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#1001

Imprint

Ruhr Economic Papers

Published by

RWI – Leibniz-Institut für Wirtschaftsforschung
Hohenzollernstr. 1-3, 45128 Essen, Germany

Ruhr-Universität Bochum (RUB), Department of Economics
Universitätsstr. 150, 44801 Bochum, Germany

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Editors

Editorial Office

Ruhr Economic Papers #1001

Responsible Editor: Manuel Frondel

ISSN 1864-4872 (online) – ISBN 978-3-96973-167-3

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Bibliografische Informationen der Deutschen Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at **http://dnb.dnb.de**

RWI is funded by the Federal Government and the federal state of North Rhine-Westphalia.

http://dx.doi.org/10.4419/96973167
ISSN 1864-4872 (online)
ISBN 978-3-96973-167-3

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Digitalisation and Sustainability Strategies at the Firm Level

Abstract

The paper analyses the relationship between digitalisation and sustainability strategies at the firm level. In a first step, operational definitions of digitalisation and sustainability allowing the development of fitting empirical indicators are discussed. The possible technical and social transmission channels of the effects of digitalisation on a sustainable firm development are analysed. From a technical side of view, less energy consumption induced by intelligent sensoring systems or the reduction of meetings in presence by video conferences or the promotion of home office work leading to less travel activities might lead to a more sustainable production. Digitalisation might also act as pre-condition of eco-process innovations (e. g. the introduction of intelligent control systems leading to material and energy savings). From a societal perspective, digitalisation might lead to a higher availability of information on sustainability issues promoting a faster spread of environmentally related social norms. The empirical analysis is based on firm data of the recent Eurobarometer 486/2020 of the European Commission. The econometric results show that "digitally active" firms seem to be more sustainable for all available indicators. All considered digitalisation measures such as artificial intelligence, machine learning, or the use of smart devices and intelligent sensors are positively correlated to eco-innovation and other sustainability-related activities of the questioned firms.

JEL-Codes: C35, O31, Q01, Q55

Keywords: Digitalisation; sustainability; eco-innovation; probit analysis; negative binomial regression

February 2023

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1. Introduction

Sustainability and digitalisation are currently under the most cited megatrends in industrialised countries. The European Commission is convinced that "Successfully managing the green and digital 'twin' transitions is the cornerstone for delivering a sustainable, fair, and competitive future." Muench et al. (2022: 5). Despite the high political attention, empirical research on the relationship between digitalisation activities and the sustainable behaviour of firms is still rare. A higher digitalisation in firms might have positive but also negative effects on sustainability. More electronic devices lead to a higher electricity consumption but, on the other side e. g. smart sensors or less traffic by using more video conferences might reduce energy and material consumption. The present paper tries to close this research gap regarding firm behaviour. Digitalisation can act on the sustainability of firms via technical and social transmission channels. Technical transmission channels are e. g. the simulation and optimisation of production processes which can lead to material and energy savings or the automation of production leading to a higher production and energy efficiency. Digitalisation might also promote the visibility of a sustainable firm behaviour thus acting as a social transmission channel.

The empirical analysis is based on data of the Eurobarometer 486/2020 of the European Commission. The database dates from December 2020 and covers all European and further countries such as Bosnia and Herzegovina, Brazil, Canada, or the USA with 16,365 firms in the sample. This data base allows a joint analysis of digitalisation and sustainability activities. The econometric analysis based on probit and negative binomial regressions tries to find out if "digitally active" firms are also more sustainable. Furthermore, the role of different digitalisation strategies for eco-innovation and other sustainability actions is explored. An interesting point is also if digitalisation activities are correlated to eco-innovations compared with other non-environmentally related innovation activities.

The paper is organised as follows: Section 2 defines the terms digitalisation and sustainability and outlines a theoretical background for their relationship. In Section 3, the existing empirical literature is summarised. Section 4 describes the estimation strategy and shows descriptive and econometric results. Section 5 concludes and contains policy recommendations.

