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Digitalization and carbon footprint: Building a path to a sustainable economic growth

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ABSTRACT

Digitalization is a primary driver of sustainable development. We investigate the impact of digitalization on the carbon footprints of the (national) government sector, households, enterprises, non-governmental organizations, and imported carbon footprints. We use panel data analysis to study the link between digitalization and sustainable economic growth by monitoring digital carbon footprint patterns. Our study results show that digitalization has a positive and statistically significant impact on sustainability development measured by the sustainable development goals (*SDG*). Furthermore, our results support the hypothesis that advancing total factor productivity, referring to green total factor productivity, is critical for meeting *SDGs*. Notably, we determine that the ecological footprint across sectors and countries is diverging, or at best, slowly converging at a pace that is not even close to that required to meet the 2030 *SDGs*. Therefore, policymakers and practitioners must strategically revise sustainability policies to ensure industrial and economic transition and adaptability to climate change and advance economic green growth and sustainable development.

Keywords: Digitalization, carbon footprint, economic growth, sustainability, sustainable development goals

1. Introduction

While previous research has dedicated considerable attention to exploring the impact of digitalization on economic growth and productivity, more comprehensive studies have to focus on the relationship

between digitalization, carbon footprint, and sustainability, particularly at a pan-European level. This study fills this gap by providing empirical evidence regarding the impact of digitalization on sustainability across different sectors within the European Union (EU).

Economies based on digital transformation produce goods and services with lower carbon dioxide (CO₂) emissions (**Hilty, 2008; Malmmodin and Lunden, 2018**), and countries with a significant proportion of advanced digital technology enterprises can attain a path of sustainable growth considerably faster (**Manyika et al., 2013**). However, the extent of digital adoption substantially impacts the carbon footprints of businesses and economies (**Ghisetti et al., 2016**). Countries with moderate digitalization and lower CO₂ emissions, such as Croatia, rely heavily on the service industry (**Croatian Bureau of Statistics, 2018**), and Romania has a low-carbon footprint due to intense land-use change and forestry (**Romanian National Institute of Statistics, 2019**). Although the correlation between trade and digital technology adoption has been demonstrated to be positive, it could certainly be stronger (**Mellouli et al., 2014**). Current literature has to include comprehensive studies regarding the effect of digitalization on carbon footprints and sustainability (**Coroama et al., 2012**).

The digital economy raises the proportion of trade in *GDP*. However, this is not a permanent effect (**Gordon, 2012**). The Netherlands, Cyprus, the Czech Republic, Slovakia, Slovenia, and Spain are prime examples of top EU member countries in digital adoption (**European Commission, 2020**). Sustainable development can be promoted through introducing resource-efficient products, technological inclusiveness, and innovative green technologies into the digital economy (**Bibri and Krogstie, 2017**). Digital foreign direct investment (FDI) policies could facilitate the incorporation of small and medium-sized enterprises (*SMEs*) into global and regional value chains (**UNCTAD, 2017**). Furthermore, sustainable economic expansion can be advanced by improving total factor productivity (*TFP*) (**Syverson, 2017**).

Previous studies have supported the hypothesis that *TFP* in the form of green productivity is crucial for meeting the United Nations 2030 Sustainable Development Goals (*SDGs*). This is particularly relevant for the sustainability of agricultural production (**Gaitán-Cremaschi et al., 2016; Alhassan, 2021**), human capital, and ecological footprints (**Yue et al., 2019; Jebali and Essid, 2020; Bai et al., 2019**). Sectoral divergence can limit energy transitions, requiring green technology adoption, decreased carbon energy intensity, and carbon trade import. This conclusion is also applicable for studies advocating sustainability integration at micro and macro levels as essential to advancing sustainable development (**Hisne et al., 2022; Hermawan et al., 2017; Abdallah et al., 2021; Sherafati et al., 2020; Gupta et al., 2019**). The green agenda must be integrated on micro and macro levels across all sectors to achieve convergence in reducing carbon footprints and ensure feasible and consistent energy transition (**Chun et al., 2019; Zhou et al., 2020; Wang and Wang, 2021; Adedoyin et al., 2020**).

A unique aspect of our study is incorporating multiple digitalization indicators to enhance our comprehension of the interplay between sustainability and digitalization. An assessment comparing these metrics is presented, supported by our selection of the Digital Economy and Society Index (*DESI*) for our research aims. We also accentuate the significance of sectoral variance in adopting digital technologies and consequent influences on associated carbon footprints. This consideration has not been engaged in existing studies, which have typically examined overall economies rather than scrutinizing sectoral differences.

Sustainable economic growth requires energy transition and a decreasing carbon footprint. We investigate the influence of digitalization on carbon footprints at the (national) government sector, household, enterprise, nongovernmental organizations (*NGOs*), and import level. The World

Inequality Database (WID; <https://wid.world>) provides our carbon footprint information. DESI, calculated as the weighted average of the four significant *DESI* variables, functions as a proxy for European digital transformation. Data and time series constraints of the EU Member States DESI from 2016 to 2020. We examine national and individual carbon footprints from EU countries, revealing considerable differences between sectors and countries. Digitalization is found to have the most significant beneficial impact on the *NGO* sector's carbon footprint (reduced CO₂ emissions).

A rising national carbon footprint (Mt CO₂) keeps a nation from advancing sustainable economic growth. The global economy's increasing digitalization is increasing the digital carbon footprint, which is detrimental to sustainable development, presenting a considerable obstacle. A nation's policies and efforts to advance sustainable development can harm financial development. Eliminating operational failures and improving data-centric operating procedures through advanced digitalization can increase sustainability by reducing the carbon footprint. Pooled ordinary least squares OLS may not be the optimal method for best-fit modeling, as CO₂ emissions, digitalization, and sustainability conditions vary significantly among nations.

The effect of *TFP* on sustainability is positive. The influence of total CO₂ emissions on sustainability is also positive. This study uses a oneway fixed (time effect) regression with time effects, demonstrating that the last decade has witnessed greener growth than previous decades, wherein a unit gain in energy efficiency causes an increase in the *SDG* index.

Trade significantly impacts sustainability, with statistically significant trade parameters. Our data sample best fits a one-way fixed regression model with a time effect. The model includes the data well to explain the dynamics and patterns in our data sample. As established by the United Nations in 2015, the 2030 *SDGs* are not currently achievable. Green growth, inclusive growth, and sustainable development depend heavily on *TFP*.

According to our results, increased national carbon footprints have a detrimental impact on sustainability, and the green agenda must permeate all sectors at local and macro levels to achieve convergence in reducing carbon footprints. Economic expansion is required for green growth and sustainable development; however, more effort is needed. Policymakers must move toward advancing sustainable growth policies and reevaluate and strategically revise existing policies. Abrupt “degrowth” through policy shock therapy, which has frequently been used to combat inflation, is not an option for the green transition.

The use of fossil fuels as primary energy sources harms sustainability, particularly for primary fuels. The ratio of fossil fuels in immediate energy consumption decreased from 85 % in 2019 to 82 %. An organized and effective policy framework is essential for advancing the global energy transition and overall green transformation. However, high levels of risk and uncertainty perceived by banks and other financial organizations can be barriers. The direct support of the global banking system continues to emphasize the fossil fuel industry, and financial education regarding the green energy industry, green labels, and environmental levies are required. Nevertheless, more is needed. Digital platforms can lower the carbon footprint of communication and coordination regarding transportation, resource use, and land use (Renn et al., 2021). Additive manufacturing, which can create lighter objects, is the most prevalent approach for lowering carbon footprints related to material use.

Our study bridges the gap in the literature by producing empirical evidence regarding the effect of digitalization on carbon footprints and sustainability. According to previous research, the link between digitalization and advancing the *SDGs* remains inconclusive. Our research validates digitalization as a crucial factor of sustainable development to achieve the 2030 *SDGs*. The findings empirically support the no-digital rebound effect on the macro level in Europe. Furthermore, our study confirms the

positive impact of digitalization on advancing sustainable development. The empirical results contribute to research on digitalization and sustainability at sectoral and macro levels.

The remainder of this paper is structured as follows. We next present the relevant literature on digitalization and carbon footprints after introducing the topic. We then detail the data sources and research framework in section, supplying the study results in the subsequent section. The final two sections discuss our study results and summarize our findings with concluding remarks.

2. Literature review

The impact of digitalization on micro and macro carbon footprints lacks solid empirical knowledge. However, one body of research, based on the hypothesis that globalization and digitalization have contributed to a spike in the carbon footprint, has demonstrated a negative link between digitalization and carbon footprint (**Sharma and Dash, 2022; Wilson, 2019**).

Another strand of literature focuses on digitalization as a primary driver in protecting against environmental degradation and achieving sustainable development targets (**Ma et al., 2022; Burinskiene and Seržante, 2022; Patsavellas and Salonitis, 2019; Zhu et al., 2022a, b**).

Table 1 presents a survey of the empirical literature on the digitalization-carbon footprint relationship.

Table 1 shows that research on digitalization and sustainability is limited and constrained to panel data studies of a few countries. The research has to include more extended time series data and intra/intersectoral studies across sectors and nations to examine country-specific sectoral and time effects too.

Digitalization and social media can potentially overcome the challenges of communicating time-sensitive disaster information in realtime. Integrating digitalization concepts, mobile devices, and big data analytics with traditional early warning systems could significantly improve disaster response time and expedient action (**Balogun et al., 2020**). Improved digital economy development has influenced the CO₂ emissions efficiency of China's industrial sector (**Xie and Zhang, 2022**). Research results (**Wu et al., 2021**) have also demonstrated that the internet has the potential to enhance green total factor energy efficiency, which can be accomplished by reducing resource mismatches, improving technological innovation, and upgrading the industrial structure. A precise identification system to track emerging ecological environment concerns in real-time and foster coordinated expansion of the digital and green economy is urgently needed (**Hao et al., 2023**). A comprehensive study of 60 countries revealed that increased digital economy development has a positive effect on the quantity of CO₂ emissions but a negative effect on intensity (**Dong et al., 2022a, b**).

In the case of Africa, **Solomon and van Klyton (2020)** study the burgeoning literature on this topic by separately examining the effects of individual, company, and government information and communications technology (*ICT*) usage on economic growth. The authors found that digitalization's impact on sustainability in Africa differs across individual, company, and government *ICT* practices. In China, regional heterogeneity characterizes the CO₂ emissions reduction effect of the digital economy, with the result being more pronounced in eastern regions than central, western, or northern regions (**Yi et al., 2022**). The technologies of the fourth industrial revolution can enhance manufacturing productivity and performance. Some studies contend that digital technologies can significantly contribute to energy conservation. Others argue that adopting technology may necessitate increased energy use and CO₂ emissions (**Lim and Son, 2022**).

Table 1 Literature survey on digitalization and carbon footprint nexus.

Source	Methods	Findings
Belkhir and Elmeligi (2018)	Detailed and rigorous analysis of ICT global carbon footprint Comparison of ICT GHGE with worldwide GHGE levels	ICT GHGE could exceed 14 % of worldwide GHGE by 2040. Smart phones' footprint will surpass desktops, laptops, and displays.
Lange et al. (2020)	Analytical model used to investigate effects Combines empirical and theoretical findings from debates.	Digitalization increases energy consumption overall Effects 2 and 4 tend to decrease energy consumption
Santarius et al. (2020)	Literature review on green IT" and "ICT for green"	Further research is needed to improve empirical implications. Methods are needed to interrelate micro and macro effects.
Patsavellas and Salonitis (2019)	Content analysis	Lack of assessment framework for CO ₂ emissions Need for evaluation of digital transformation in manufacturing
Gomez-Trujillo and Gonzalez-Perez (2022)	Systematic literature review Content analysis	Digital transformation is a driver and predecessor of sustainability. Companies need to balance economic, environmental, and social impacts.
Nikmehr et al. (2021)	Outlines requirements for achieving digitalization Discusses various approaches to developing a digitalization strategy	Digitalization can improve construction performance and sustainability outcomes. A comprehensive digitalization strategy is required for success.
Wilson et al. (2020)	Conducted a directed and selective literature review Carried out empirical research in real-world settings	Consumers can play a role in climate change mitigation. Digital consumer innovations challenge mainstream consumption practices.
Li et al. (2021)	Introduced digital economy into Solow growth model Fixed-effects regressions on global panel data	Inverted U-shaped relationship between CO ₂ emissions and digital economy Governments should adopt hedging policies and promote digital economy for environmental protection.
Sareen and Haarstad (2021)	Examining the ubiquitous unfolding of digitalization Studying digitalization as a real socio-material phenomenon	Digitalization is a key driver of transformative environmental change and innovation. Scholars must critically engage with digitalization's impact on low-carbon transitions.
Liu et al. (2022)	Panel data analysis	Digital technology can significantly reduce carbon emissions by improving energy efficiency, promoting green technology innovation, and promoting virtual agglomeration.
Wang et al. (2022a, b)	Literature review and analysis	Digital technology is crucial in promoting cities' green and low-carbon transformation, especially in carbon-trading and smart cities.
Zhang et al. (2022)	Policy analysis	Improving resource allocation, seizing the digital economy dividend, and investing in science and technology innovation are recommended to promote low-carbon development.

