the variable that has the greatest effect on SP, with an inverse relationship found between the two. This is followed by the trend effect corresponding to the SI_PS of the preceding period, and the different aspects of digitalization. The exception is the model where human capital is analysed, where this variable has the greatest influence. The level of environmental taxes reflects a country's position on climate change; results reveal that the levying of these taxes has a positive effect on SP, as does private spending on environmental protection. Decision-makers must assess their stance on climate change, establishing measures that contribute to climate change mitigation. This will enable compliance not only with the SDGs, but also with the agreements adopted by the European Commission in the European Green Pact. In this respect, authors such as Puertas and Marti (2021) conclude that environmental taxes foster the reduction of GHG emissions, and the involvement of companies in the form of expenditure on environmental protection contributes to the development of SP in European countries.

5. Conclusions

The effects of climate change are becoming increasingly visible, not only in terms of disease and loss of human life, but also in terms of significant economic damage that can act as a destabilizing force affecting countries' growth. Close cooperation between the public and private sectors is required to ensure that they work effectively together to facilitate the establishment of a new, more environmentally-friendly production model. The consumption of polluting products such as carbon must be replaced by renewable energies and alternative recycling practices must be adopted in order to reduce GHG emissions and thus guarantee the transition to a new form of manufacturing that ensures countries' SD.

This research focuses only on EU countries, all of which appear to be strongly committed to climate change agreements. The SI proposed here to measure SP reveals that wealth is not a determinant of proactive attitudes towards the introduction of sustainable practices. For example, Luxembourg and Ireland, with a GDP per capita well above the average, lag behind countries such as Estonia and Latvia in terms of SP. Moreover, Malta, which is wealthier than the European average, ranks second to last in the SI_PS.

The analysis of the nexus between SP and digitalization reveals the importance of each and every aspect that defines Industry 4.0. Furthermore, it can be seen that European countries have not yet been able to break the negative link between progress in sustainability and the level of production. However, there is a need to simultaneously bolster innovation and environmental policies in order to intensify and accelerate the conversion of production processes to make them more respectful of the planet.

Despite the clear conclusions drawn, which point to a need for policies that facilitate the mitigation of environmental degradation, this research is not without its limitations. The universe analysed should be broadened to include countries with different economic profiles and environmental stances, in order to determine whether European countries are really making faster progress in their efforts to achieve climate neutrality. The availability of statistical information often makes it difficult to include the most recent years in the analysis, preventing conclusive results from being obtained for developing countries.

It is proposed to continue this line of research by considering the link with other aspects such as the level of education of the country analysed, the conditions for knowledge-intensive industrialized economies, and even the international trade level, with the SP. Countries will also be classified according to their position regarding digital development and SP, in order to be able to examine development models.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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