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1

Is digitalization leading to CO_2 emission cutting?

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Abstract

Purpose – Our article aims to contribute to the main research question of whether digitalization can be used to mitigate carbon emissions. One of the main challenges in capturing the effects of digitalization on carbon emissions lies within the measurement.

Design/methodology/approach – We create six proxies to measure digitalization that represent the dynamics of the ICT sector, relative size, relative business expenditures of R&D in the ICT sector, the relative imports and exports of ICT goods and relative digital capital. We perform OLS regression on a sample covering 26 European Union countries during the time period 2003–2019. To add statistical robustness, we perform the quantile panel regression.

Findings – Our results show that the relative size of the ICT sector and digital capital have a neutral impact on the country's carbon emissions. An increase in ICT imports of goods and ICT exports of goods as a ratio of the overall country's imports and exports, on the other hand, could lead to an increase in carbon emissions. On the other hand, the net trading balance of ICT goods (ICT exports minus ICT imports) in our data set for EU countries lowers carbon emissions. Our results provide no conclusive evidence for a relationship between business expenditures on R&D in the ICT sector and carbon emissions.

Originality/value – We contribute to existing literature by creating new measurements to capture digitalization and identifying which digitalization aspects either enhance or diminish carbon emissions, and we apply this approach to the European Union based on 26 countries for the period of 2003–2019.

Keywords ICT, Climate economics, Digitalization, CO_2, Impact valuation

Paper type Research article

1. Introduction

This paper aims to contribute to the question of whether digitalization can be used to mitigate carbon emissions. Over the last centuries, the impact of digitalization on the world has been increasing. Digitalization nowadays is an important factor that changes the value chain of almost every industry. The most recent developments in data science and artificial intelligence have accelerated the idea that digitalization can be used to mitigate environmental problems in many cases to help fight climate change (Cao *et al*., 2023). All around the world, large organizations set goals to reduce their carbon emissions. The UN aims to reduce their emissions by 45% in 2030, and the EU aims to cut their emissions by 55% (United Nations, 2019; European Commission, 2021). The main idea of the impact of digitalization on the environment can be separated into the direct effects that mainly relate to the product life cycle, the enabling effects of which examples are the dematerialization effect and optimization and the systematic effect of which the rebound effect is important to consider (Mickoleit, 2010). The dematerialization effect triggered by digitalization can be explained as the shift from paper and physical communication toward online, lowering travel costs and related carbon emissions (Chen, 2022). The possible rebound effect of digitalization arises when the demand for products increases due to efficiency improvements in the supply chain due to digitalization, leading to lower production costs, reversing the environmental benefits gained by the optimization effect (Plepys, 2002). Chen (2022) also claims that ICT provides intelligent and

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automated solutions that can contribute to the reduction of carbon emissions, like power generation, digital transformation and smart cities. ICT is regarded as the cornerstone of digitalization and will play a key role in this paper (Lin and Huang, 2023). ICT can be described as a complex combination, including hardware, communication equipment and software services (Zhong *et al*., 2022). ICT promotes innovation and knowledge diffusion to remove barriers caused by distance, improving productivity of the industrial sector to accelerate expansion (Zhong *et al*., 2022). According to Andreopoulou (2013), ICT can play an important role in environmental sustainability. However, the impact of digitalization and ICT on the environment remains complex and consists of multiple concepts. Therefore, multiple ICT measurements are created to capture the different dynamics of the ICT sector at the country level.

By performing fixed effects OLS regression for 288 to 416 observations covering 26 countries, we aim to find the impact of digitalization on carbon emissions at the country level. We contribute to existing literature by creating new measurements to capture digitalization and identifying which digitalization aspects either enhance or diminish carbon emissions. We apply this methodology to the EU, covering the suggestion of Chen (2022) to apply the analysis to different economies. We extend the methodology of Nguyen *et al*. (2020) by analyzing not only the import and exports of ICT goods but also estimating the impact of the net trading balance of ICT goods. To add robustness to our results, we also perform the regression on the percentage change in carbon emissions and apply the quantile panel regression approach following the methodology of Nguyen *et al*. (2020). Our results show that the relative size of the ICT sector and expenditures in R&D in the ICT sector can lead to a steeper decline in carbon emissions. ICT imports and exports, on the other hand, could lead to an increase in carbon emissions, showing that the relation between digitalization and carbon emissions differs among various measurements and further research for both different variables and applications to different economies is required to fully understand this relation.

Section 2 contains the discussion of literature and formulates the hypotheses. Section 3 provides an explanation of methodology, variables and empirical models. Section 4 presents empirical results, for which section 5 provided additional robustness checks. Section 6 presents the conclusion and discussion.

2. Literature review

2.1 Digitalization concept and CO_2 emissions

Over the last centuries, the impact of digitalization on the world has been increasing. The most recent developments in data science and artificial intelligence have accelerated the idea that digitalization can be used to mitigate environmental problems in many cases (Cao *et al*., 2023). The digital economy can be defined as an important factor enclosing a technological revolution changing the value chain of almost every industry (Ma *et al*., 2022). Digitalization captures multiple concepts and technologies: cyber-physical systems, the Internet of Things, systems of systems, machine-to-machine, Industry 4.0, artificial intelligence and big data analytic capabilities (Cao *et al*., 2023; Ma *et al*., 2022; Akter *et al*., 2016). But, for example, the results of Aldieri *et al*. (2025) show that in Italy regulatory quality is an important enabling force for digitalization, suggesting the important role of governmental entities. Thus the large number of different concepts and technologies creates challenges regarding the measurement of digitalization in literature. As described by Raheem *et al*. (2020), the measurement of ICT is limited to usage and readiness, which we aim to extend. Zhong *et al*. (2022) describe ICT as a complex combination, including hardware communication equipment and software services. They write that ICT promotes innovation, increases the spread of and access to information and improves efficiency and productivity among different sectors. Gökgöz and Turan (2024) write that ICT affects the economy in several different aspects, including production, usage of capital and contribution to technological change Table 1 provides an overview of the main sources of literature analyzed in this literature review. The existing body of literature consists mainly of