Table 1 (continued)

Source	Methods	Findings
Lahouel et al. (2021)	Econometric analysis	Digital technology has a significant impact on energy consumption and CO2 emissions, with both positive and negative effects depending on the context.
Wang et al. (2023a, b)	Regression analysis	Digital technology, such as e-commerce and artificial intelligence, can promote the reduction of urban carbon emission intensity.
Chen et al. (2022)	Spatial-temporal analysis and spatial Durbin model	Green technology innovation has a significant impact on reducing carbon emissions, especially in cities with high levels of green total factor productivity.
Zhang and Wei (2019)	Survey analysis	Information and communication technology can reduce enterprise energy consumption, contributing to energy efficiency and carbon emission reduction.
Al-mulali and Binti Che Sab (2012)	Panel data analysis	Energy consumption has a positive impact on economic growth and financial development but also leads to high pollution consequences.
Dong et al. (2022a, b)	Multi-regional input-output	The manufacturing of computer, electronic, and optical products accounts for a significant portion of global ICT implied carbon emissions.
Li et al. (2021)	Theoretical and empirical analysis	The digital economy has the potential to reduce CO2 emissions through various channels, including energy efficiency and green total factor productivity.
Shan et al. (2022)	Statistical analysis	City-level carbon emission peak is influenced by various factors, including economic structure, energy structure, and urbanization level.
Zhang (2023)	Econometric analysis	Digital transition can contribute to carbon neutrality by reducing carbon emissions and promoting sustainable development.
Zhu et al. (2022a, b)	Inter-country input-output model	The ICT industry has a significant impact on carbon emissions, particularly in the manufacturing of computer, electronic, and optical products.
Feng and Shanthikumar (2018)	Conceptual analysis	Big data and digital technology can facilitate organizational evolution and contribute to sustainable development.
Zhang et al. (2021c)	Empirical analysis	The digital economy has a positive impact on high-quality economic development, including environmental sustainability.
Zhao et al. (2023)	Econometric analysis	The digital economy can increase green total factor productivity, contributing to sustainable development and carbon emission reduction.

Source: Authors' research.

Theoretical and review research (Kunkel and Tyfield, 2021; Ufua et al., 2021; Onyango and Ondiek, 2021) has investigated the importance of digital technology adoption and digitalization, advancing the theoretical body of knowledge on digitalization.

Empirical studies on the link between digitalization and the SDGs have focused on specific digitalization effects, including supply chain digitization (Nayal et al., 2021), digital inequality (Rothe et al., 2022), industrialization (Kunkel and Tyfield, 2021), digital entrepreneurship (Herman, 2022), health (Asi and Williams, 2018), digital government (Janowski, 2016; Saner et al., 2020), smart cities (Allam and Jones, 2021), and education (Anasi et al., 2018), finding positive implications regarding the impact of digitalization on sustainability. However, digital rebound research demands caution in setting up a clear, positive empirical link between digitalization and sustainability (Sorrell, 2009a, b; Wiesmeth, 2021; Lange et al., 2020; Pereira et al., 2020; Lange et al., 2021), considering the discrepancies in previous studies.

The findings indicate that the digital economy reduces the growth of CO₂ emissions significantly and that this effect remains significant despite changes in the magnitude of the coefficient when control variables are gradually increased (Zhu et al., 2022a, b). The *ICT* component will decrease power consumption, meaning that *ICT* has the potential to cut household electricity demand in the short term (Adha et al., 2022). The other studies (Wang et al., 2022a, b ... chýbajú ďalšie) have investigated the impact of sub-indicators of the digital economy (infrastructure, social impact, innovation and application, and economic growth and jobs) on CO₂ emissions, identifying the reasons for reducing the effects of digital emissions and providing governments with clear strategic directions for developing the digital economy. Technological progress in the energy sector can effectively reduce CO₂ emissions with a hysteresis effect (Jin et al., 2017).

Our study contributes to the scholarly body of literature by seeking to unravel the link between digitalization and sectoral carbon footprints.

3. Data and methods

This study examines the empirical link between digitalization and sustainable economic growth. The path to sustainable economic growth is led by energy transition and a carbon footprint moving toward zero. The strategic development and implementation of efficient economic policies to advance the sustainable global economy requires empirical (quantitative) knowledge of the primary determinants of sustainable growth. It is safe to assume that the link between digitalization and carbon footprints differs across sectors; thus, we examine the impact of digitalization on carbon footprints at total (national), government sector, household, business sector (investment), *NGO*, and imported CO₂ emissions levels. The data on carbon footprints are obtained from the *WID*, measuring related carbon footprints from 2016 to 2020. Although data on carbon footprints are available in longer time series, we are limited by data availability on digitalization. Many globally acknowledged indicators of digitalization are reported by government institutions or professional business analytics companies. The differences in methodologies used for collecting and assessing the level of digitalization are significant. After comparing different digitalization indicators (Table 2), we determine that the *DESI* is appropriate for conducting our analysis.

The *DESI* measures the progress of the digital economy toward digital transformation, offering country profiles and thematic chapters at a European level of analysis across critical digital areas, providing EU member states with the research needed to identify areas that require priority action. See European Commission *DESI* methodological note (2022) for details and the methodological parameters used for the *DESI* (human capital, connectivity, integration of digital technology, and digital public services).

We use *DESI* data from 2016 to 2020 as a proxy for digital transformation in Europe, calculated as the weighted average of the four main *DESI* dimensions with selected weights. Since the sample selection and aggregation methodology are beyond the scope of this study, we do not discuss each component or dimension. *DESI* is an appropriate indicator for monitoring member states' progress toward advancing a digital society, which is the intent of this study. *DESI* is limited to data for EU member states and time series from 2016 to 2020; thus, our sample is constructed within this data framework.

We use a comprehensive global data sample from the *WID* for the carbon footprint data (**Chancel, 2022**), with data on EU countries' national and individual carbon footprints (time series data from 2016 to 2020) to determine the following:

- Total direct emissions from production and institutional sectors of a given country under production-based accountancy (*NAT*).
- Governments' total emissions (*GOV*).
- Households' total emissions (*HOUSE*).
- Investment-related emissions (*GFCE*).
- Nongovernmental organizations' total emissions (*NGO*).
- National net imports of CO₂ emissions (*IMPORT*).

For detailed explanations of methodology and sample variables definition, see (**Chancel, 2022**). All carbon footprint variables are expressed in per capita and constant local purchasing power parity at 2021 prices.

This study investigates the following hypotheses:

- H_1 : A causal link exists between digitalization and sustainability (Granger causality);
- H_2 : This link is generally positive;
- H_3 : However, the strength and impact of the link depends on economic structure (natural resources availability; natural resources management), institutional economics (differences across economic sectors), energy import dependence, technological progress, digital adoption, financial development, energy transition, and urbanization.

Table 2 Summary of different digitalization indicators.

Indicator	Source
Digital Business Indicator	World Bank, 2020a
Digital Adoption Index	World Bank, 2020b
Digital Economy Report	UNCTAD, 2020
OECD Digital Economy Outlook	OECD, 2020
The Digitalisation Index	BBVA Research, 2020
IMD World Digital Competitiveness Ranking	IMD World Competitiveness Center, 2020
STOXX Global Digitalisation Index	STOXX Ltd., 2020
Digital Intelligence Index	The Fletcher School at Tufts University and Mastercard, 2020
Digital Economy and Society Index (DESI)	European Commission, 2020

Source: Authors' research.

We use panel data analysis to examine the link between digitalization and sustainability by monitoring digital carbon footprint patterns for 27 EU member states from 2016 to 2020. Since the time dimension of the sample is minimal, we do not use dynamic panel data modeling since the system generalized method of moments requires a large sample approach. We apply pooled data regression with group fixed effects. Emissions per capita include emissions from domestic consumption, governmental and private investments, imports and exports of carbon-containing goods, and services traded with the rest of the world (Francois Burq, 2021; Chancel, 2022). The data measure definitions and sources are as follows:

- $dt = DESI$; level of digitalization in the society, $DESI$ (<https://digital-strategy.ec.europa.eu/en/policies/desi>);
- $tfp = TFP$ index 2015 = 100, *AMECO* database (https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-databases/ameco-database_en);
- $totalCO_2$ = national CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- $govCO_2$ = governments' CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- $houseCO_2$ = households' CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- $investCO_2$ = investments' CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- $ngoCO_2$ = nongovernmental organizations' CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- $impCO_2$ = net imports of CO_2 footprint, total population, per-capita emissions ($Mt CO_2$), *WID* (<https://wid.world>);
- GDP = gross domestic product, GDP per capita (constant 2015 US\$), World Bank national accounts data and OECD National Accounts data files;

- *energy* = primary energy consumption per capita, Gigajoule per capita, BP stats review 2022 (<https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf>);
- *trade* = the sum of exports and imports of goods and services measured as a share of GDP, World Bank national accounts data and OECD National Accounts data files;
- *finance* = proxy for financial development, gross portfolio equity and investment fund shares liabilities / GDP, International Financial Statistics, International Monetary Fund;
- *FDI* = foreign direct investment, net inflow (% of GDP), World Development Indicators (<https://databank.worldbank.org/source/world-development-indicators>);
- *Urban* = urbanization rate, urban population (% of the total population), Our world in data (<https://ourworldindata.org/urbanization>);
- *SDG* = sustainability indicator, *SDG* index (Sachs et al., 2022).

DESI has been employed in research endeavors exploring digital advancement and its implications across various nations. The studies of **Oryani et al. (2021)** and **Gomez-Barroso and Feijoo (2016)** exemplify such investigations.

Environmental economics research has frequently employed CO₂ footprint data from the *WID*. For instance, **Sperling and Yeh (2010)**, **Balsalobre-Lorente et al. (2018)**, and **Chancel (2022)** used this data to examine carbon inequality.

The unique approach of our study is merging these two variable types to evaluate the influence of digitalization on CO₂ footprints across various sectors.

We seek to determine the association between digitalization level and sustainable development while controlling for other available factors (technological progress, carbon footprint, output, energy demand, trade, financial development, *FDI*, and urbanization). We use the following panel regression model:

$$sdg_{it} = \beta_0 + \beta_1 tfp_{it} + \beta_2 totalCO2_{it} + \beta_3 gGDP_{it} + \beta_4 energy_{it} + \beta_5 trade_{it} + \beta_6 finance_{it} + \beta_7 dt_{it} + v_i + \epsilon_{it} \quad (1)$$

where *SDG* (sustainability) is the dependent variable; *TFP*, carbon footprint, *GDP*, primary energy consumption, trade share in the *GDP*, financial development, and digitalization are regression variables; v_i is countries' effect (cross-sectional effect); and ϵ_{it} is the error term.

Regarding the exclusion of time and spatial/country effects in the model, we made a conscious decision to do so since our primary concern was with cross-sectional variation over time to examine the differences between countries over time as opposed to changes within. Our study primarily endeavors to explore the influence of digitalization on sustainability in diverse countries, with less emphasis on the spatial progression in each country. We argue that this approach will offer a clearer understanding of the overall impact of digitalization on sustainability on a global level. We use Stata 17 commercial package for panel regression estimation.

To estimate the impact of regression variables on sustainability, we use the following (Greene, 2017) pooled regression model (no time or country effect):

$$y_{it} = \mathbf{x}_{it}\boldsymbol{\beta} + \mathbf{z}_i\boldsymbol{\alpha} + \epsilon_{it} \quad (2)$$

where z_i is a constant term.

To account for heterogeneity (country effects), we use the following fixed effect model with the group-specific constant term (fixed effect within regression):

$$y_{it} = \mathbf{x}_{it}'\boldsymbol{\beta} + \alpha_i + \varepsilon_{it} \quad (3)$$

and the following random effect model (generalized least squares, random constant term):

$$\begin{aligned} y_{it} &= \mathbf{x}_{it}'\boldsymbol{\beta} + E[\mathbf{z}_i'\boldsymbol{\alpha}] + \{\mathbf{z}_i'\boldsymbol{\alpha} - E[\mathbf{z}_i'\boldsymbol{\alpha}]\} + \varepsilon_{it} \\ &= \mathbf{x}_{it}'\boldsymbol{\beta} + \alpha + u_i + \varepsilon_{it}, \end{aligned} \quad (4)$$

For the financial development indicator, missing data for Ireland and Luxembourg, we use domestic credit to the private sector (% of the GDP) from the same financial database.

4. Results

Our previous research (in print) demonstrated that carbon footprints differ significantly across sectors and countries; therefore, we expect that the impact of digital transformation on carbon footprints will vary between sectors and countries. Investigating the differences in *DESI* impact on sectors' and countries' carbon footprint, we seek to isolate the primary determinants accounting for the observed heterogeneity. **Fig. 1** illustrates the relationship between digital transformation measured by the *DESI* and national carbon footprint emissions.