2. Definition of digitalisation and sustainability and theoretical background

Definition and measurement of digitalisation and sustainability

The Brundtland Report characterizes sustainability as "a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are made consistent with future as well as present needs" (WCED 1987:17). In other words, sustainability means a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987:41). The use of exhaustible resources or the long-term destruction of the environment restricts the possibilities of future generations. In the case of exhaustible resources, it is thus necessary that backstop technologies such as the extended use of renewable energy are developed that provide future generations with adequate substitutes. Such eco-innovations are an important tool for a successful sustainability strategy (Horbach 2019). Following Kemp and Pearson (2008:7): "Eco-innovation is the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organisation (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives." Eco-innovations can thus be understood as subsets of the broader concept of sustainable innovations (Horbach 2019). The sustainability concept not only includes the environmental and resources dimension but also the economic and the social one denoting social equity or a low unemployment rate. In that sense, an innovation is only sustainable if economic, ecological and social goals are considered. The focus of the present paper lies on the ecological aspect of sustainability. In what way do digitalisation activities affect a sustainable development within firms? To answer this question, in a first step, a definition of the term digitalisation is necessary.

Reddy and Reinartz (2017:11) define digital transformation as "[…] the use of computer and internet technology for a more efficient and effective economic value creation process" and in a broader sense "[…] it refers to the changes that new technology has on the whole; on how we operate, interact, and configure, and how wealth is created within this system". Digitalisation or digital transformation thus might affect the whole value creation process. For empirical analyses, operational indicators are needed describing these digital transformation processes. A useful concept seems to be the DESI indicator of the European Commission. It captures four main dimensions to measure the digitalisation of an economy/society (European Commission 2022 a, b): 1): Human capital (e. g. internet user skills, 2) Connectivity (broadband coverage), 3)

Integration of digital technology (AI, Cloud computing, big data, business digitalisation), 4) Digital public services for customers or businesses.

Relationship between digitalisation and sustainable development

In the following, the different transmission channels of digitalisation activities and a sustainable development are discussed. The analysis is restricted to the firm-level.

Following the theory of sustainability transitions (Fuenfschilling 2019:219): Sustainability transitions are "… long-term, multi-dimensional and deep-structural changes of existing sectors and industries towards more sustainable modes of consumption and production." All these changes of production processes and products might be accompanied by higher digitalisation levels. The crucial question is if these digitalisation efforts promote or even hinder the sustainable transition of an economy.

Technical transmission channels

From a technical perspective less energy consumption might result from the use of intelligent sensoring systems or the reduction of meetings in presence by video conferences but on the other side digital technologies also consume a high amount of electricity (e. g. blockchain technologies). Digitalisation (e. g. cloud-computing or the use of efficient video conference systems) also enables more home office work leading to less travel and commuting activities. Furthermore, digitalisation might be a pre-condition for the realisation of eco-process innovations. As an example, intelligent control systems might lead to material and energy savings. In a recent study, Bitcom (2021) analysed different examples for the effects of digitalisation on sustainability:

- Industrial Production: Simulation and optimisation of production processes (digital twins) can lead to material and energy savings,
- Automation of production leads to more production efficiency and thus to less material and energy consumption,
- Intelligent logistics and automized traffic control reduces fuel consumption,
- Smart grids and sensor-controlled networks lead to a reduction of electricity consumption and emissions,
- Big Data analyses help to calculate downtimes of wind turbines thus extending their life cycle,

- Smart homes and digitally linked buildings may lead to energy savings.

Social transmission channels

On the other side, social transmission channels of digitalisation activities to a sustainable behaviour of firms might also be relevant. A higher availability of information on sustainability issues by internet activities and social media might lead to a faster spread of environmentally related consumer behaviour thus demanding a more sustainable firm behaviour. Furthermore, digitalisation might also promote the visibility of a sustainable firm behaviour so that it is easier for consumers to recognize environmentally friendly production processes and characteristics of different products.