Table 1. Overview of literature

Authors	Economy	Methodology	Digitalization Indicator	Results
Akter *et al.* (2016)	US	RBT	BDAC	BDAC ↑ FP ↑
Higón *et al.* (2017)	Global	POLS, D-K, IV		ICT Ω CO_2
Appiah Otoo *et al.* (2023)	BRI	D-K, PMQR	ICT development	ICT ↑ CO_2 ↓
Chen (2022)	BRICS	ARDL	Internet users	DIG ↑ CO_2 ↓
Choi and Han (2018)	Global	GMM	EPA	EPA ↑ CO_2 ↓
Lin and Huang (2023)	Global	2SLS	DIG	DIG Ω CO_2
Ma *et al.* (2022)	China	AMG & CCMG	Digital economy	DE ↑ CO_2↓ DE ↔ CO_2
Nguyen *et al.* (2020)	Global	FMOLS, Quantile regression	ICT_IMP, ICT_EXP	ICT_IMP ↑ CO_2 ↓↑ ICT_EXP ↑ CO_2 ↑
Petrovic and Lobanov (2020)	OECD	CCEMG, AMG	R&D expenditures	RD ↑ CO_2 ↓
Raheem *et al.* (2020)	G7	PMG	ICT	ICT ↑ CO_2 ↑
Shabani and Shahnazi (2019)	Iran	DOLS	ICT Capital stock	Sector dependent

Note(s): BDAC shows Big Data Analytics Capability, FP shows Financial Performance, RD shows Research and Development expenditures, CO_2 shows carbon emissions, DIG shows the countries digital level, DE shows Digital Economy, ICT shows Information and Communication Technology, EPA shows Environmental Patent Applications, RBT shows Resource-Based Theory, CCEMG shows Common Correlated Effects Mean Group estimator, AMG shows Augmented Mean Group estimator, ARDL shows Autoregressive Distributed Lag model, 2SLS shows Two-Stage Least Squares regression, DOLS shows Dynamic Ordinary Least Squares regression, POLS shows Pooled Ordinary Least Squares regression, D-K regression shows Driscoll–Kraay regression, IV shows Instrumental Variable fixed-effects regression, PMQR shows Panel Moment Quantile Regression method, FMOLS, show Fixed effects model OLS regression PMG shows Pooled Mean Group estimator, GMM shows Generalized Method of Moments. ↓ shows decreases, ↑ shows increases, ↔ shows bidirectional relation, ↓↑ shows mixed results for different methods and Ω shows inverted U-shaped relationship
Source(s): Authors' own work

three different approaches to measuring digitalization while analyzing the relationship between digitalization and carbon emissions. The first segment of papers uses a proxy to capture Internet users and penetration or mobile and fixed phone subscriptions and penetration. The second segment of papers analyzes the imports and exports of ICT goods. The final segment uses the principal component analysis to combine multiple proxies into one variable that represents digitalization. Our analysis focuses on elaborating on the findings of the second segment and further exploring the dynamics of the ICT sector and their environmental impact. ICT forms the cornerstones of digitalization and will therefore form the foundation of our methodology that is created to measure digitalization (Lin and Huang, 2023).

The OECD distinguishes three types of impact that digitalization has on the environment: direct, enabling and systematic (Mickoleit, 2010). The direct impact on carbon emissions is related to the physical existence of ICT products and processes and mainly relates to the product life cycle of ICT products. Enabling environmental impact can be distinguished into four categories. The dematerialization and substitution effect involving the replacement of physical products and processes and the optimization effect in which ICT can be used to reduce the environmental impact of other products by optimizing processes, which both have a mitigating impact on the environment. On the other hand, induction relates to the increase in demand of other products due to ICT products and degradation that can occur if the embedment of ICT products creates challenges in the waste management process, both have a degrading effect on the environment. The systematic impact involves the intended and unintended effects caused by the wide acceptance of digitalization (Mickoleit, 2010). There are four different categories of systemic effects. The provision and disclosure of information that helps bridging information gaps that enhances decision-making processes. The enabling of dynamic pricing and the fostering of price sensitivity which allows forms an important part of green growth strategies aiming to encourage sustainable behavior (Mickoleit, 2010). The fostering of technology involves behavioral changes due to technology. Also, the rebound effect could occur if efficiencies on the micro level do not lead to savings at the macro level. This occurs when process optimization leads to lower production costs and therefore the demand for those products increases, degrading the positive environmental impact of the optimization. These influencing factors contain both positive and negative effects of digitalization on the environment. Magazzino *et al*. (2025) recommend OECD countries to focus on green innovations, since their digital and R&D systems are more developed.

Chen (2022) argues that digitalization provides smart solutions in power generation, smart cities and the overall digital transformation. Shabani and Shahnazi (2019) distinguish three separate effects of ICT on carbon emissions: the direct impact of the production of ICT goods increasing CO_2 emissions, the enabling impact decreasing carbon emissions due to the dematerialization effect and the increase in demand of products due to lower production costs increases CO_2 emissions, supported by the findings of Mirza *et al*. (2020). Houghton (2015) analyzed the direct impact of the production of digitalization products, arguing that this production uses many minerals and rare metals that cause environmental problems while extracting and during the recycling process, extending to non-digital products. Chen (2022) also argues for the dematerialization effect, which nowadays, with the increasing globalization, is more important than ever from an environmental perspective. Due to the large number of different effects of digitalization on the environment, the main challenge of this paper will be the identification of the different effects and determining the main influencing factors of digitalization on carbon emissions.

Appiah-Otoo *et al*. (2023) find that the impact of ICT on carbon emissions depends on the ICT quality within a country. They find that in countries with high ICT quality, digitalization has a positive impact on carbon emissions and a degrading effect on countries with a moderate or low ICT quality, based on the Digital Quality of Life Index (Appiah-Otoo *et al*., 2023). Choi and Han (2018) find that the relation between digitalization and carbon emissions differs among countries, separating them based on the income per capita, finding that the positive impact of digitalization is stronger in high-income countries. Añón Higón *et al*. (2017) find comparable results, arguing that developed countries in many cases have already achieved a certain level of ICT development in which digitalization can contribute to reducing emissions. Añón Higón *et al*. (2017) also provide evidence for the presence of an inverted U-shape, indicating the support of the environmental Kuznets curve (EKC). The EKC hypothesis argues that in the early stages, digitalization increases emissions to a certain level of ICT development and from that point onwards, emissions are reduced. To analyze the impact of digitalization, measured by the share of the ICT sector within the country's GDP, on the country's overall carbon emissions, we create the following hypotheses.