The relationship between digital economy level and carbon footprint differs between the entire economy (*totalCO₂*), the government sector (*govCO₂*), households (*houseCO₂*), investment-related carbon footprint (*investCO₂*), the nongovernmental sector (*govCO₂*), and net CO₂ imports (*impCO₂*). Moreover, the impact of digital transformation is unequal across sectors (government, *NGOs*) and activities (investments, imports). Digitalization has the most significant positive effect on the *NGO* sector's carbon footprint (less CO₂ emissions). The household sector is progressing in digital technology adoption, driving CO₂ emissions down (medium impact). In contrast, the government sector does not register a significant decrease in CO₂ emissions associated with a higher level of digitalization, and investment activities exhibit a negative correlation between investments and the resulting carbon footprint. The interaction of the business sector investments with digitalization leads to a decrease in CO₂ emissions. As for investment activities, countries with a higher level of digitalization have less imported CO₂ emissions (embedded in traded goods). Economies actively promoting digital transformation, with solid digital industries, produce goods and services with lower embedded levels of CO₂. European firms adopting advanced digital technology produce significantly less CO₂ emissions. Countries with a larger share of progressive digital technology enterprises move significantly more quickly toward a sustainable growth path.

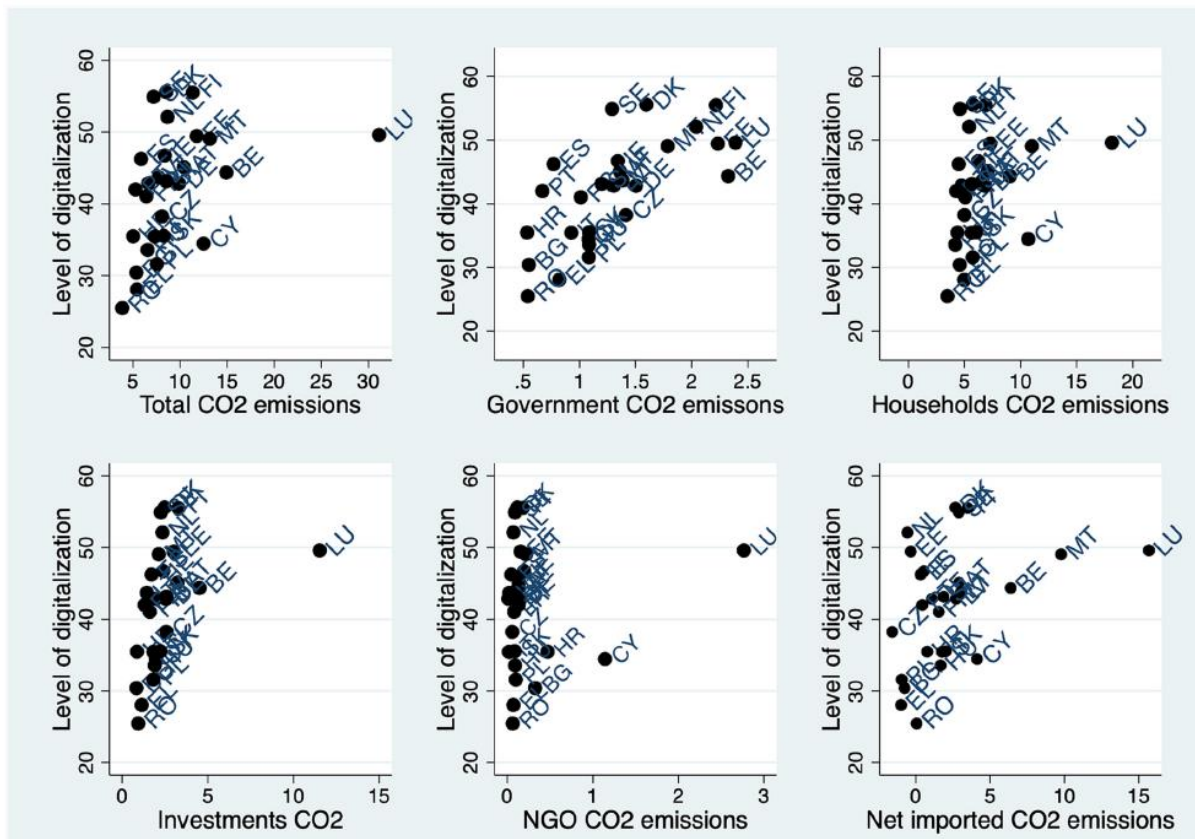


Fig. 1. Relationship between the digital economy and carbon footprint. Source: Authors' research.

Fig. 1 has an outlier country on the right, which is Luxembourg. It is also notable that countries relying on the service sector (such as Croatia) register medium levels of digitalization with a lower level of CO₂ emission. The trajectory of digital adoption significantly affects firms' and economies' carbon footprints (European Investment Bank, 2022). Countries below the EU average level of digital adoption register higher CO₂ emissions (i.e., Luxembourg). An interesting case is Romania, which is below the EU intermediate level of digital adoption (low *DESI* index) but has a low registered carbon footprint. This results from intensive land-use and forestry changes, bringing down greenhouse gas emissions (*GHGE*) in Romania by — 22.9 million tons (CO₂ equivalent).

Moreover, Romania mirrors the decoupling effect between *GDP* growth and consumption/production-based CO₂ emissions. Globalization drives an increasing digital carbon footprint (Sharma and Dash, 2022); however, industry 4.0 and big cloud data centers' carbon footprint patterns remain unsolved (Patsavellas and Salonitis, 2019). Carbon neutrality should be actively promoted by leveraging the Internet of Things and big data; however, measuring digital carbon footprints is arduous, requiring new business model development (green management) and energy management models (Olvera, 2022).

Compared with traditional industries, the digital sector has significantly lower production and distribution costs (Chowdhury, 2010). Nevertheless, the carbon footprint of the internet has not yet been assessed or adequately measured (Agarwal et al., 2020; Baliga et al., 2009). In terms of CO₂ emissions, the daily weighted average of internet video streaming is 51 times more than a 14-hour flight (Batmunkh, 2022). Rising competition between streaming services like Netflix, Disney+, and HBO Max could effectively push sustainability targets beyond 2050, and the same effect has been found for the *ICT* industry. By 2040, the contribution of *ICT* to the global carbon footprint might increase from

approximately 1 %-1.6 % in 2007 to more than 14 % of the worldwide GHGE in 2016 levels (Belkhir and Elmeligi, 2018).

The summary and descriptive statistics (correlation analysis in Fig. 2) echoes the link revealed in Fig. 1. (See Fig. 3.)

The correlation analysis in Fig. 2 shows that advanced digitalization is associated with significantly heterogeneous technological progress (tfp). Countries with high levels of digital adoption (i.e., Sweden, The Netherlands, Denmark, and Finland) register higher total productivity growth. Latvia and Romania (two outliers) have significant TFP growth, with Latvia being slightly above the EU average rate of digital adoption at 64 % and Romania at the bottom at 53 % (European Investment Bank, 2022). Notably, digital adoption is only sometimes associated with increasing TFP; therefore, digital adoption is a necessary but insufficient condition for TFP growth. The fitting linear regression line shows a weak negative correlation between DESI and TFP growth (top left panel graph).

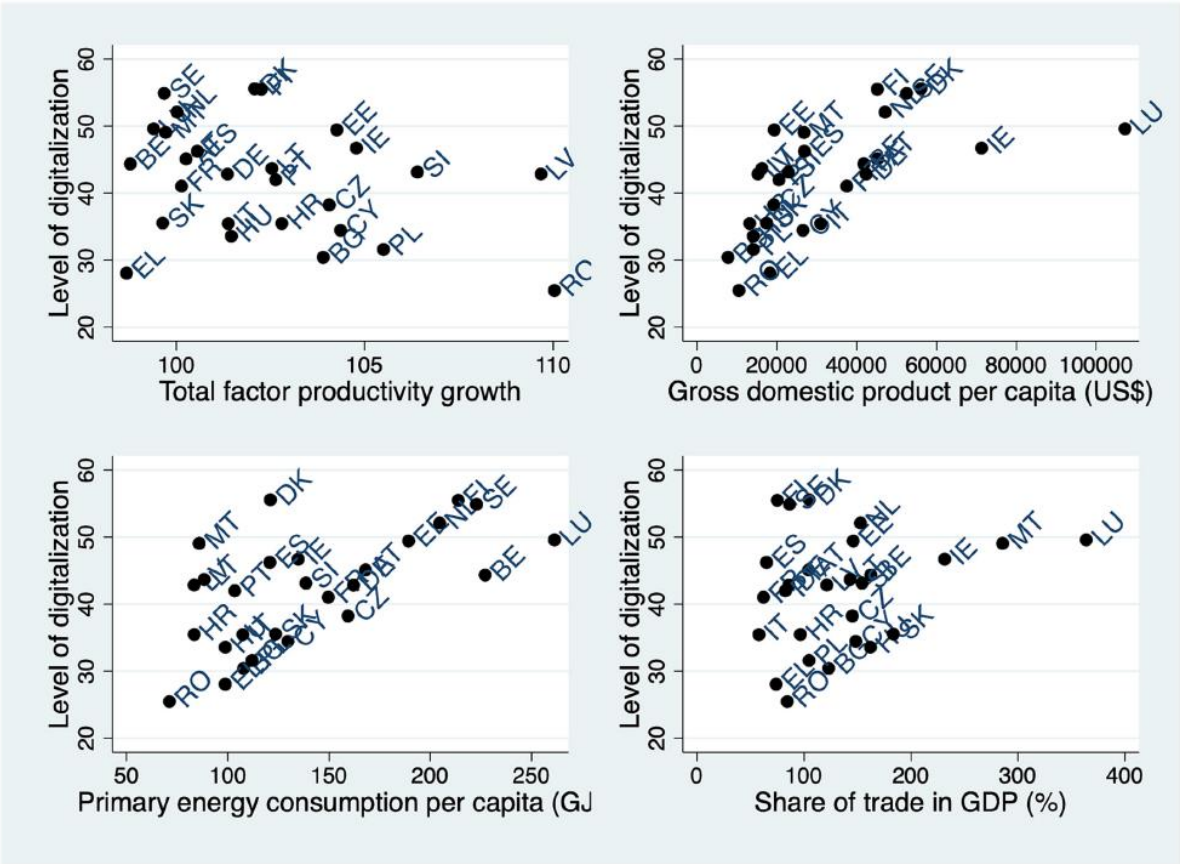


Fig. 2. Relationship Between Digitalization and TFP, GDP, Energy, and Trade. Source: Authors' research.

Digital adoption shows a positive correlation with GDP growth. Countries with a higher level of digital adoption achieve faster output growth; however, Ireland and Luxembourg are exceptions to the rule. Both countries register digital adoption rates below the EU average, while still having the highest GDP per capita. Once again, the digital adoption rate is a prerequisite for economic growth, but other conditions are also needed (top right panel graph).

The relationship between digital technology adoption and primary energy consumption per capita follows Jevon's paradox rule (Sorrell, 2009a, b; Polimeni and Iorgulescu, 2018; Alcott et al., 2012; York and McGee, 2015; Sorrell, 2009a, b). Fitted linear regression reveals a strong positive correlation

between the level of digitalization and primary energy consumption. A rise in digital adoption is followed by an increase in primary energy consumption (bottom left panel).

The link between digital technology adoption and trade is also positive, but the correlation is less pronounced. The digital economy increases the share of trade in the *GDP*, but the effect is transitory and impermanent, and a threshold effect is evident in Fig. 2 (bottom right panel).

We find a positive association between a country's level of digitalization and financial development. More developed financial markets and systems contribute to faster and more straightforward digitalization of an economy (top left panel). The Netherlands is a perfect example of being among the top EU members in digital adoption, along with Cyprus, the Czech Republic, Slovakia, Slovenia, and Spain.

FDI is essential for digital adoption (top right panel) but requires a well-designed *FDI* policy framework, which is currently absent in the EU. Development agencies must identify, target, and attract desirable investors in the digital economy while establishing or upgrading digital tools and infrastructure. Agencies and policymakers should develop an *FDI* strategy that enables and encourages investment. A digital *FDI* policy could facilitate *SMEs'* integration into global and regional value chains (Satyanand, 2021).

The urbanization process is essential to advancing economic digitalization (bottom left panel). A strong positive correlation is revealed between the urbanization process and digital adoption, wherein countries with a higher rate of urbanization foster significant digitalization processes.

The bottom right panel illustrates the relationship between digitalization and European sustainable development. Countries with significant digital adoption rates tend to achieve sustainable development and meet required *SDGs*. Furthermore, the digital economy drives sustainable development through resource-efficient products, technological inclusion, and new green technologies, accelerating global progress toward the 2030 *SDGs* (Satyanand, 2021).

Table 3 presents a statistical summary of our data sample.

Source: Authors' research.

We do not use logarithm transformation on the data since many variables are expressed as index points or shared on a scale from 0 to 1 or 0 to 100. In addition, we do not present the results for the impact of *FDI* and urbanization rate on sustainable development as the effect is not statistically significant.

Table 4 presents the results of the pooled regression estimation.