3. Overview of the empirical literature

Up to now, empirical and especially econometric analyses on the relationship between digitalisation and sustainability are rare. In a recent literature overview, Guandalini (2022) analyse 154 papers but only 23% of these papers use econometric or structural equation modelling. Axenbeck and Niebel (2021) analyse the climate protection effects of digitalised production processes. Using administrative panel data on 28,600 manufacturing firms between 2009 and 2017, the authors find a significant negative correlation between software capital as an indicator for the firm-level degree of digitalization and energy intensity. The effect size is only small which might also be due to the counter-effect that information and communication technologies consume energy. In a more recent analysis, Axenbeck et al. (2022:1) using German administrative panel data for more than 25,000 firms find digital technologies "…relate more frequently to an increase in energy use". Contrary to this analysis, Lange et al. (2020) find negative effects of digitalisation on energy consumption resulting from direct effects of the production, usage and disposal of ICT and economic growth from increases in labour and energy productivities. These effects seem to overcompensate the positive effects stemming from a higher energy efficiency and sectoral change in favour of ICT branches.

Schulte et al. (2016) analyse the relationship between ICT and the demand for energy for 10 OECD countries covering 13 years and 27 industries. Their econometric results show that ICT is significantly correlated to a reduction in total energy demand. The reduction of energy demand mainly relates to non-electric energy whereas the demand for electric energy remains nearly unchanged.

Ahmadova et al. (2022:1) find an inverted U-shaped relationship between home country digitalisation and environmental performance. Based on panel data of 5015 firms from 47 countries in 10 sectors for the period 2014-2019 the authors find that "…country digitalization has a positive impact on environmental performance (e.g. enhanced energy efficiency and resource management), but then it reaches a tipping point at which an excessive level of digitalization causes a "rebound effect," hence increasing the use of resources and resulting in higher pollution."

Based on a database of 25 European countries for the time period 2015-2020, Thanh et al. (2022) explore the relationship between digitalisation and environmental performance. The results show that digital skills, business digitisation, and digital public services, improves environmental performance in the long but not in the short run. Appiah-Otoo et al. (2022) analyse the impact of information and communication technologies (ICT) on carbon dioxide emissions. The authors use a panel dataset of 110 countries between 2000 to 2018 and an IV approach. The results show that the impact of ICT on environmental sustainability in countries with an already high ICT quality is positive whereas this is not the case in countries characterised by a moderate or low ICT quality.

Neligan (2018) uses a recent data set of 600 German manufacturing firms to analyse the relevance of digitalisation for material efficiency. She finds out that the use of digital networking for increasing material efficiency is still quite limited. Based on a literature survey, Chauhan et al. (2022) show that the Internet of Things and Artificial Intelligence promote the transition towards the Circular Economy but there are still barriers such as the lack of predictability, psychological issues or information problems.

Denicolai et al. (2021) rely on a sample of 438 SMEs from different countries. Artificial Intelligence (AI) seems to improve the international performance of the firms. Digitalisation and sustainability are also positively correlated, but internationalisation efforts lead to competing growth paths of these two variables.

Guaita Martínez et al. (2022) analyse the role of digitalisation, innovation and environmental policies for a sustainable production using macroeconomic data for 27 EU member states from 2015 to 2019. The authors use the Digital Economy and Society Index (DESI, see above) as indicator for the effect of digitalisation on a sustainable production measured by a synthetic index. Their results show that there is still a negative link between GDP and sustainability but digitalisation, innovation and environmental policies show positive impacts on sustainability.

Cicerone et al. (2022) study AI as a regional determinant for green technologies. They use patent data of NUTS-3 regions for 28 EU countries over the period 1982 to 2017. For regions that are already specialised in green technologies, AI supports innovation activities in this field.