H1. A higher share of the ICT sector in GDP decreases CO_2 emissions.

Within this framework, it is important to consider the impact of the digital assets within a country and their impact on carbon emissions. Based on the results of Matthess *et al*. (2023), we analyze the impact of digital capital on carbon emissions; their results provide evidence that digital capital increases energy intensity. Therefore, we extend this work to see the impact of digital capital on carbon emissions, for which we create the following hypothesis.

H2. Higher amount of ICT capital increases CO_2 emissions.

We use a similar approach to Wang *et al*. (2024), who include the import of ICT goods to represent the country's demand and utilization of ICT goods. They argue that the utilization of ICT goods offers more direct insight into the impact of ICT developments on carbon emissions

(Wang *et al.*, 2024). The production of ICT goods is an important direct driver of carbon emissions (Mickoleit, 2010). Therefore, it is important to consider that countries that import ICT goods consume goods that are not produced locally and carbon emissions emitted during the production process are not accounted for within the importing country's carbon footprint, lowering overall emissions (Nguyen *et al.*, 2020). To analyze the impact of ICT imports on carbon emissions, we create the following hypothesis.

H3. A higher amount of ICT imports decreases CO_2 emissions.

In contradiction to the lowering impact of imports, we also consider the increasing impact of ICT Exports on carbon emissions. The addition of measuring digitalization by the country's ICT exports is in line with the research of Nguyen *et al.* (2020), who argue that the export of ICT goods leads to higher carbon emissions that are caused by the production of ICT goods. Therefore, the following hypothesis is created to test whether the export of ICT goods increases carbon emissions.

H4. A higher amount of ICT exports increases CO_2 emissions.

As an extension of the research of Nguyen *et al.* (2020), we analyze the impact of the net trading balance of ICT goods on carbon emissions. By analyzing the balance between ICT exports and imports, we aim to estimate the net effect of the trade of ICT goods on the environment. Based on the individual increasing impact of exports and decreasing impact of imports on the environment, we expect the trade balance to increase carbon emissions. To analyze this relation, the following hypothesis is created.

H5. A positive trade balance of ICT goods increases carbon emissions.

Another important factor of digitalization lies in the development of new technologies. The second part of the paper will focus on the R&D expenditures of firms that operate in the ICT sector. According to the results of Petrovic and Lobanov (2020), R&D expenditures mitigate carbon emissions in the long run; however, this does not hold for about 40% of the countries in their sample. In line with earlier findings on digitalization and decarbonization and their dependence on a third variable (Añón Higón *et al.*, 2017; Choi and Han, 2018; Appiah-Otoo *et al.*, 2023). In the short run, Petrovic and Lobanov (2020) find mixed results indicating that R&D expenditures can have an increasing, lowering or neutral influence on carbon emissions. This is in line with the findings of Ma *et al.* (2022), who find that R&D has a moderating impact on the relationship between digitalization and carbon emissions. Petrovic and Lobanov (2020) suggest that future research should expand to different types of R&D investment and their influence on sectoral carbon emissions. Anser *et al.* (2021) add that even though the impact of ICT on the environment is not supported, the absorptive capacity of innovation can be very helpful in the development of cleaner production technologies by increasing R&D expenditures. To analyze the impact of digitalization, measured by the R&D expenditures on carbon emissions, we create the following hypotheses.

H6. Higher amount of R&D investments decreases CO_2 emissions.

3. Research methodology

3.1 Data and variables

This research uses a sample containing annual data of EU countries covering 26 countries during the period 2003–2019; the number of observations varies among different digitalization indicators. The digitalization data is gathered from the Eurostat, the EU KLEMS Database and the World Bank. The number of observations varies by digitalization method to align with the aim of this paper to capture the largest sample for analysis. The EU Klems Database provides the opportunity to extend our sample and is used in prior digitalization research in the EU (Matthess *et al.*, 2023). The emission data and control variables are gathered from the World

Bank Database. Carbon emission data is retrieved from the World Bank Database and is calculated as the natural logarithm of the total carbon emissions of a country, following the methodology of Chen (2022).

Table 2 provides an overview of the variables that are included in the analysis. The six main independent variables that are computed aim to represent the dynamics of the ICT sector. We calculate the size of the ICT sector by calculating the value added of the ICT sector, scaling it by the country's total GDP and creating the variable *ICT _TOT*. To capture the impact of digital capital, the variable *ICT_TOT_AS* is constructed that captures the relative proportion of digital capital. We use a different approach compared to Matthess *et al*. (2023) to analyze the relative impact of digital capital by scaling the digital assets by the total assets. Following the existing body of literature, we compute additional measurements to represent the ICT sector trade dynamics (Nguyen *et al*., 2020; Anser *et al*., 2021; Wang *et al*., 2024) by analyzing the import and export of ICT goods. Wang *et al*. (2024) argue that the ICT imports can be used to represent the demand and utilization of ICT goods; therefore, the variable *ICT_IMP* is computed, representing the percentage of imported ICT goods of the total goods imported in a country by year. To measure the impact of carbon emissions caused by the production of ICT goods that are exported to other countries, we compute the variable *ICT_EXP*, representing the percentage of ICT goods in the overall exports of a country by year. To estimate the impact of the trade balance of ICT goods, the variable *ICT_TRADE* is computed by calculating the exports of ICT goods minus the imports of ICT goods and scaling the outcome by the country's GDP. To capture the impact of the investments of the ICT sector within a country, we compute the variable *BERD* that indicates the business expenditures on R&D made in the ICT sector, scaled by the total business expenditures on R&D.