The pooled regression results exhibit the expected variable signs and the impact on the countries' sustainable development (*SDG*). The model fits the data well with adjusted $R^2 = 0.69$, explaining about 70 % of the countries' sustainable development dynamics variation. The variables in our model are all statistically significant at standard estimation levels (marked by asterisks in the table). The *tfp* variable measures the impact of change in a country's *TFP* on the *SDG* index. *TFP* has a positive effect on a country's sustainability. A 1 % increase in *tfp* raises the value of *SDG* by 0.085 index points. A rise in *TFP* moves the economy closer to the sustainable economic growth path.

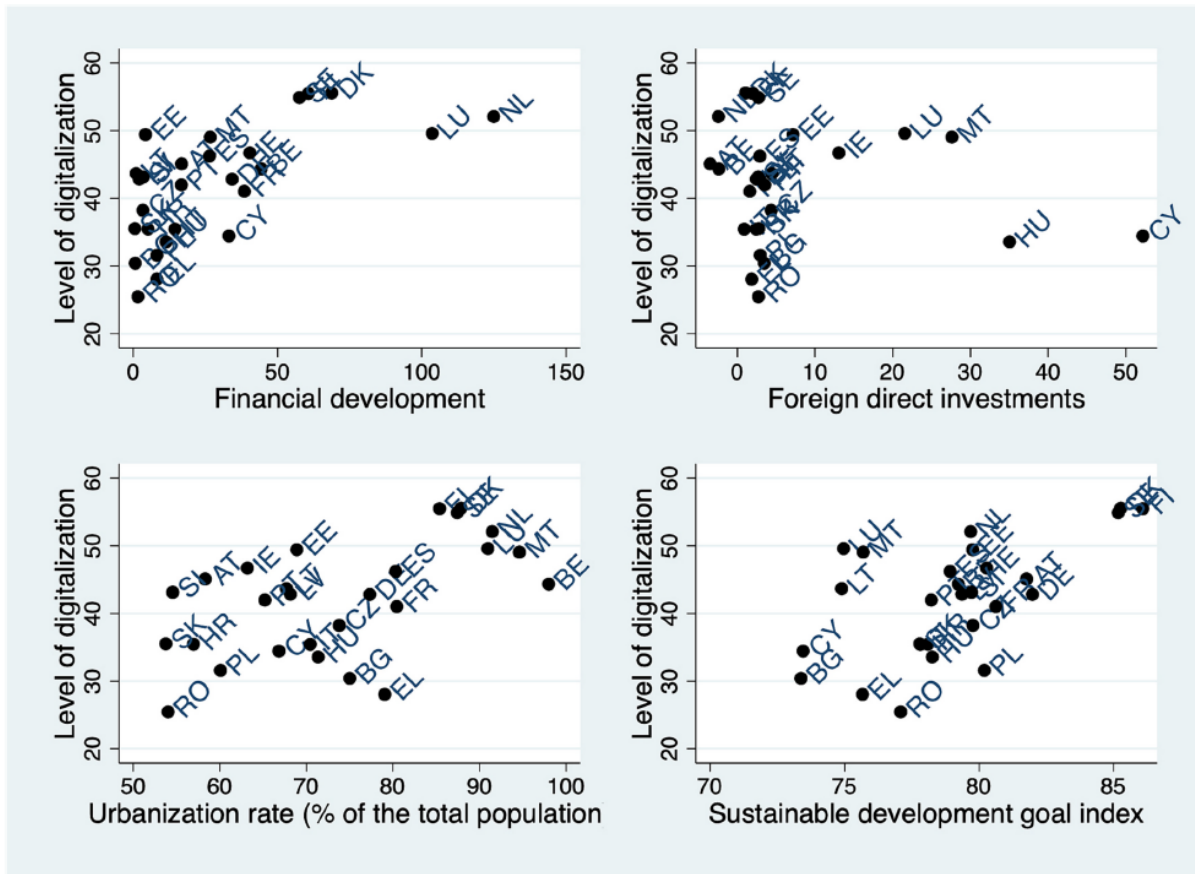


Fig. 3. Correlation analysis between digitalization and financial development, Source: Authors' research.

Table 3 Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
dt	135	41.944	9.171	21.4	62.8
tfp	135	102.459	3.901	91.8	114.9
totalCO2	135	9.103	5.105	3.587	32.298
govCO2	135	1.316	0.55	0.497	2.483
houseCO2	135	6.438	2.955	3.216	18.842
investCO2	135	2.456	1.967	0.754	11.974
ngoCO2	135	0.26	0.539	0.014	2.871
impCO2	135	2.236	3.579	-1.916	16.623
gdp	135	32,094.478	21,735.753	7341.048	108,570.03
energy	135	139.505	51.067	69.013	274.292
trade	135	133.557	69.189	55.368	380.104
finance	135	28.032	32.327	0.402	139.365
fdi	135	7.256	24.443	-41.651	163.044
urban	135	73.375	12.944	53.726	98.079
sdg	135	79.003	3.263	72.166	86.424

Source: Authors' research.

A rise in the total national carbon footprint ($Mt CO_2$), as surmised, moves a country away from the sustainable economic growth path. A unit rise in total CO_2 ($Mt CO_2$), the *SDG* index falls by -0.317 index points. The impact grows in strength significantly with the rise of total CO_2 . A 10 ($Mt CO_2$)

increase in carbon footprint per capita causes *SDG* to fall by 3.17 index points on the *SDG* scale. These results are expected and demonstrate that total national CO₂ emissions must decline drastically to meet the *SDGs* and targets. The data in our sample shows we are far from such a scenario. A significant obstacle is the world economy becoming globally digitalized, and the digital carbon footprint is rising, harming sustainable development.

Increasing output measured in the GDP causes a rise in the national carbon footprint, as shown in **Table 2**. A 10,000US\$ increase in the *GDP* per capita causes *SDG* to increase by 0.67 index points. Because of increasing energy efficiency and falling energy intensity, the **International energy agency (IEA)'s (2021)** World Energy Balances report shows that energy intensity has declined since 1990.

Primary energy consumption has a positive link with the *SDG* variable. A one unit increase in primary energy consumption (Gigajoules per capita) results in an *SDG* rise of 0.025 index points. Countries with significant primary energy use (rich in resources) (i.e., Finland, Sweden, The Netherlands, and Estonia) register higher levels of sustainability.

Table 4 Pooled OLS regression results.

sdg	Coef.	St.Err.	t-Value	p-Value	[95 % Conf	Interval]	Sig
tip	0.085	0.043	1.99	0.049	0.001	0.17	**
totalCO ₂	-0.317	0.071	-4.48	0.000	-0.0456	-0.177	***
gdp	0.000067	0.706	4.58	0.000	0.000	0.000	***
energy	0.025	0.005	4.73	0.000	0.015	0.036	***
trade	-0.0017	0.004	-4.40	0.000	-0.024	-0.009	***
finance	-0.022	0.008	-2.59	0.011	-0.038	-0.005	**
dt	0.182	0.023	8.07	0.000	0.137	0.226	***
Constant	62.693	4.58	13.69	0.000	53.631	71.755	***
Mean dependent var		79.003		SD dependent var.			3.263
R-squared		0.710		Number of obs			135
F-test		44.482		Prob > F			0.000
Akaike crit. (AIC)		550.177		Bayesian crit. (BIC)			573.419

*** $p < .01$, ** $p < .05$, * $p < .1$. Source: Authors' research.

A positive correlation exists between the *SDG* index and primary energy consumption. Transitioning to sustainability demands resources, and energy is the most essential factor in the production function. Moreover, to accelerate the sustainability transition, we must also fast-track the energy transition.

Trade harms a country's sustainable development path, with a negative link between the *SDG* index and trade share in the GDP. A unit change in trade share in *GDP* (1 % change) causes a decline in the sustainability index of — 0.017 index points. Countries with a significant share of trade in the *GDP* register high net CO₂ imports (Luxembourg, Malta, and Belgium). A 10 % increase in trade would cause a decline in *SDG* of — 0.17 index points. Countries that are net emissions importers (importing more CO₂ in goods than exported) face more constraints to fast and successful energy transition under globalization and trends.

Financial development harms a country's sustainable development policies and efforts. Such results are exciting but expected. Our results show that a unit change in financial development (gross portfolio equity and investment fund shares liabilities / *GDP*) results in *SDG* deterioration by —0.022 index points. Nevertheless, the financial industry and the largest banks still invest aggressively in industries that are reliant on carbon fuels. One study found that financial markets were crucial for the low-carbon energy transition in Germany from 2000 to 2017. Data for 26 countries from 1996 to 2018 revealed close links between environmental policy and financial sector development, higher green technology

adoption costs, debt margin for renewable and nonrenewable energy firms, and high-rise default risk (Egli et al., 2019; Kempa et al., 2021).

Our results demonstrate the positive impact of digitalization on sustainability, supporting H_1 and revealing a positive Granger causality link between digitalization and sustainability. Digitalization improves sustainability by decreasing carbon footprint, reducing operational failures, and improving data-centric operating processes. Companies focus on external thinking, simplifying procedures, minimizing wasteful work, and creating value and sustainable development to drive agility and resilience. An increase in dt by one index point raises SDG by 0.18 index points. The impact is positive and significant, reflecting the importance of digitalization for achieving sustainability. Digitalization is an important driver of sustainability and the net-zero sustainability strategy.

Since carbon emissions, digitalization, and sustainability conditions differ significantly across countries, better approaches may be available for best-fit modeling than pooled OLS regression; therefore, before moving to the fixed effect regression model, we test for fixed effects in the data using F - and Wald tests. The Wald test after fitting the least squares dummy variable model and the F -test after running the fixed effect model reject the null hypothesis of no fixed effects in the data ($F(26, 101) = 108.33$, $\text{Prob} > F = 0.0000$). Therefore, the fixed group effect model (one-way) and fixed time effect model (one-way) are preferred to the pooled OLS because of the correct estimation (country/ group effect inclusion).

Table 5 presents the results of the fixed group effect model (one-way) and fixed time effect model (one-way) modeling.

Fixed effect regression results support the results obtained from the pooled OLS (expected signs and relationships). The one-way fixed effect regression (country fixed effect) results are presented in Table 4 under country effects.

The impact of TFP on sustainability is positive, with a coefficient of 0.033, but the parameter is not statistically significant at an acceptable significance level. The same holds for total CO_2 emissions' impact on sustainability, with a parameter of 0.033, not satisfying the standard statistical acceptance level. As shown in **Table 3**, the results for other parameters in the model (GDP, primary energy consumption, trade, and financial development) are also not statistically significant. The two parameters at acceptable statistical significance levels are the constant term (impact of other variables outside the model) and digitalization. Although the country fixed effect F -test (21.55) is statistically significant, a one-way fixed country effect regression does not fit the data well. This is expected since fixed effect regression assumes time-invariant characteristics across countries in the panel. The same calculation for the time effect, in the absence of the country effect, gives us an $F(7, 123)$ statistic of 45.22. Comparing the time-to-country impact on the fixed regression model indicates that the time effect is considerably more significant than the country effect, producing a better fit for our data. One-way fixed (time) effect regression results are presented in **Table 3** under time effects results.

The fixed time effect model produces statistically significant parameters and a higher adjusted R^2 , which is better fit for explaining our data sample. The impact of TFP on sustainability is statistically significant with a parameter of 0.104. With an index point TFP increase, sustainability improves with a SDG index increase by 0.104 index points. Thus, a TFP rise is favorable for achieving $SDGs$. Conversely, as expected, an increase in total CO_2 emissions harms sustainability. A unit increase in ($MT CO_2$) emissions significantly lowers the SDG index by -0.309 (statistically significant parameter).

Output increase (GDP) raises sustainability if accompanied by increased energy efficiency. Countries with solid digital penetration and GDP move toward sustainable economic growth more rapidly and

can reach most *SDG* targets. Fixed regression results demonstrate a causal link between sustainability and national output measured by *GDP*. Growth in the last decade has become “greener” than before. A 10,000US\$ increase in the *GDP* per capita causes *SDG* to increase by 0.64 index points.

Table 5 Fixed effects regression results with fixed country and time period effect.

Model specification	Parameter estimation								R ²	s ²
	Const	β ₁ (tfp)	β ₂ (total CO ₂)	β ₃ (GDP)	β ₄ (energy)	β ₅ (trade)	β ₆ (finance)	β ₇ (dt)		
No effect	62.69***	0.085**	-0.317***	0.000067***	0.025***	-0.017***	-0.022**	0.182***	0.71	3.254
Group means	57.77***	0.127	-0.296*	0.000064*	0.024*	-0.016*	-0.028	0.215***	0.65	3.417
Country effects	72.92***	0.033	-0.0060	0.000038	0.002	-0.009	-0.001	0.106***	0.60	
Time effects	59.65***	0.104**	-0.309***	0.000064***	0.023***	-0.017***	-0.023***	0.215***	0.72	

*** $p < .01$, ** $p < .05$, * $p < .1$. Source: Authors' research.

Fiscal austerity following the financial crises of 2008 and 2012 caused growth to slow down in the last years, 2016-2020. With increased awareness of the necessity for energy transition and meeting the sustainability targets, a greener *GDP* had a positive effect on sustainability, as our findings demonstrate. The estimated fixed regression parameter for energy efficiency (0.023) supports this thesis. A unit increase in energy efficiency results in a statistically significant 0.023 index point rise in *SDG*. The combined effects of greener *GDP* and energy transition (increased energy efficiency) positively impact *SDG*.