Rusch et al. (2022) explore the application of digital technologies for sustainable product management in a circular economy based on a literature review of 146 case studies. The authors show that the use of digital technologies lead to only incremental improvements of a circular economy. Santoalha et al. (2021) use panel data on 142 European regions for the period 2006-2013 for analysing the relationship between ICT related workforce skills and regional green specialisations. The authors find that "… e-skills endowment is a positive predictor of regions' ability to specialise in new technological domains, and especially for green specializations". (Santoalha et al. 2021:1). Pan et al. (2022) analyse the impact of Global Value Chain (GVC) embeddedness and digital economy on green innovation. The authors use panel data of 30 Chinese provinces from 2002 to 2016. The results of fixed effects panel regression models show that GVC embeddedness and digital economy promote green innovation activities measured by green patents. For China, too, Guo et al. (2022) find that digitalisation activities significantly increase eco-innovation. Their patent analysis uses a database of Chinese firms matched with provincial-level digitalisation information from 2012 to 2018.

In a recent analysis on regional aspects on the relationship between digitalisation and eco-innovation, Cattani et al. (2022) use Eurobarometer data for European firms. The authors find that firms in rural areas are characterised by a lower digital propensity and, interestingly, higher eco-innovation capacities but an urban location promotes the eco-innovation impact of digital technologies.

Chatzistamoulou (2023) analyses the role digital transformation and the importance of public procurement as external funding source for the sustainability transition of European SME´s. The author uses data over more than 20,000 SMEs in the EU-28 over the period 2015-2019. The econometric results confirm that digital transformation promotes the sustainability transition.

General studies of digitalisation on innovation

Gaglio et al. (2022:1) analyse the effects of digital transformation on innovation and productivity for 711 South African firms in 2019: "Our results show that selected digital communication technologies including the use of social media and of a business mobile phone for surfing the internet have a positive effect on innovation, and that innovation conditional on the use of these technologies has a positive effect on labor productivity."

On the basis of German firm-level data from Community Innovation Survey (CIS) 2018, Rammer et al. (2022) analyse the role of different AI methods and applications to product and process innovation outcomes. The authors find out that firms developing AI by combining in-house and external resources show significantly higher innovation results.

4. Empirical and econometric analysis

Databasis

The empirical analysis is based on Eurobarometer 486/2020 (European Commission 2020) conducted by TNS Political & Social at the request of the European Commission. The database dates from December 2020 and covers all European countries and Bosnia and Herzegovina, Brazil, Canada, Croatia, Great Britain, Iceland, Japan, Kosovo, Makedonia, Norway, Serbia, Turkey and USA with 16,365 firms in the sample. The Eurobarometer 486/2020 allows a joint analysis of digitalisation and sustainability activities (see Table 1 and 2).

Table 1: Digitalisation activities

Digitalisation activities	In % of all questioned firms
Artificial Intelligence, machine learning, pattern recognition	7.7
Cloud-Computing	47.9
Use of robots, automation of processes in construction or design	8.6
Smart devices, intelligent sensors, smart thermostats	27.8
Big Data analytics, e. g. data mining or predictive analytics	14.5
Use of a highspeed infrastructure	33.7
Use of blockchain technologies	3.3

Source: European Commission (2020), own calculations.

Whereas it is not surprising that only few firms use artificial intelligence (7.7%) or blockchain technologies (3.3%), the relatively low shares of 34% for the use of a highspeed infrastructure or 28% for smart devices, intelligent sensors or smart thermostats show that there still remains much potential for digitalisation efforts (Table 1).

Table 2: Sustainability relevant activities

Sustainability activities	In % of all questioned firms
Eco-innovation: During the last 12 months, an innovation with an ecological value-added including innovations improving energy and resources use	22.1
Recycling or reuse of materials	59.8
Reduction of material use and other resources (e. g. water), use of sustainable resources	49.6
Energy saving measures or use of renewables	50.5
Development of sustainable products or services	32.0
Improvement of working conditions	69.0
Support of diversity and equal treatment	54.1
Assessment of the interaction and effects of the firm on the society	29.7
Inclusion of workers in senior management teams	46.1

Source: European Commission (2020), own calculations.