The dependent variable in this model is CO_2, which is computed as the natural logarithm of the total annual CO_2 emissions in tons, following the methodology of Chen (2022). To reduce the influence of omitted variable bias, multiple control variables are included in the analysis. The control variables within the model are: *GCF* gross capital formation, following the methodology of Chen (2022), to control for the stock of capital. To control for the influence of a country's energy composition, according to Ferhi and Kamel (2024), an important force to mitigate carbon emissions, we create the variable *REC* that indicates the energy composition of a country by scaling the amount of renewable energy consumption by their overall energy consumption. Following the methodology of Choi and Han (2018), we also control for density by including the variable *DEN*, which is calculated by taking the natural logarithm of the people per square kilometer of land area. Constructed to control for the pressure of the population on the environment (Choi and Han, 2018). The variable *ENV_TAX* is constructed to control for the impact of carbon taxation and is calculated as the natural logarithm of the total raised environmental taxes in millions within a year by country.

Table 2. Variable description

Variable	Description
CO_2	Total CO_2 emissions in tonnes (Ln.)
ICT_TOT	Value added of ICT sector (% of total GDP)
ICT_TOT_AS	ICT assets (% total assets)
ICT_IMP	ICT goods imports (% of total goods imports)
ICT_EXP	ICT goods exports (% of total goods exports)
ICT_TRADE	Export of ICT goods minus import of ICT goods (% of GDP)
BERD	Business expenditure on R&D (BERD) in ICT sector (% of total R&D expenditure)
GCF	Gross capital Formation (% of GDP)
REC	Renewable energy consumption (% of total)
DEN	People per sq. km of land area (Ln.)
ENV_TAX	Total environmental taxes (% of GDP)

Source(s): Authors' own work

3.2 Empirical models

The main body of literature used in this analysis, as presented in Table 1 provides a wide range of applied methodologies within the research field. To identify the appropriate empirical model, we focus mainly on multi-country analysis, for which the GMM method, D-K regression and OLS regression seem the most appropriate options given our dataset. To increase the comparability of our outcomes to different economies, we follow the methodology of Nguyen *et al*. (2020) by applying the OLS regression. The standard errors are clustered on the firm level, and the main independent variables indicating digitalization are lagged with *t-1* within all the models. The results of the Hausman test presented in Table 11 in appendix (C) provide insight into whether to use random or fixed effects regression in the analysis. This test checks whether the errors are correlated to the regressors and provides the coefficients of the model for both random and fixed effects regression. The result of the *P*-value of the Chi-square estimator is close to the threshold of 0.05 ($p = 0.055$), suggesting systematic differences between the fixed and random effects models. Since we analyze most EU countries and the outcome of the Hausman test, we will use fixed effects regression to analyze the hypotheses. We use OLS regression to test the main hypothesis of this analysis; the first baseline model (1) is created to test hypothesis (H1) by measuring digitalization by the share of ICT in the overall GDP of country *i* in year *t-1*.

$$\begin{aligned} CO_{2i,t} = & \beta_0 + \beta_1 \text{ICT\_TOT}_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} \\ & + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \end{aligned} \tag{1}$$

To test hypothesis (H2), model (2) is created in which digitalization is represented by the relative level of digital assets to measure their impact on carbon emissions.

$$\begin{aligned} CO_{2i,t} = & \beta_0 + \beta_1 \text{ICT\_TOT\_AS}_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} \\ & + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \end{aligned} \tag{2}$$

To test hypotheses (H3) and (H4), models (3) and (4) are created that measure digitalization as the share of ICT goods in the overall imports and exports of country *i* in year *t-1*.

$$CO_{2i,t} = \beta_0 + \beta_1 \text{ICT\_IMP}_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \tag{3}$$

$$\begin{aligned} CO_{2i,t} = & \beta_0 + \beta_1 \text{ICT\_EXP}_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} \\ & + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \end{aligned} \tag{4}$$

Model (5) is created to measure the impact of the net trading balance of ICT goods to test hypothesis (H5).

$$\begin{aligned} CO_{2i,t} = & \beta_0 + ICT\_TRADE_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} \\ & + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \end{aligned} \tag{5}$$

Models (6) is created to represent the relative Business Expenditures on R&D and to test hypothesis (H6).

$$CO_{2\,i,t} = \beta_0 + \beta_1 BERD_{i,t-1} + \beta_2 CONTROL\ VARIABLES_{i,t} + \beta_3 FIXED\ EFFECTS_i + \epsilon_t \quad (6)$$

In model (1)–(6), i represents the country and t represents the year of the observations. We implement year and country fixed effects in the OLS models to control for differences caused by unobserved time and country characteristics, which is supported by the results of the performed Hausman test presented in Table 12. All models include robust standard errors that are clustered on the country level.

Figure 1 presents the structure of our empirical research by presenting the hypotheses, variables, models and data sources. Implementing the framework of the OECD into different hypotheses and measurements (Mickoleit, 2010). While distinguishing the different types of impact for the digitalization measurements, it is important to consider that there is overlap between the different variables and type of impact and only the main impact has been presented in Figure 1. Looking at the direct impact of digitalization on the environment, which is mainly related to the product life cycle of ICT products, we distinguish that this is the main impact source for carbon emissions for the ICT sector size, imports, exports and assets. According to Mickoleit (2010), R&D impacts involve both direct and enabling effects driven by innovation and optimization, which can support the achievement of environmental targets. Since our analysis focuses on the R&D expenditures that influence carbon emissions in the long run, we identify optimization as the main driver. The systematic impact of digitalization on carbon emissions is present to some extent in all the variables, but not as the main carbon-emitting source.