Trade harms sustainability, with statistically significant trade parameters (-0.017). Our results show that the impact of trade is a notable constraint to meeting SDGs. Exactly how trade impacts sustainability is open to debate since previous studies have provided inconclusive results (**Xu et al., 2020**). The fact that the financial sector (specifically, banking) still strongly supports fossil fuel industries is reflected in the negative impact of the finance parameter on *SDG* (-0.023). A 1 % increase in gross portfolio equity and investment fund shares liabilities / *GDP* decreases *SDG* by -0.023 index points.

Digitalization positively affects *SDGs*, with a statistically significant parameter of 0.215. *SDG* rises by 0.215 index points for an index point increase in *DESI*; therefore, the impact of digitalization on sustainability is a significant, and sizable increase in *DESI* can result in considerable improvement in sustainability conditions. For example, in Sweden, the *DESI* index in the last five years of our study period increased by 13 index points. At the same time, according to our one-way fixed regression model, sustainability in Sweden measured by *SDG* has improved by 2.8 index points during the same period, indicating a noteworthy effect of digitalization on sustainability in Sweden.

To test for the possibility of using the random effect model as the most appropriate to fit our data, we apply the Breusch-Pagan Lagrange multiplier (*LM*) test (**Breusch and Pagan, 1980**). Test results for random effects fail to reject the null hypothesis of no panel effect. Therefore, we can conclude that the random effect model is inappropriate for estimating our data sample since the *LM* test Prob > chibar2 = 1.0000, confirming that the one-way fixed (time) regression model best fits our research data.

This finding also supports the robustness of our results since we use pooled *OLS* and fixed effects to examine the data. We also use random effect regression to test fixed effect model robustness (**Table 6**), obtaining results that are similar to those of our fixed regression.

Table 6 Random effects regression results with random country and time period effect.

Model specification	Parameter estimation							R ²	s ²	
	Const	β_1 (tfp)	β_2 (total CO ₂)	β_3 (GDP)	β_4 (energy)	β_5 (trade)	β_6 (finance)			β_7 (dt)
No effect	62.69***	0.085**	-0.317***	0.000067***	0.025***	-0.017***	-0.022**	0.182***	0.71	3.254
Group means	57.77***	0.127	-0.296*	0.000064*	0.024*	-0.016*	-0.028	0.215***	0.65	3.417
Country effects	73.64***	0.018	-0.114	0.000032	0.011**	-0.016***	0.0009	0.098***	0.68	
Time effects	62.69***	0.085**	-0.317***	0.000067***	0.025***	-0.017***	-0.022**	0.182***	0.72	

*** $p < .01$, ** $p < .05$, * $p < .1$. Source: Authors' research.

5. Discussion

Here, we next present the primary determinants of sustainable development from 2016 to 2020. Our sample is limited by the data availability and timing of the *DESI* index that we use as a proxy to measure the level of digitalization in society and its effect on sustainability. Reaching sustainability targets by 2030, as set by the United Nations in 2015, does not appear to be possible, and we revealed a significant undershooting in the scenarios, indicating critical miscalculation or unrealistic overreach in the 172,030 *SDGs*. Our study affirms the role of digitalization as one of the primary drivers of sustainable development. The empirical results support the thesis of digitalization as a vital driver of sustainability.

We examine the main global determinants of sustainability, focusing on *TFP*, national carbon footprint, *GDP*, primary energy consumption, trade, financial development, and digitalization. Statistical testing indicates that a one-way fixed regression model with a time effect best fits our sample data. With an adjusted R^2 of 0.72, we show that the model fits the data well and explains the dynamics and patterns in our data sample.

The results show that *TFP* has a positive and statistically significant impact on sustainability development measured by *SDG*. First, *TFP* is an essential factor in green, inclusive growth and sustainable development. Green *TFP* is critical for sustainable development (Zhang et al., 2021a, b). Second, *TFP* is linked to sustainable development through energy efficiency (Santos et al., 2021; Haider and Bhat, 2020; Sohag et al., 2021; Song et al., 2022). This finding particularly holds for sustainability in agricultural production (Gaitán-Cremaschi et al., 2016; Alhassan, 2021). Third, sustainable growth and development are linked to *TFP* through human capital and ecological footprints (Yue et al., 2019; Al-Ayouty and Hassaballa, 2020; Jebali and Essid, 2020; Bai et al., 2019). Our results support the hypothesis that green *TFP* is critical for achieving the *SDGs*.

Transforming ecological footprints is an essential driver of sustainability; however, our analysis shows that ecological footprint convergence differs across sectors and countries, indicating a crucial constraint to sustainability targeting that policymakers must address. Our results demonstrate that the ecological footprint across sectors and countries is diverging, or at least slowly converging at a pace that is not even close to that required to reach the 2030 *SDGs*. The same divergence across sectors limits energy transitions, necessitating green technology adoption, decreased carbon energy intensity, and carbon trade import (Bai et al., 2019). Our results confirm that increased national carbon footprint harms sustainability. The same conclusion holds in studies indicating that sustainability integration at micro and macro levels is crucial for advancing sustainable development (Hisne et al., 2022; Hermawan et al., 2017; Abdallah et al., 2021; Sherafati et al., 2020; Gupta et al., 2019). The green agenda must be integrated across all sectors at micro and macro levels to achieve convergence in carbon footprint reduction and ensure feasible and consistent energy transition (Chun et al., 2019; Zhou et al., 2020; Wang et al., 2020; Adedoyin et al., 2020).

Economic growth is necessary for all nations and sectors; however, more is needed to advance green growth and achieve sustainable development. Adopting green technology and investment is impossible without raising income and wages, which requires an increase in *GDP*, not an unconditional one (Coscieme et al., 2020). Our study results support the hypothesis of the necessity of increased growth to support energy and green growth transitions. It is not possible to attain sustainability and green growth without primarily expanding an economy's capacity for change by rising economic growth rates. National output in the form of the *GDP* is an essential driver of sustainability, but its role in sustainable development must be reassessed (Adrangi and Kerr, 2022; Fioramonti et al., 2019; Pais et al., 2019; Giannetti et al., 2015; Barroso et al., 2016). Although positive *GDP* growth is an essential aspect of green growth transitions, policymakers must endeavor to achieve such growth by reassessing and moving growth policies toward advancing sustainable practices. Sudden degrowth in the form of a policy shock therapy, which is sometimes used to fight inflation, is not an option for the green transition that the 2030 *SDGs* seek to achieve.

As firmly stated by Keen et al. (2019), energy is a primary factor of production. Following the logic of the role of the *GDP* in the green transition, the same applies to that of energy. Primary energy consumption that is primarily based on fossil fuels inhibits the sustainability transition. The share of fossil fuels in primary energy consumption remains at 82 %, which decreased compared with 85 % in 2019 (Petroleum, 2022). Just as with green transition, energy transition requires a strategically planned and efficient policy framework as it is impossible to achieve decarbonization through degrowth or halting primary energy consumption. Achieving decarbonization will require massive investment in green infrastructure, green technology adoption, and establishing a sustainable standard of living. This transition necessitates stable and relatively high individual purchasing power since green technologies and energy are more costly to average consumers and entrepreneurs. Our study results corroborate this hypothesis, confirming that primary energy consumption affects *SDGs*. In 2021, primary energy consumption increased by 6 %. In relation to our empirical results, this means that sustainability increased by 0.14 index points in 2021 and primary energy also increased by 0.14 index points. Primary energy is essential for production to achieve energy transition (Keen, 2020; Islam and Hasanuzzaman, 2020; Golas et al., 2019; Cantarero, 2020; Zoundi, 2017; Ding et al., 2021).

Our study results confirm that trade negatively affects sustainable development and its impact differs across countries and sectors. The effect of trade on sustainability is noteworthy and must be addressed when designing *SDG* policies. Xu et al. (2020) revealed that while trade increases scores for environmental *SDGs* in affluent nations, it diminishes them in underdeveloped countries, with distant commerce contributing more to scores than trade between neighboring nations. The causality between trade and sustainable development still demands investigation (Gopalakrishnan and Nawani, 2020; Pradhan et al., 2017; Dogan and Seker, 2016; Alola et al., 2019; Nathaniel and Khan, 2020). We reveal a negative link between trade and sustainability; however, further research is required since previous studies have shown differences in causality across developing and developed economies. An economy's structure and technological advancement and its geopolitical position as a trade partner affect the influence of trade on sustainability (Xu et al., 2020). As Xu et al. (2020) showed, the impact of trade differs across *SDGs* and must be revisited to determine the role of trade in *SDGs*.

Green financing is imperative for future sustainable development. The cost of money, debt, equity, and assets for green investors is commonly 30 % greater than for non-green investors. This is represented in the increased amount of return on equity and assets and the expected internal rate of return on green investments that is necessary for such endeavors. Banks and other financial institutions are hesitant to take this chance because of high risk and uncertainty. Instead, they finance investments in fossil fuel-reliant businesses with guaranteed profit, reduced risk, and government

support through subsidies. Financial education in the green energy businesses, green labels, and environmental levies are required, but more is needed to financially support the green energy industry. The contemporary global financial system predominantly supports fossil fuel industries and is reluctant to enter green financing markets as reflected in our study results, which reveal a negative relationship between financial and sustainable development. Financial markets, regulations, and financial instruments must be transformed to adequately support green financing (Zhang et al., 2021; Nasir et al., 2021; Wang and Wang, 2021; Tang et al., 2022; Xu and Tan, 2020).

Finally, our study reveals digitalization's positive, significant role in sustainable development. Digital technology adoption improves firms' agility and flexibility, advancing an economy's capacity to address and overcome uncertain business cycles and shocks (Renn et al., 2021). The case of the COVID-19 pandemic proves this (Bai et al., 2021; Chiaramonti and Maniatis, 2020; Nieuwenhuijsen, 2021; Rahimi et al., 2021; Soldatos et al., 2021).

Digital platforms can facilitate communication and coordination to reduce carbon footprints in mobility, material use, and land use (Renn et al., 2021). One of the defining features of the new digital innovation era is replacing energy and materials with information. This Industry 4.0 (Fritzsche et al., 2018) transition can help optimize production processes to limit material and energy consumption in digitalized production. For example, the systemic optimization of the kinematic properties of large robot fleets (Riazi et al., 2017) and flexible adaptation of industrial loads to renewable energy (Ma et al., 2020) are innovative strategies that can increase energy efficiency through the application of digital technologies. Additive manufacturing is the most common strategy for reducing material consumption, which can also be used to produce lighter products and may elicit additional material savings during the use phase (Rinaldi et al., 2021).

Our research also emphasizes the potential bias in investigating the relationship between digitalization and sustainability if accurate indicators are not employed. By using the official *DESI* database and a comprehensive global study on *SDGs*, we ensure the robustness of our findings.

6. Conclusion

Our study contributes significantly to understanding the importance of digital technology adoption and digitalization and its effects on sustainability and advancing the 2030 *SDGs*. As digitalization and sustainability indicators are complex phenomena that present challenges for accurate monitoring and explanation, our research adds valuable empirical knowledge to the existing literature that has previously found the link between digitalization and *SDGs* inconclusive.

Our study provides empirical support indicating the absence of a macro level digital rebound effect in Europe, revealing the positive impact of digitalization on sustainable development in the EU. These findings have significant implications for policymakers responsible for formulating European sustainability development policy frameworks.

A practical implication of our study highlights the need to examine the links between digitalization and sustainability at inter- and intrasectoral levels as the effects differ across sectors. Our study also emphasizes the potential bias that can arise when examining the relationship between digitalization and the 2030 *SDGs* if accurate indicators are not used. To mitigate this, we employ the official *DESI* database and a comprehensive global study on *SDGs*, adding robustness to our results.

Nevertheless, our study does have limitations, including sample constraints (observations were limited to European countries) and time limitations due to the constricted data availability from *DESI*.

Moreover, we cannot account for dynamic effects in the panel or apply more advanced panel regression techniques. Despite these limitations, robustness testing of our results confirms that our findings are not biased or compromised.

Future research should include larger samples, expanded regional considerations, and inter- and intra-sectoral data, which will enable a more comprehensive understanding of digitalization and sustainability employing data mining and estimation modeling techniques. The impact of digitalization on sustainability requires additional investigation at micro, meso, macro, and global levels. In this context, our study contributes to the macro analysis of digitalization and sustainability significantly.

We provide empirical support confirming no macro level digital rebound effect in Europe, validating the positive impact of digitalization on sustainable development in Europe. The results are insightful for policymakers in charge of establishing European sustainability development policy frameworks. A practical implication of our study is the need to examine the link between digitalization and sustainability on inter- and intra-sectoral levels since the effects differ across sectors. We also highlight potential bias of examining the relationship between digitalization and SDGs if accurate indicators are not used, employing the official *DESI* database and a comprehensive study of *SDGs*, providing robust results.

Our study results are limited by sample constraints (including only EU countries) and time limitations (due to *DESI*'s limited data availability). Moreover, we cannot account for dynamic effects in the panel, long-term research, or persistence, stationarity, and cointegration, or apply more advanced panel regression techniques. However, robustness testing of our results shows that the results of our study are not biased or compromised due to objective sample or modeling technique limitations in our study.

Our study contributes to the macro analysis of digitalization and sustainability. Future research should focus on larger samples (more countries), examining regional aspects, and considering inter- and intrasectoral data, which will allow more comprehensive digitalization and sustainability research linking data mining and estimation modeling techniques. Investigations regarding the impact of digitalization on sustainability should focus on micro, meso, macro, and global considerations.

References

Abdallah, M., Shabib, A., Alozi, A.R., Hussein, M., 2021. A multisectoral assessment framework for the carbon footprint of integrated sustainable development systems in Dubai. *Environ. Dev. Sustain.* 24, 6246-6270. <https://doi.org/10.1007/s10668-021-01700-w>.

Adedoyin, F.F., Alola, A.A., Bekun, F.V., 2020. An assessment of environmental sustainability corridor: the role of economic expansion and research and development in EU countries. *Sci. Total Environ.* 713, 136726 <https://doi.org/10.1016/j.scitotenv.2020.136726>.

Adha, R., Hong, C.-Y., Agrawal, S., Li, L.-H., 2022. ICT, carbon emissions, climate change, and energy demand nexus: the potential benefit of digitalization in Taiwan. *Energy Environ.* 0958305X221093458 <https://doi.org/10.1177/0958305X221093458>.

Adrangi, B., Kerr, L., 2022. Sustainable development indicators and their relationship to GDP: evidence from emerging economies. *Sustainability* 14, 658. <https://doi.org/10.3390/su14020658>.

Agarwal, A., Agarwal, K., Misra, G., 2020. Is Internet becoming a Major Contributor for Global Warming The Online Carbon Footprint!! December 2020 02, pp. 217-220. <https://doi.org/10.36548/jitdw.2020.4.005>.

Al-Ayouty, I., Hassaballa, H., 2020. Towards sustainable development: measuring environmental Total factor productivity in Egypt. *Eur. J. Sustain. Dev.* 9, 55. <https://doi.org/10.14207/ejsd.2020.v9n2p55>.

Alcott, B., Giampietro, M., Mayumi, K., Polimeni, J., 2012. The Jevons Paradox and the Myth of Resource Efficiency Improvements. Routledge. <https://doi.org/10.4324/9781849773102>.

Alhassan, H., 2021. The effect of agricultural total factor productivity on environmental degradation in sub-Saharan Africa. *Sci. Air.* 12, e00740 <https://doi.org/10.1016/j.sciaf.2021.e00740>.

Allam, Z., Jones, D.S., 2021. Future (post-COVID) digital smart and sustainable cities in the wake of 6G: digital twins, immersive realities and new urban economies. *Land Use Policy* 101, 105201. <https://doi.org/10.1016/j.landusepol.2020.105201>.

Al-mulali, U., Binti Che Sab, C.N., 2012. The impact of energy consumption and CO2 emission on the economic growth and financial development in the Sub Saharan African countries. *Energy* 39 (1), 180-186. <https://doi.org/10.1016/j.energy.2012.01.032>.

Alola, A.A., Bekun, F.V., Sarkodie, S.A., 2019. Dynamic impact of trade policy economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Sci. Total Environ.* 685, 702-709. <https://doi.org/10.1016/j.scitotenv.2019.05.139>.

Anasi, S.N., Ukangwa, C.C., Fagbe, A., 2018. University libraries-bridging digital gaps and accelerating the achievement of sustainable development goals through information and communication technologies. *World J. Sci. Technol. Sustain. Dev.* 15, 13-25. <https://doi.org/10.1108/wjstsd-11-2016-0059>.

Asi, Y.M., Williams, C., 2018. The role of digital health in making progress toward Sustainable Development Goal (SDG) 3 in conflict-affected populations. *Int. J. Med. Inform.* 114, 114-120. <https://doi.org/10.1016/j.ijmedinf.2017.11.003>.

Bai, C., Du, K., Yu, Y., Feng, C., 2019. Understanding the trend of total factor carbon productivity in the world: insights from convergence analysis. *Energy Econ.* 81, 698-708. <https://doi.org/10.1016/j.eneco.2019.05.004>.

Bai, C., Quayson, M., Sarkis, J., 2021. COVID-19 pandemic digitization lessons for sustainable development of micro-and small- enterprises. *Sustain. Prod. Consum.* 27, 1989-2001. <https://doi.org/10.1016/j.spc.2021.04.035>.

Baliga, J., Hinton, K., Ayre, R., Tucker, R.S., 2009. Carbon footprint of the Internet. *Telecommun. J. Australia* 59, 5.1-5.14. <https://doi.org/10.2104/tja09005>.

Balogun, A.-L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., Arshad, A., Salehi, P., 2020. Assessing the potentials of digitalization as a tool for climate change adaptation and sustainable development in urban centres. *Sustain. Cities Soc.* 53, 101888 <https://doi.org/10.1016/j.scs.2019.101888>.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., Farhani, Sahbi, 2018. How economic growth, renewable electricity and natural resources contribute to CO2 emissions?, 113, 356-367. <https://doi.org/10.1016/j.enpol.2017.10.050>.

Barroso, A., Chaves, C., Martins, F.V., Branco, M.C., 2016. On the possibility of sustainable development with less economic growth: a research note. *Environ. Dev. Sustain.* 18, 1399-1414. <https://doi.org/10.1007/s10668-016-9802-y>.

Batmunkh, A., 2022. Carbon footprint of the most popular social media platforms. *Sustainability* 14, 2195. <https://doi.org/10.3390/su14042195>.

BBVA Research, 2020. The Digitalisation Index. BBVA. Available at: https://www.bbva.com/wp-content/uploads/2018/07/Report_DigitalisationIndex.pdf.

Belkhir, L., Elmeligi, A., 2018. Assessing ICT global emissions footprint: trends to 2040 & recommendations. *J. Clean. Prod.* 177, 448-463. <https://doi.org/10.1016/j.jclepro.2017.12.239>.

Bibri, S.E., Krogstie, J., 2017. Smart sustainable cities of the future: an extensive interdisciplinary literature review. *Sustain. Cities Soc.* 31, 183-212. <https://doi.org/10.1016/j.scs.2017.02.016>.

Breusch, T.S., Pagan, A.R., 1980. The Lagrange multiplier test and its applications to model specification in econometrics. *Rev. Econ. Stud.* 47, 239. <https://doi.org/10.2307/2297111>.

Burinskiene, A., Serzante, M., 2022. Digitalisation as the indicator of the evidence of sustainability in the European Union. *Sustainability* 14, 8371. <https://doi.org/10.3390/su14148371>.

Cantarero, M.M.V., 2020. Of renewable energy democracy, and sustainable development: a roadmap to accelerate the energy transition in developing countries. *Energy Res. Soc. Sci.* 70, 101716. <https://doi.org/10.1016/j.erss.2020.101716>.

Chancel, L., 2022. Global carbon inequality over 1990-2019. *Nat. Sustain.* 5, 931-938. <https://doi.org/10.1038/s41893-022-00955-z>.

Chen, H., Yi, J., Chen, A., Peng, D., Yang, J., 2022. Green technology innovation and CO₂ emission in China: evidence from a spatial-temporal analysis and a nonlinear spatial durbin model. *Energy Policy* 172, 113338. <https://doi.org/10.1016/j.enpol.2022.113338>.

Chiaramonti, D., Maniatis, K., 2020. Security of supply, strategic storage and Covid19: which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? *Appl. Energy* 271, 115216.

Chowdhury, G., 2010. Carbon footprint of the knowledge sector: what's the future? *J. Doc.* 66, 934-946. <https://doi.org/10.1108/00220411011087878>.

Chun, J., Kim, C.-K., Kang, W., Park, H., Kim, G., Lee, W.-K., 2019. Sustainable management of carbon sequestration service in areas with high development pressure: considering land use changes and carbon costs. *Sustainability* 11, 5116. <https://doi.org/10.3390/su11185116>.

Coroama, V.C., Hilty, L., M., Birtel, M., 2012. Effects of internet-based multiple-site conferences on greenhouse gas emissions. *Telematics Inform.* 29 (4), 362-374. <https://doi.org/10.1016/j.tele.2011.n.006>.

Coscieme, L., Mortensen, L.F., Anderson, S., Ward, J., Donohue, I., Sutton, P.C., 2020. Going beyond gross domestic product as an indicator to bring coherence to the Sustainable Development Goals. *J. Clean. Prod.* 248, 119232. <https://doi.org/10.1016/j.jclepro.2019.119232>.

Croatian Bureau of Statistics, 2018. Statistical Yearbook of the Republic of Croatia 2018.

Ding, Q., Khattak, S.I., Ahmad, M., 2021. Towards sustainable production and consumption: assessing the impact of energy productivity and eco-innovation on consumption-based carbon dioxide emissions (CCO₂) in G-7 nations. *Sustain. Prod. Consum.* 27, 254-268. <https://doi.org/10.1016/j.spc.2020.11.004>.

Dogan, E., Seker, F., 2016. The influence of real output renewable and non-renewable energy, trade and financial development on carbon emissions in the top renewable energy countries. *Renew. Sust. Energ. Rev.* 60, 1074-1085. <https://doi.org/10.1016/j.rser.2016.02.006>.

Dong, F., Hu, M., Gao, Y., Liu, Y., Zhu, J., Pan, Y., 2022a. How does digital economy affect carbon emissions? Evidence from global 60 countries. *Sci. Total Environ.* 852, 158401 <https://doi.org/10.1016/J.SCITOTENV.2022.158401>.

Dong, K., Wang, J., Taghizadeh-Hesary, F., 2022b. Assessing the embodied CO₂ emissions of ICT industry and its mitigation pathways under sustainable development: a global case. *Appl. Soft Comput.* 131, 109760 <https://doi.org/10.1016/J.AS0C.2022.109760>.

Egli, F., Steffen, B., Schmidt, T.S., 2019. Learning in the financial sector is essential for reducing renewable energy costs. *Nat. Energy* 4, 835-836. <https://doi.org/10.1038/s41560-019-0482-3>.

European Commission, 2020. Digital Economy and Society Index (DESI). Available at: <https://digital-strategy.ec.europa.eu/en/policies/desi>.

European Investment Bank, 2022. The Story of Digital Adoption Significantly Affects Firms' and Economies' Carbon Footprints. Report. European Investment Bank. <https://www.eib.org/en/publications/20220215-eib-project-carbon-footprint-methodologies>.

Feng, Q., Shanthikumar, J.G., 2018. How research in production and operations management may evolve in the era of big data. *Prod. Oper. Manag.* 27 (9), 1670-1684. <https://doi.org/10.1111/poms.12836>.

Fioramonti, L., Coscieme, L., Mortensen, L.F., 2019. From gross domestic product to wellbeing: how alternative indicators can help connect the new economy with the sustainable development goals. *Anthropocene Rev.* 6, 207-222. <https://doi.org/10.1177/2053019619869947>.

Francois Burq, L.C., 2021. Aggregate carbon footprints on WID.world. In: WID.world Technical Note 2021/03. World Inequality Lab.

Fritzsche, K., Niehoff, S., Beier, G., 2018. Industry 4.0 and climate change exploring the science-policy gap. *Sustainability* 10, 4511. <https://doi.org/10.3390/su10124511>.

Gaitán-Cremaschi, D., Meuwissen, M.P.M., Lansink, A.G.J.M.O., 2016. Total factor productivity: a framework for measuring agri-food supply chain performance towards sustainability. *Appl. Econ. Perspect. Policy* 39, 259-285. <https://doi.org/10.1093/aep/ppw008>.

Ghisetti, C., Mancinelli, S., Mazzanti, M., Zoli, M., 2016. Financial barriers and environmental innovations: evidence from EU manufacturing firms. *Clim. Pol.* 17, S131-S147. <https://doi.org/10.1080/14693062.2016.1242057>.

Giannetti, B.F., Agostinho, F., Almeida, C.M.V.B., Huisingh, D., 2015. A review of limitations of GDP and alternative indices to monitor human wellbeing and to manage eco-system functionality. *J. Clean. Prod.* 87, 11-25. <https://doi.org/10.1016/j.jclepro.2014.10.051>.

Golas, J., Zarbska, K., Nosek, K., Szramowiat-Sala, K., Marczak, M., 2019. Energy and environment as the foundations for sustainable development. *Environ. Sci. Pollut. Res.* 26, 8359-8361. <https://doi.org/10.1007/s11356-019-04299-8>.