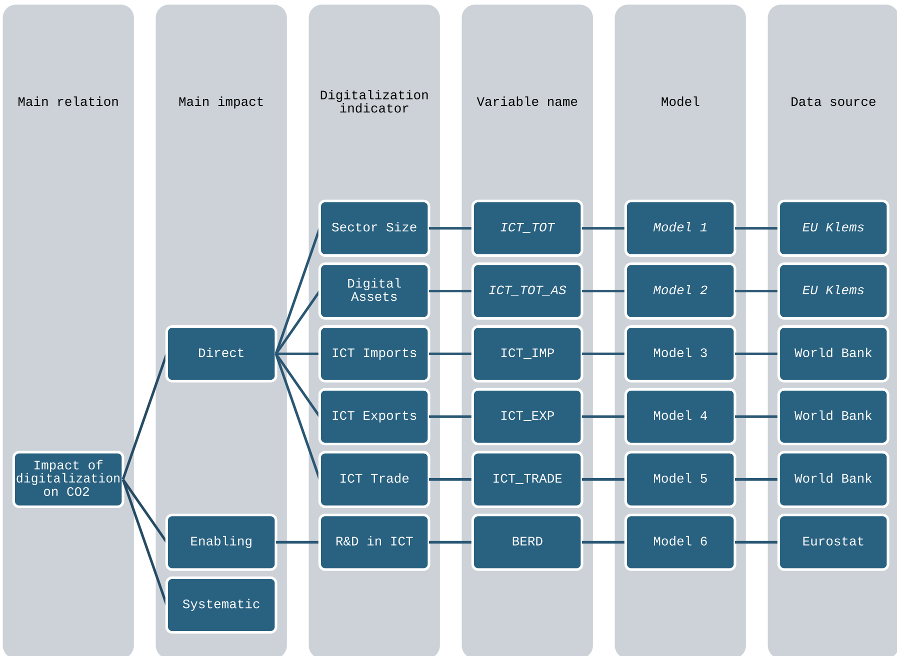

Figure 1. Structure of empirical research. **Source(s):** Authors' own work

4. Empirical results

4.1 Descriptive statistics

The results for the main descriptive statistics are presented in Table 3, additional descriptive statistics by country and year are presented, respectively, in Table 9 in appendix (A) and Table 10 in appendix (B).

The ICT sector size measured by the value added of the ICT sector scaled by the country's GDP ranges from 3.4 to 14.9%, and on average 5.8%. The relative digital assets captured in variable *ICT_TOT_AS* range from 3.4 to 14.9%, with a mean value of 8.9%, the median value of 8.9% is close to the mean value, indicating a symmetrical distribution. The ICT imports as a ratio of the overall imported goods range from 1.1 to 51.1%. The width of this range is caused by differences between countries rather than variety over time, as presented in Tables 9 and 10, presented in appendix (A) and appendix (B). For the relative exports of ICT goods, the range width is smaller, and the width between the maximum value and the mean and median is less than the ICT imports. The business expenditures on R&D in the ICT sector as a percentage of the overall R&D expenditures are on average 16.9%. The results from Table 9 in appendix (A) show that Cyprus and Malta have, on average, the highest ratio of BERD in the ICT sector. The positive mean and median value of the variable *ICT_TRADE* indicate that, on average, most of the countries within the EU export more ICT goods than they import. The results in Table 9 in appendix (A) show that only six EU countries have a negative trading balance on ICT goods, indicating that most countries within the EU export more ICT goods than they import.

Table 12 in appendix (D) presents the results for the performed for the Dumitrescu and Hurlin (2012) causality test, applying a similar methodology as Islam and Rahaman (2023). One of the main conditions for the causality test is having a balanced dataset with no gaps. This criterion is not met for the variables *ICT_TOT, ICT_TOT_AS* and *BERD;* therefore, these variables are excluded from the causality test. The results of the causality test show that between the remaining digitalization indicators and CO_2, the relations are bidirectional, providing no additional evidence for a causal relation between digitalization and CO_2 emissions.

4.2 Correlation matrix

The results of the correlation matrix are presented in Table 4. These results show one value above the 0.8 threshold, the relation between ICT imports and exports. This result could be an indication that countries that export relatively more ICT goods also import more ICT goods in comparison to their overall imports. To overcome the high correlation between these variables, both will be presented in different regression models.

Table 3. Descriptive statistics

	N	Mean	p50	SD	Min	Max
CO_2	442	6.264	6.237	1.388	2.614	9.071
ICT_TOT	442	0.058	0.056	0.017	0.034	0.149
ICT_TOT_AS	396	0.089	0.089	0.056	0.000	0.268
ICT_IMP	416	0.075	0.047	0.073	0.011	0.511
ICT_EXP	416	0.084	0.072	0.044	0.031	0.288
ICT_TRADE	414	0.001	0.006	0.027	−0.184	0.049
BERD	314	0.169	0.143	0.124	0.000	0.618
GCF	442	0.232	0.225	0.046	0.127	0.548
REC	442	0.177	0.152	0.118	0.001	0.529
DEN	442	4.678	4.716	0.911	2.840	7.362
ENV_TAX	442	0.021	0.020	0.005	0.011	0.043

Source(s): Authors' own work

Table 4. Correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
(1) CO_2	1.000										
(2) ICT_TOT	−0.071	1.000									
(3) ICT_TOT_AS	0.186	0.190	1.000								
(4) ICT_IMP	−0.274	0.378	−0.115	1.000							
(5) ICT_EXP	0.075	0.488	0.039	0.851	1.000						
(6) ICT_TRADE	0.518	−0.041	0.268	−0.731	−0.302	1.000					
(7) BERD	−0.411	−0.024	−0.339	0.144	−0.123	−0.411	1.000				
(8) GCF	0.032	0.248	−0.131	0.173	0.254	−0.019	−0.135	1.000			
(9) REC	−0.174	0.206	0.396	−0.290	−0.197	0.237	−0.140	0.058	1.000		
(10) DEN	0.054	−0.229	−0.084	0.273	0.109	−0.289	0.191	−0.267	−0.755	1.000	
(11) ENV_TAX	−0.214	0.030	0.058	−0.048	−0.043	0.068	0.069	−0.237	0.147	0.078	1.000

Note(s): The Pearson correlation matrix illustrates the relationships among variables, with coefficients from 193 observations. The matrix displays the correlations between the dependent variable, CO_2, and the independent variables ICT_TOT, and ICT_TOT_AS, ICT_IMP, ICT_EXP, ICT_TRADE and BERD. Additionally, it includes control variables GCF, REC, DEN and ENV_TAX. Definitions of the variables are presented in Table 2

Source(s): Authors' own work

The remaining results in Table 4 have no values above 0.8, indicating that there are no strong correlations between variables in the created models, providing no evidence for the presence of multicollinearity.