Gomez-Barroso, J.L., Feijoo, C., 2016. A conceptual framework for the digital economy. In: Mansell, R., et al. (Eds.), International Encyclopedia of Digital Communication and Society. Wiley-Blackwell, Chichester, UK.

Gomez-Trujillo, A.M., Gonzalez-Perez, M.A., 2022. Digital transformation as a strategy to reach sustainability. *Smart Sustain. Built Environ.* 11 (4), 1137-1162. <https://doi.org/10.1108/SASBE-01-2021-0011>.

Gopalakrishnan, B.N., Nawani, S., 2020. Trade and sustainable development goals: a multiscenario analysis for India and other Asia-Pacific countries. In: Hazra, S., Bhukta, A. (Eds.), *Sustainable Development Goals: An Indian Perspective*. Springer International Publishing, Cham, pp. 253-267. https://doi.org/10.1007/978-3-030-42488-6_17.

Gordon, R.J., 2012. Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds [WWW Document]. NBER. URL. <https://www.nber.org/papers/w18315> (accessed 7.27.23).

Greene, W.H., 2017. Econometric Analysis. Pearson.

Gupta, D., Ghersi, F., Vishwanathan, S.S., Garg, A., 2019. Achieving sustainable development in India along low carbon pathways: macroeconomic assessment. *World Dev.* 123, 104623 <https://doi.org/10.1016/j.worlddev.2019.104623>.

Haider, S., Bhat, J.A., 2020. Does total factor productivity affect the energy efficiency. *Int. J. Energy Sect. Manag.* 14, 108-125. <https://doi.org/10.1108/ijesm-11-2018-0010>.

Hao, X., Li, Y., Ren, S., Wu, H., Hao, Y., 2023. The role of digitalization on green economic growth: does industrial structure optimization and green innovation matter? *J. Environ. Manag.* 325, 116504 <https://doi.org/10.1016/j.jenvman.2022.116504>.

Herman, E., 2022. The interplay between digital entrepreneurship and sustainable development in the context of the EU digital economy: a multivariate analysis. *Mathematics* 10, 1682. <https://doi.org/10.3390/math10101682>.

Hermawan, Marzuki, P.F., Abduh, M., Driejana, R., 2017. The sustainable infrastructure through the construction supply chain carbon footprint approach. *Procedia Eng.* 171, 312-322. <https://doi.org/10.1016/j.proeng.2017.01.339>.

Hilty, L.M., 2008. Information_Technology_and_Sustainability: Essays on the Relationship between ICT and Sustainable Development, 1. BoD - Books on Demand.

Hisne, F.I.J., Hughes, K.D., Su, L.Y., 2022. Carbon footprint assessment for decarbonisation strategy development. In: Day 3 Thu March 24, 2022. OTC. <https://doi.org/10.4043/31534-ms>.

IMD World Competitiveness Center, 2020. IMD World Digital Competitiveness Ranking. Available at: <https://www.imd.org/wcc/world-competitiveness-center-rankings/world-digital-competitiveness-rankings-2020/>.

International energy agency (IEA), 2021. World Energy Balances: Overview. IEA Paris. <https://www.iea.org/data-and-statistics/data-product/world-energy-balances>.

Islam, M.M., Hasanuzzaman, M., 2020. Introduction to energy and sustainable development. In: Energy for Sustainable Development. Elsevier, pp. 1-18. <https://doi.org/10.1016/b978-0-12-814645-3.00001-8>.

Janowski, T., 2016. Implementing sustainable development goals with digital government aspiration-capacity gap. Gov. Inf. Q. 33, 603-613. <https://doi.org/10.1016/j.giq.2016.12.001>.

Jebali, E., Essid, H., 2020. Total factor environmental productivity in the Mediterranean countries: a MalmquistLuenberger Index Approach. Int. J. Appl. Manag. Technol. 19 <https://doi.org/10.5590/ijamt.2020.19.1.05>.

Jin, L., Duan, K., Shi, C., Ju, X., 2017. The impact of technological progress in the energy sector on carbon emissions: an empirical analysis from China. Int. J. Environ. Res. Public Health 14, 1505. <https://doi.org/10.3390/ijerph14121505>.

Keen, S., 2020. The appallingly bad neoclassical economics of climate change. Globalizations 18, 1149-1177. <https://doi.org/10.1080/14747731.2020.1807856>.

Keen, S., Ayres, R.U., Standish, R., 2019. A note on the role of energy in production. Ecol. Econ. 157, 40-46. <https://doi.org/10.1016/j.ecolecon.2018.11.002>.

Kempa, K., Moslener, U., Schenker, O., 2021. The cost of debt of renewable and nonrenewable energy firms. Nat. Energy 6, 135-142. <https://doi.org/10.1038/s41560-020-00745-x>.

Kunkel, S., Tyfield, D., 2021. Digitalisation sustainable industrialisation and digital rebound Asking the right questions for a strategic research agenda. Energy Res. Soc. Sci. 82, 102295 <https://doi.org/10.1016/j.erss.2021.102295>.

Lahouel, B.B., Zaied, Y.B., Song, Y., Yang, G., 2021. Corporate social performance and financial performance relationship: a data envelopment analysis approach without explicit input. Financ. Res. Lett. 39, 101656 <https://doi.org/10.1016/j.frl.2020.101656>.

Lange, S., Pohl, J., Santarius, T., 2020. Digitalization and energy consumption. Does ICT reduce energy demand? Ecol. Econ. 176, 106760 <https://doi.org/10.1016/J.ECOLECON.2020.106760>.

Lange, S., Kern, F., Peuckert, J., Santarius, T., 2021. The Jevons paradox unraveled: a multi-level typology of rebound effects and mechanisms. Energy Res. Soc. Sci. 74, 101982 <https://doi.org/10.1016/j.erss.2021.101982>.

Li, X., Liu, J., Ni, P., 2021. The impact of the digital economy on CO2 emissions: a theoretical and empirical analysis. Sustainability 13 (13), 7267. <https://doi.org/10.3390/SU13137267>.

Lim, H., Son, K.-Nyeong, 2022. Does digitalization really improve environmental and energy sustainability? Evidence from industry 4.0 Technologies in the Manufacturing Sectors in South Korea. SSRN Electron. J. <https://doi.org/10.2139/ssrn.4083083>.

Liu, J., Yu, Q., Chen, Y., Liu, J., 2022. The impact of digital technology development on carbon emissions: a spatial effect analysis for China. Resour. Conserv. Recycl. 185, 106445 <https://doi.org/10.1016/J.RESCONREC.2022.106445>.

Ma, S., Zhang, Y., Liu, Y., Yang, H., Lv, J., Ren, S., 2020. Data-driven sustainable intelligent manufacturing based on demand response for energy-intensive industries. J. Clean. Prod. 274, 123155 <https://doi.org/10.1016/j.jclepro.2020.123155>.

Ma, Q., Khan, Z., Tariq, M., ISik, H., Rjoub, H., 2022. Sustainable digital economy and trade adjusted carbon emissions: evidence from China's provincial data. *Econ. Res.-Ekon. Istraz.* 35, 5469-5485. <https://doi.org/10.1080/1331677x.2022.2028179>.

Malmodin, J., Lundeán, D., 2018. The energy and carbon footprint of the global ICT and E&M sectors 2010-2015. *Sustainability* 10 (9), 3027. <https://doi.org/10.3390/su10093027>.

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., Marrs, A., 2013. *Disruptive Technologies: Advances that Will Transform Life, Business, and the Global Economy*. McKinsey Global Institute.

Mellouli, S., Luna-Reyes, L.F., Zhang, J., 2014. Smart government, citizen participation and open data. *Inf. Polity* 19, 1-4.

Nasir, M.A., Canh, N.P., Le, T.N.L., 2021. Environmental degradation & role of financialisation, economic development, industrialisation and trade liberalisation. *J. Environ. Manag.* 277, 111471 <https://doi.org/10.1016/j.jenvman.2020.111471>.

Nathaniel, S., Khan, S.A.R., 2020. The nexus between urbanization renewable energy, trade, and ecological footprint in ASEAN countries. *J. Clean. Prod.* 272, 122709 <https://doi.org/10.1016/j.jclepro.2020.122709>.

Nayal, K., Kumar, S., Raut, R.D., Queiroz, M.M., Priyadarshinee, P., Narkhede, B.E., 2021. Supply chain firm performance in circular economy and digital era to achieve sustainable development goals. *Bus. Strateg. Environ.* 31, 1058-1073. <https://doi.org/10.1002/bse.2935>.

Nieuwenhuijsen, M.J., 2021. New urban models for more sustainable liveable and healthier cities post covid19\mathsemicolon\$ reducing air pollution, noise and heat island effects and increasing green space and physical activity. *Environ. Int.* 157, 106850 <https://doi.org/10.1016/j.envint.2021.106850>.

Nikmehr, B., Hosseini, M.R., Martek, I., Zavadskas, E.K., Antucheviciene, J., 2021. Digitalization as a strategic means of achieving sustainable efficiencies in construction management: a critical review. *Sustainability* 13 (9), 5040. <https://doi.org/10.3390/SU13095040>.

OECD, 2020. OECD Digital Economy Outlook. Organisation for Economic Co-operation and Development. Available at: <https://www.oecd.org/digital/oecd-digital-economy-outlook-2020-7374e0c5-en.htm>.

Olvera, D.R.C., 2022. The Polluting Cloud. A SOCIO-Environmental Analysis of the Digital Carbon Footprint, 12. PAAKAT: Revista de Tecnología y Sociedad. <https://doi.org/10.32870/pk.a12n22.730>.

Onyango, G., Ondiek, J.O., 2021. Digitalization and integration of sustainable development goals (SDGs) in public organizations in Kenya. *Public Organ. Rev.* 21, 511-526. <https://doi.org/10.1007/sm15-020-00504-2>.

Oryani, B., Koo, Y., Rezaia, S., Shafiee, A., 2021. Barriers to renewable energy technologies penetration: perspective in Iran. *Renew. Energy* 174, 971-983. <https://doi.org/10.1016/J.RENENE.2021.04.052>.

Pais, D.F., Afonso, T.L., Marques, A.C., Fuinhas, J.A., 2019. Are economic growth and sustainable development converging? Evidence from the comparable genuine progress indicator for organisation for economic co-operation and development countries. *Int. J. Energy Econ. Policy* 9, 202-213. <https://doi.org/10.32479/ijeep.7678>.

Patsavellas, J., Salonitis, K., 2019. The carbon footprint of manufacturing digitalization: critical literature review and future research agenda. *Procedia CIRP* 81, 1354-1359. <https://doi.org/10.1016/J.PROCIR.2019.04.026>.

Pereira, G.V., Estevez, E., Cardona, D., Chesnevar, C., Collazzo-Yelpo, P., Cunha, M.A., Diniz, E.H., Ferraresi, A.A., Fischer, F.M., Garcia, F.C.O., Joia, L.A., Luciano, E.M., de Albuquerque, J.P., Quandt, C.O., Rios, R.S., Sánchez, A., da Silva, E.D., Silva-Junior, J.S., Scholz, R.W., 2020. South American expert roundtable: increasing adaptive governance capacity for coping with unintended side effects of digital transformation. *Sustainability* 12, 718. <https://doi.org/10.3390/su12020718>.

Petroleum, B., 2022. bp Statistical Review of World Energy. <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf>.

Polimeni, J.M., Iorgulescu, R.I., 2018. The Jevons paradox. In: *Companion to Environmental Studies*. Routledge, pp. 60-65. <https://doi.org/10.4324/9781315640051-13>.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., Kropp, J.P., 2017. A systematic study of sustainable development goal (SDG) interactions. *Earth's Future* 5, 1169-1179.

Rahimi, N.R., Fouladi-Fard, R., Aali, R., Shahryari, A., Rezaali, M., Ghafouri, Y., Ghalhari, M.R., Asadi-Ghalhari, M., Farzinnia, B., Gea, O.C., Fiore, M., 2021. Bidirectional association between COVID-19 and the environment: a systematic review. *Environ. Res.* 194, 110692 <https://doi.org/10.1016/j.envres.2020.110692>.

Renn, O., Beier, G., Schweizer, P.-J., 2021. The opportunities and risks of digitalisation for sustainable development: a systemic perspective. *GAIA - Ecol. Perspect. Sci. Soc.* 30, 23-28. <https://doi.org/10.14512/gaia.30.1.6>.

Riazi, S., Wigstrom, O., Bengtsson, K., Lennartson, B., 2017. Energy and peak power optimization of time-bounded robot trajectories. *IEEE Trans. Autom. Sci. Eng.* 14, 646-657. <https://doi.org/10.1109/tase.2016.2641743>.

Rinaldi, M., Caterino, M., Fera, M., Manco, P., Macchiaroli, R., 2021. Technology selection in green supply chains - the effects of additive and traditional manufacturing. *J. Clean. Prod.* 282, 124554 <https://doi.org/10.1016/j.jclepro.2020.124554>.

Romanian National Institute of Statistics, 2019. Romanian Statistical Yearbook 2019.

Rothe, F.-F., Audenhove, L.V., Loisen, J., 2022. Digital development inequalities & the Sustainable Development Goals: what does 'Leave No-One Behind' mean for ICT4D? *Inf. Technol. Dev.* 1-18 <https://doi.org/10.1080/02681102.2022.2076640>.

Sachs, J., Kroll, C., Lafortune, G., Fuller, G., Woelm, F., 2022. *Sustainable Development Report 2022*. Cambridge University Press. <https://doi.org/10.1017/9781009210058>.

Saner, R., Yiu, L., Nguyen, M., 2020. Monitoring the SDGs: digital and social technologies to ensure citizen participation inclusiveness and transparency. *Dev. Policy Rev.* 38, 483-500. <https://doi.org/10.1111/dpr.12433>.

Santarius, T., Pohl, J., Lange, S., 2020. Digitalization and the decoupling debate: can ICT help to reduce environmental impacts while the economy keeps growing? *Sustainability* 12 (18), 7496. <https://doi.org/10.3390/SU12187496>.

Santos, J., Borges, A.S., Domingos, T., 2021. Exploring the links between total factor productivity and energy efficiency: Portugal 1960-2014. *Energy Econ.* 101, 105407 <https://doi.org/10.1016/j.eneco.2021.105407>.

Sareen, S., Haarstad, H., 2021. Digitalization as a driver of transformative environmental innovation. *Environ. Innov. Soc. Trans.* 41, 93-95. <https://doi.org/10.1016/J.EIST.2021.09.016>.

Satyanand, P.N., 2021. Foreign direct investment and the digital economy. In: ARTNeT on FDI Working Paper Series, No. 2, July 2021. Asia-Pacific Research and Training Network on FDI.

Shan, Y., Guan, Y., Hang, Y., Zheng, H., Li, Y., Guan, D., Li, J., Zhou, Y., Li, L., Hubacek, K., 2022. City-level emission peak and drivers in China. *Sci. Bull.* 67 (18), 1910-1920. <https://doi.org/10.1016/J.SCIB.2022.08.024>.

Sharma, P., Dash, B., 2022. The digital carbon footprint: threat to an environmentally sustainable future. *Int. J. Comput. Sci. Inf. Technol. Res.* 14, 19-29. <https://doi.org/10.5121/ijcsit.2022.14302>.

Sherafati, M., Bashiri, M., Tavakkoli-Moghaddam, R., Pishvaei, M.S., 2020. Achieving sustainable development of supply chain by incorporating various carbon regulatory mechanisms. *Transp. Res. Part D: Transp. Environ.* 81, 102253 <https://doi.org/10.1016/j.trd.2020.102253>.

Sohag, K., Chukavina, K., Samargandi, N., 2021. Renewable energy and total factor productivity in OECD member countries. *J. Clean. Prod.* 296, 126499 <https://doi.org/10.1016/j.jclepro.2021.126499>.

Soldatos, J., Kefalakis, N., Makantasis, G., Marguglio, A., Lazaro, O., 2021. Digital platform and operator 4.0 services for manufacturing repurposing during COVID19. In: *Advances in Production Management Systems. Artificial Intelligence for Sustainable and Resilient Production Systems*. Springer International Publishing, pp. 311-320. https://doi.org/10.1007/978-3-030-85910-7_33.

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

Song, M., Peng, L., Shang, Y., Zhao, X., 2022. Green technology progress and total factor productivity of resource-based enterprises: a perspective of technical compensation of environmental regulation. *Technol. Forecast. Soc. Chang.* 174, 121276 <https://doi.org/10.1016/j.techfore.2021.121276>.

Sorrell, S., 2009a. Exploring Jevons' paradox. In: *Energy Efficiency and Sustainable Consumption*. Palgrave Macmillan UK, pp. 136-164. https://doi.org/10.1057/9780230583108_7.

Sorrell, S., 2009b. Jevons' paradox revisited: the evidence for backfire from improved energy efficiency. *Energy Policy* 37, 1456-1469. <https://doi.org/10.1016/j.enpol.2008.12.003>.

Sperling, D., Yeh, S., 2010. Toward a global low carbon fuel standard. *Transp. Policy* 17 (1), 47-49. <https://doi.org/10.1016/J.TRANPOL.2009.08.009>.

STOXX Ltd., 2020. STOXX Global Digitalisation Index. Available at: <https://www.stoxx.com/index-details?symbol=STXDGL0>.

Syverson, C., 2017. Challenges to mismeasurement explanations for the US productivity slowdown - American economic association. *J. Econ. Perspect.* 31, 165-186. <https://doi.org/10.1257/jep.31.2.165>.

Tang, C., Irfan, M., Razaq, A., Dagar, V., 2022. Natural resources and financial development: role of business regulations in testing the resource-curse hypothesis in ASEAN countries. *Res. Policy* 76, 102612. <https://doi.org/10.1016/j.resourpol.2022.102612>.

The Fletcher School at Tufts University and Mastercard, 2020. Digital Intelligence Index. Available at: <https://sites.tufts.edu/digitalplanet/the-digital-evolution-index/>.

Ufua, D.E., Emielu, E.T., Olujobi, O.J., Lakhani, F., Borishade, T.T., Ibidunni, A.S., Osabuohien, E.S., 2021. Digital transformation: a conceptual framing for attaining Sustainable Development Goals 4 and 9 in Nigeria. *J. Manag. Organ.* 27, 836-849. <https://doi.org/10.1017/jmo.2021.45>.

UNCTAD, 2017. The role of foreign direct investment in the digital economy. In: United Nations Conference on Trade and Development. *World Investment Report 2017*. <https://unctad.org/publication/world-investment-report-2017> (accessed 7.27.23).

UNCTAD, 2020. Digital economy report. In: United Nations Conference on Trade and Development. Available at: <https://unctad.org/webflyer/digital-economy-report-2020>.

Wang, X., Wang, Q., 2021. Research on the impact of green finance on the upgrading of Chinas regional industrial structure from the perspective of sustainable development. *Res. Policy* 74, 102436. <https://doi.org/10.1016/j.resourpol.2021.102436>.

Wang, L., Su, C.-W., Ali, S., Chang, H.-L., 2020. How China is fostering sustainable growth: the interplay of green investment and production-based emission. *Environ. Sci. Pollut. Res.* 27, 39607-39618. <https://doi.org/10.1007/s11356-020-09933-4>.

Wang, J., Dong, K., Dong, X., Taghizadeh-Hesary, F., 2022a. Assessing the digital economy and its carbon-mitigation effects: the case of China. *Energy Econ.* 113, 106198 <https://doi.org/10.1016/j.eneco.2022.106198>.

Wang, J., Luo, X., Zhu, J., 2022b. Does the digital economy contribute to carbon emissions reduction? A city-level spatial analysis in China. *Chinese J. Popul. Resour. Environ.* 20 (2), 105-114. <https://doi.org/10.1016/J.CJPRE.2022.06.001>.

Wang, H., Li, Y., Lin, W., Wei, W., 2023a. How does digital technology promote carbon emission reduction? Empirical evidence based on e-commerce pilot city policy in China. *J. Environ. Manag.* 325 (Pt A) <https://doi.org/10.1016/J.JENVMAN.2022.116524>.

Wang, C., Zhang, R., Ibrahim, H., Liu, P., 2023b. Can the digital economy enable carbon emission reduction: analysis of mechanisms and China's experience. *Sustainability* 15 (13). <https://doi.org/10.3390/su151310368>.

Wiesmeth, H., 2021. The rebound effect and path dependencies. In: *Implementing the Circular Economy for Sustainable Development*. Elsevier, pp. 141-152. <https://doi.org/10.1016/b978-0-12-821798-6.00012-0>.

Wilson, M., 2019. The dangerous path of nature commoditization. *Consilience* 86-99.

Wilson, C., Kerr, L., Sprei, F., Vrain, E., Wilson, M., 2020. Potential climate benefits of digital consumer innovations. *Annu. Rev. Environ. Resour.* 45, 113-144. <https://doi.org/10.1146/ANNUREV-ENVIRON-012320-082424>.

World Bank, 2020a. Digital Adoption Index. World Bank. Available at: <https://www.worldbank.org/en/publication/wdr2016/Digital-Adoption-Index>.

World Bank, 2020b. Digital Business Indicator. World Bank. Available at: <https://databank.worldbank.org/source/world-development-indicators>.

Wu, H., Hao, Y., Ren, S., Yang, X., Xie, G., 2021. Does internet development improve green total factor energy efficiency? Evidence from China. *Energy Policy* 153, 112247. <https://doi.org/10.1016/j.enpol.2021.112247>.

Xie, N.-Y., Zhang, Y., 2022. The impact of digital economy on industrial carbon emission efficiency: evidence from Chinese provincial data. *Math. Probl. Eng.* 2022, 1-12. <https://doi.org/10.1155/2022/6583809>.

Xu, L., Tan, J., 2020. Financial development industrial structure and natural resource utilization efficiency in China. *Res. Policy* 66, 101642. <https://doi.org/10.1016/j.resourpol.2020.101642>.

Xu, Z., Li, Y., Chau, S.N., Dietz, T., Li, C., Wan, L., Zhang, J., Zhang, L., Li, Y., Chung, M. G., Liu, J., 2020. Impacts of international trade on global sustainable development. *Nat. Sustain.* 3, 964-971. <https://doi.org/10.1038/s41893-020-0572-z>.

Yi, M., Liu, Y., Sheng, M.S., Wen, L., 2022. Effects of digital economy on carbon emission reduction: new evidence from China. *Energy Policy* 171, 113271. <https://doi.org/10.1016/j.enpol.2022.113271>.

York, R., McGee, J.A., 2015. Understanding the Jevons paradox. *Environ. Sociol.* 2, 77-87. <https://doi.org/10.1080/23251042.2015.1106060>.

Yue, S., Shen, Y., Yuan, J., 2019. Sustainable total factor productivity growth for 55 states: an application of the new Malmquist index considering ecological footprint and human development index. *Resour. Conserv. Recycl.* 146, 475-483. <https://doi.org/10.1016/j.resconrec.2019.03.035>.

Zhang, H., 2023. Pathways to carbon neutrality in major exporting countries: the threshold effect of digital transition. *Environ. Sci. Pollut. Res.* 30 (3), 7522-7542. <https://doi.org/10.1007/S11356-022-22592-X/TABLES29>.

Zhang, S., Wei, X., 2019. Does information and communication technology reduce enterprise's energy consumption? Evidence from Chinese manufacturing enterprises survey. *China Ind. Econ.* 2, 155-173.

Zhang, J., Lu, G., Skitmore, M., Ballesteros-Perez, P., 2021a. A critical review of the current research mainstreams and the influencing factors of green total factor productivity. *Environ. Sci. Pollut. Res.* 28, 35392-35405. <https://doi.org/10.1007/s11356-021-14467-4>.

Zhang, S., Wu, Z., Wang, Y., Hao, Y., 2021b. Fostering green development with green finance: an empirical study on the environmental effect of green credit policy in China. *J. Environ. Manag.* 296, 113159 <https://doi.org/10.1016/j.jenvman.2021.113159>.

Zhang, W., Zhao, S., Wan, X., Yao, Y., 2021c. Study on the effect of digital economy on high-quality economic development in China. *PLoS One* 16 (9), e0257365. <https://doi.org/10.1371/journal.pone.0257365>. Sep 21; PMID: 34547019; PMCID: PMC8454970.

Zhang, K., Jiang, L., Jin, Y., Liu, W., 2022. The carbon emission characteristics and reduction potential in developing areas: case study from Anhui Province, China. *Int. J. Environ. Res. Public Health* 19 (24), 16424. <https://doi.org/10.3390/IJERPH192416424>.

Zhao, C., Liu, Z., Yan, X., 2023. Does the digital economy increase green TFP in cities? *Int. J. Environ. Res. Public Health* 20 (2), 1442. <https://doi.org/10.3390/ijerph20021442>. Jan 12. PMID: 36674198; PMCID: PMC9860744.

Zhou, Z., Li, K., Liu, Q., Tao, Z., Lin, L., 2020. Carbon footprint and eco-efficiency of Chinas regional construction industry: a life cycle perspective. *J. Oper. Res. Soc.* 72, 2704-2719. <https://doi.org/10.1080/01605682.2020.1811168>.

Zhu, Z., Liu, B., Yu, Z., Cao, J., 2022a. Effects of the digital economy on carbon emissions: evidence from China. *Int. J. Environ. Res. Public Health* 19, 9450. <https://doi.org/10.3390/ijerph19159450>.

Zhu, Z., Liu, B., Yu, Z., Cao, J., 2022b. Effects of the digital economy on carbon emissions: evidence from China. *Int. J. Environ. Res. Public Health* 19. <https://doi.org/10.3390/ijerph19159450>.

Zoundi, Z., 2017. CO2 emissions renewable energy and the environmental Kuznets curve, a panel cointegration approach. *Renew. Sust. Energ. Rev.* 72, 1067-1075. <https://doi.org/10.1016/j.rser.2016.10.018>.