4.3 Regression results for ICT dynamics and CO_2 emissions

The regression results for the models created for the variables *ICT_TOT* and *ICT_TOT_AS* are presented in Table 13 in Appendix E. The negative insignificant coefficient for the main independent variable *ICT_TOT* ($\beta_1 A = -0.007$, $p > 0.1$) provides no clear evidence that ICT sector size impacts CO_2 emissions, the inclusion of control variables changes the sign of the coefficient but is also lacking significance. The positive insignificant coefficients for the main variable *ICT_TOT_AS* ($\beta_2 A = 0.573$, $\beta_2 B = 0.121$, $p > 0.1$) indicate no significant relation between digital assets and a country's overall carbon emissions. Regarding the control variables, the results show that for the variable *GCF* ($\beta_1 B = 0.188$, $\beta_2 B = 0.091$, $p > 0.05$), the signs of the coefficients are positive and insignificant. Furthermore, for the variable *REC*, representing the proportion of renewable energy in total energy consumption, the coefficients ($\beta_1 B = -1.639$, $\beta_2 B = -1.673$, $p < 0.01$) are strongly negative and significant, indicating that an increased proportion of renewable energy consumption decreases carbon emissions, confirming the major impact of renewable energy on overall carbon reduction. The results for the variables *DEN* ($\beta_1 B = -0.753$, $\beta_2 B = -0.783$, $p < 0.05$) and *ENV_TAX* ($\beta_1 B = -3.235$, $\beta_2 B = -3.428$, $p > 0.1$) show negative coefficients indicating a lowering impact on carbon emissions; however, for the results for the variable *ENV_TAX* lack significance. Table 5 presents the results of the performed regression analysis with ICT imports and exports as the main independent variables as digitalization indicators in models 3A, 3B, 4A and 4B

For models 3A and 3B, the coefficient for *ICT _IMP* ($\beta_3 A = 0.560$, $\beta_3 B = 0.418$, $p < 0.1$). Suggesting that countries with relatively higher imports of ICT goods emit more carbon emissions. These coefficients contradict the results of Nguyen *et al*. (2020), who found a

Table 5. Regression results: Models 3 and 4

	Model 3A	Model 3B	Model 4A	Model 4B
ICT_IMP	0.560**	0.418**		
	(0.220)	(0.199)		
ICT_EXP			0.959**	0.830**
			(0.395)	(0.328)
GCF		0.169		0.184
		(0.147)		(0.139)
REC		−1.679***		−1.729***
		(0.455)		(0.457)
DEN		−0.637*		−0.623*
		(0.322)		(0.319)
ENV_TAX		−4.919*		−5.557**
		(2.639)		(2.563)
Constant	6.209***	9.574***	6.170***	9.489***
	(0.0167)	(1.519)	(0.033)	(1.509)
Observations	390	390	390	390
Within R-squared	0.088	0.346	0.092	0.361

Note(s): The table presents the estimates of the OLS regression models. The regression includes coefficients for the independent variables ICT_IMP and ICT_EXP that are lagged with *t-1* and the control variables GCF, REC, DEN and ENV_TAX. Variable definitions are provided in Table 1. The models account for year and country-fixed effects. Robust standard errors, clustered at the country's level, are shown in brackets. Statistical significance is indicated by ***, ** and * for the 1, 5 and 10% levels, respectively

Source(s): Authors' own work

significant negative impact of ICT imports within G20 countries, which could indicate differences among countries in the usage of their ICT imports. For the control variables, the results for *GCF* are positive but insignificant. For the variables, *REC, DEN* and *ENV_TAX*, the coefficients in model 3 and 4B are negative and significant; however, the level of significance varies. Models 4 A and 4B in Table 5 present the results for the regression analysis with ICT exports as the main independent variable. For the baseline model 4A the coefficient for *ICT_EXP* ($\beta_4 A = 0.959$, $p < 0.05$) is positive and significant, and this result remains for *ICT_EXP* in model 4B that introduces the control variables ($\beta_4 B = 0.830$, $p < 0.05$). Indicating that a higher proportion of ICT exports could lead to higher carbon emissions for both models. This finding is in line with the findings of Nguyen *et al*. (2020) and could be an indication that countries that export relatively more ICT goods produce more carbon emissions that may arise during the production process of ICT goods. The signs of the coefficients of the control variables are mainly in line with the results in the previous regression tables. Table 6 presents the results for the variables *BERD* and *ICT_TRADE*, indicating the difference between the export and import of digital goods as a ratio of the country's GDP.

Table 6 contains the results of the performed regression analysis for the main independent variables, *ICT_TRADE in* models 5A and 5B and *BERD in* models 6A and 6B, for the variable *ICT _TRADE*, the coefficients ($\beta_6 A = -1.341$, $p < 0.05$, $\beta_6 B = -1.022$, $p > 0.1$) are negative and but the level of significance varies, indicating that a trade surplus on ICT goods could lower carbon emissions in some cases, contradicting the stated hypothesis. For the main independent variable, *BERD*, the coefficients ($\beta_6 A = -0.187$, $\beta_6 B = -0.114$, $p > 0.1$) are presented in models 6A and 6B and are negative and insignificant, providing no clear evidence for the relation between the relative business expenditures on R&D in the ICT sector and CO_2 emissions. The results for the control variables are in line with prior findings. However, the level of significance varies for the variables *DEN* and *ENV_TAX*.

Table 6. Regression results: Models 5 and 6

	Model 5A	Model 5B	Model 6A	Model 6B
ICT_TRADE	−1.341**	−1.022		
	(0.630)	(0.603)		
BERD			−0.187	−0.114
			(0.140)	(0.0944)
GCF		0.133		0.321
		(0.165)		(0.240)
REC		−1.686***		−1.685***
		(0.458)		(0.383)
DEN		−0.697**		−1.216***
		(0.334)		(0.419)
ENV_TAX		−4.638		−6.906***
		(2.735)		(2.420)
Constant	6.251***	9.892***	6.295***	12.38***
	(0.000158)	(1.570)	(0.0235)	(2.027)
Observations	388	388	288	288
R-squared	0.063	0.339	0.029	0.408

Note(s): The table presents the estimates of the OLS regression models. The regression includes coefficients for the independent variables ICT_TRADE and BERD that are lagged with *T-1* and the control variables GCF, REC, DEN and ENV_TAX. Variable definitions are provided in Table 1. The models account for year and country-fixed effects. Robust standard errors, clustered at the country's level, are shown in brackets. Statistical significance is indicated by ***, ** and * for the 1, 5 and 10% levels, respectively

Source(s): Authors' own work

5. Robustness checks

This section covers the results of the two robustness checks performed. The first results aim to recreate the regression results using a different dependent variable to measure carbon emissions. In the main regression results, CO_2 is calculated as the natural logarithm of CO_2 emissions in country *i* in year *t*. In this section, we will analyze the impact of digitalization on carbon emissions change compared to year *t-1*. The second robustness check involves the application of a different regression model to differentiate the results among more and less polluting countries and add statistical significance to the main results.

5.1 Regression results for ICT dynamics and change in CO_2 emissions

Table 7 presents the regression results of the analysis, including *DELTA_CO_2*, to see whether ICT dynamics are estimators for change in carbon emissions. *DELTA_CO_2* is computed as the percentual change in carbon emissions compared to year *t-1*. The model that is used in this analysis is (7).

$$\text{DELTA CO}_{2i,t} = \beta_0 + \beta_1 \text{ICT\_DYNAMICS}_{i,t-1} + \beta_2 \text{CONTROL VARIABLES}_{i,t} + \beta_3 \text{FIXED EFFECTS}_i + \epsilon_t \quad (7)$$

Table 7. Regression results DELTA_CO_2

	Model 7A	Model 7B	Model 7C	Model 7D	Model 7E	Model 7F
ICT_TOT	−0.323***					
	(0.093)					
ICT_TOT_AS		−0.004				
		(0.039)				
ICT_IMP			−0.002			
			(0.030)			
ICT_EXP				−0.033		
				(0.051)		
ICT_TRADE					−0.084	
					(0.050)	
BERD						−0.042**
						(0.019)
GCF	0.053	0.043	0.038	0.044	−0.070**	−0.120
	(0.048)	(0.066)	(0.060)	(0.060)	(0.028)	(0.106)
REC	−0.076***	−0.081**	−0.068**	−0.070***	−0.008**	−0.086***
	(0.018)	(0.033)	(0.026)	(0.025)	(0.004)	(0.024)
DEN	−0.009***	−0.008**	−0.007**	−0.007**	−0.226	−0.009***
	(0.002)	(0.003)	(0.003)	(0.003)	(0.395)	(0.003)
ENV_TAX	−0.399	−0.495	−0.220	−0.190	0.036	−0.438
	(0.432)	(0.457)	(0.399)	(0.389)	(0.034)	(0.395)
Constant	0.058**	0.041	0.029	0.030	−0.084	0.086**
	(0.024)	(0.030)	(0.029)	(0.026)	(0.050)	(0.040)
Observations	416	383	390	390	388	288
R-squared	0.262	0.258	0.258	0.258	0.258	0.302

Note(s): The table presents the estimates of the OLS regression models for DELTA_CO_2. The regression includes coefficients for the independent variables DELTA CO_2, along with the dependent variables ICT_TOT, ICT_TOT_AS, ICT_IMP, ICT_EXP, ICT_TRADE and BERD all lagged by one period. Control variables include GCF, REC, DEN and ENV_TAX. Variable definitions are provided in Table 1. The models account for year and country-fixed effects. Robust standard errors, clustered at the country's level, are shown in brackets. Statistical significance is indicated by ***, ** and * for the 1, 5 and 10% levels, respectively

Source(s): Authors' own work

in which *ICT_DYNAMICS* represent the main independent variables used throughout model (1) till (6) that represents ICT dynamics.

The results for the variable *ICT_TOT* ($\beta_7 A = -0.323$, $p < 0.01$) indicate the size of the ICT sector leads to lower carbon emissions in year *t+1*. A similar trend continues for the variable *ICT_TOT_AS* ($\beta_7 B = -0.004$, $p > 0.1$), however, the results are insignificant, indicating no significant impact on the change in carbon emissions of digital capital. For the ICT import ($\beta_7 X = -0.002$, $p > 0.1$) and export dynamics ($\beta_7 D = -0.033$, $p > 0.1$), the coefficients are both negative and insignificant. For the variable *ICT _TRADE* ($\beta_7 F = -0.084$, $p > 0.1$), the coefficient is negative and insignificant, suggesting no impact on carbon emissions of the trade balance of ICT goods. And for the variable *BERD* ($\beta_7 E = -0.042$, $p < 0.05$) the coefficient is negative and significant, suggesting the impact of business expenditures on R&D in the ICT sector on carbon emissions. For the control variables, most results are insignificant, except the coefficients for *DEN* and *REC* throughout models 7A till 7F, for these variables the coefficients are negative. In general, the signs of the coefficients for the control variables respond similarly to earlier presented regression results; however, the level of significance differs, suggesting that the implementation of carbon emission change as the main dependent variable provides neither new insights nor better results.

5.2 Quantile panel regression results for ICT dynamics and CO_2 emissions

Table 8 presents the results of the performed quantile panel regression. These results aim to create a better understanding of the differences in relations between digitalization among the highest and lowest polluting countries by running separate regression analyses by quantiles, following the methodology of Nguyen *et al*. (2020), and applying this to a different economy.

Table 8. Quantile panel regression results for CO_2

	Q10	Q25	Q50	Q75	Q90
ICT_TOT	−1.608	−0.957	−0.226	0.558	1.253
	(1.715)	(1.202)	(0.924)	(1.212)	(1.761)
ICT_TOT_AS	−0.0348	−0.0250	−0.0141	−0.00239	0.00801
	(0.203)	(0.142)	(0.108)	(0.143)	(0.209)
ICT_IMP	0.338	0.214	0.0737	−0.0764	−0.209
	(0.594)	(0.416)	(0.318)	(0.419)	(0.611)
ICT_EXP	1.398	1.360*	1.318**	1.274*	1.234
	(1.046)	(0.732)	(0.558)	(0.737)	(1.076)
ICT_TRADE	9.408	8.274	7.000	5.633	4.421
	(8.142)	(5.702)	(4.351)	(5.743)	(8.378)
BERD	−0.0331	−0.0307	−0.0280	−0.0251	−0.0225
	(0.118)	(0.0823)	(0.0627)	(0.0829)	(0.121)
GCF	0.528	0.481**	0.428**	0.371	0.321
	(0.345)	(0.241)	(0.184)	(0.243)	(0.355)
REC	−1.720***	−1.740***	−1.762***	−1.786***	−1.807***
	(0.295)	(0.207)	(0.157)	(0.208)	(0.304)
DEN	−0.930**	−0.954***	−0.980***	−1.009***	−1.034***
	(0.382)	(0.267)	(0.204)	(0.269)	(0.393)
ENV_TAX	−3.728	−4.072**	−4.459***	−4.874***	−5.242**
	(2.574)	(1.802)	(1.374)	(1.815)	(2.650)
Observations	266	266	266	266	266

Note(s): The table presents the estimates of the quantile regression models for CO_2. The regression includes coefficients for the independent variables CO_2, along with the dependent variables ICT_TOT, ICT_TOT_AS, ICT_IMP, ICT_EXP, ICT_TRADE and BERD all lagged with *t-1*. Control variables include R&D, REC, DEN and ENV_TAX. Variable definitions are provided in Table 1. Statistical significance is indicated by ***, ** and * for the 1, 5 and 10% levels, respectively

Source(s): Authors' own work

The quantile panel regression methodology was first introduced by Koenker and Bassett (1978), where regression results are estimated by applying an extension of median regression to quantiles. The main advantage of this methodology is that the regression coefficients are placed in different quantiles, representing different levels of carbon emissions. We use the regression equation (8) in which τ represents the quantile of the conditional distribution of the model, and the regression model is written as:

$$Q_\tau\left(\mathrm{CO}_{2i,t}\right) = \beta_0(\tau) + \beta_1(\tau)\mathrm{ICT\ DYNAMICS}_{i,t-1} + \beta_2(\tau)\mathrm{CONTROL\ VARIABLES}_{i,t} + \epsilon_{i,t}(\tau) \quad (8)$$

The main results in Table 8 for the variables *ICT_TOT* and *ICT_TOT_AS* show no significant results but a declining trend. The results for the variables *ICT_IMP* and *ICT_EXP* provide a contradicting trend, and for the variable *ICT_EXP* are also significant on the 25, 50 and 75th quantiles, suggesting that ICT exports increase carbon emissions for countries within those quantiles. The trade balance captured in the variable *ICT_TRADE* is positive and insignificant among all quantiles with a decreasing trend, providing no significant evidence for the relation between the trade balance and carbon emissions. The results for the variable *BERD* are negative and insignificant and provide an increasing trend among higher quantiles.

6. Conclusion

In this article, we aim to contribute to the existing literature by analyzing the relation between digitalization and carbon emissions at the country level. By implementing new measurements that represent digitalization, we explore the influence of ICT sector dynamics on carbon emission reduction targets. We performed OLS regression covering 288 to 416 observations containing 26 EU countries over the period 2003–2019. We aim to answer the question – whether digitalization is supporting the mitigation of carbon emissions by specifically zooming in onto the ICT sector as a measurement for digitalization?

We found that ICT sector size and the relative level of digital assets have a neutral relation to carbon emissions within the EU. Also, in our models, we found positive and significant interaction between carbon emission variables and both individual ICT trade indicators (imports and exports) of ICT goods. This could indicate that countries that import also export more ICT goods and therefore contribute to the production of these goods, what is an important direct driver of carbon emissions. The findings of the impact of the ICT goods trade balance contradict the hypothesis that a positive trade balance increases carbon emissions. One of the main drivers of this contradiction could lie in the high found correlation between the export and import of ICT goods indicators, suggesting that EU countries export ICT goods that are not produced locally (re-exporting). However, our findings show that a statistically significant and negative relation could lead to the conclusion that in this EU countries case, a low but still positive trade balance (exports minus imports) contributes to lower carbon emissions. This could also explain why our results for the export of ICT goods are not in line with the findings of Nguyen *et al*. (2020). No significant evidence was found determining the role of business expenditures on R&D in the ICT sector on the environment.

As robustness checks, we analyze the impact of digitalization on the change in carbon emissions compared to year *t-1*. These results show a different trend compared to the main result, indicating that ICT sector size and relative R&D expenditures on ICT lower carbon emissions. For the ICT imports, exports and the trade balance, the results are negative but insignificant. The second robustness check applies the quantile panel regression model on the main relation to add statistical significance and provide insight into the differences among countries in quantiles based on their carbon emissions. From the results of the analysis, we learn that for most digitalization variables, the coefficients become smaller for higher quantiles, indicating that the effect of digitalization is weaker for countries that emit more carbon emissions. However, it could be noticed that quantile panel regression results showed positive interaction between lagged exports of ICT goods but negative and significant interaction for the total value added of the ICT sector at Q25, Q50 and Q75 quantiles.

These findings are also supported by other variables that impact valuation, as renewable energy consumption and environmental taxes reveal significant and negative interactions with carbon emissions in our models.

One of the main challenges in analyzing the relationship between digitalization and carbon emissions lies in data availability. We contribute to existing literature by providing new measurements for digitalization. However, the sample size that ranges from 288 to 416 is relatively small and we only analyze EU countries, lowering the generalizability on a global scale. Future research should focus on applying these and different indicators for digitalization or other statistical approaches to explore differences among countries and continents. We also have used data for 2003–2019, which is for the pre COVID-19 period. And as pandemic stimulated general use of ICT, the effect in post COVID – 19 period could also be bringing new insights, leading to new evidence-based policy implications.

Supplementary material

The supplementary material for this article can be found online.

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