Table 2 shows the descriptive statistics for the different indicators indicating a sustainable behaviour of a firm. Besides environmental indicators, the social dimension of a sustainable behaviour is also captured by e. g. the support of diversity and equal treatment or the assessment of the effects of the firm on society.

Estimation strategy

The dependent variables denoting different sustainable activity fields are binary so that the use of probit models is adequate for estimation. For each activity, a firm must decide whether to realise the activity (Y=1) or not (Y=0). Different digitalisation strategies such as the use of artificial intelligence, of smart devices and further control variables summarised by a vector **x**, may be important for sustainability activities. Therefore, an estimation of the probability $Prob(Y = 1 | \mathbf{x}) = F(\mathbf{x}, \beta)$ is needed. The β parameters reflect the impact of changes in x on this probability (Greene 2008:772). Average marginal effects for all covariates are calculated, allowing comparisons of the different sustainable activity fields.

The analysis of our dependent count variable *sustain*, ranging from 0 to 9, requires the use of a negative binomial regression model because the tested and significant existence of overdispersion in all model variants (denoting that the variance is bigger than the mean of the Poisson process ($Var(y|\mathbf{x}) > E(y|\mathbf{x})$) does not allow the use of a mere Poisson model (see also Cameron & Trivedi 2009 for a detailed description of the model).

Econometric results

In a first step, the relevance of digitalisation strategies for a sustainable firm behaviour are analysed for different environmentally related sustainability activities (Table 3). The results show that all digitalisation measures (*AI*: artificial intelligence, machine learning, pattern recognition, *cloud*-computing, use of *robot*s including automation of processes in construction or design, *smart* devices including intelligent sensors and smart thermostats, *big data* analytics and *highspeed* infrastructure) are positively correlated to eco-innovation activities.

The highest marginal effect is estimated for smart devices (45.2%) including intelligent sensors and smart thermostats e. g. leading to energy savings. The analysis of different environmentally relevant sustainability actions shows the highest marginal effects for *AI* (18.3%), *bigdata* (24.3%) and *robot* (19.6%) for sustainable products and services. Smart devices and intelligent sensors are especially important for material (37.9%) and energy (39.9%) savings but also recycling activities profit from digitalisation strategies, e. g. the use of *robot*s (13.9%) might reduce the high labour intensity of recycling activities, *smart* sensors can improve the recyclability of plastic waste. *Cloud* computing (21.7%) and *highspeed* (19.2%) internet connection might lead to a better information flow and lower costs so that they are also important for recycling firms and activities.

Concerning control variables, big (*size*) and *export* oriented, and highly growing (*highgrowth*) firms are also more likely to realise eco-innovations whereas this is not the case for recycling firms. Family-ownership (*familyowned*) is positively correlated to all considered sustainability actions. Not surprisingly, recycling activities are more likely in the proximity of other industrial firms (localisation) whereas this variable does not play a significant role for the other sustainability related activities.

Table 3: Digitalisation and sustainability activities

Correlates	Dependent variables				
	Eco-innovations	Recycling	Material savings	Energy savings	Sustainable products
AI	0.144**	-0.030	0.088+	0.099*	0.183**
	(0.044)	(0.046)	(0.045)	(0.044)	(0.043)
Bigdata	0.237**	0.152**	0.166**	0.110**	0.243**
	(0.034)	(0.036)	(0.034)	(0.034)	(0.033)
Cloud	0.082**	0.217**	0.182**	0.125**	0.174**
	(0.026)	(0.024)	(0.024)	(0.023)	(0.025)
Highspeed	0.130**	0.192**	0.235**	0.170**	0.155**
	(0.027)	(0.026)	(0.025)	(0.025)	(0.026)
Robot	0.186**	0.139**	0.147**	0.153**	0.196**
	(0.042)	(0.045)	(0.043)	(0.042)	(0.041)
Smart	0.452**	0.273**	0.379**	0.399**	0.287**
	(0.027)	(0.027)	(0.026)	(0.026)	(0.026)
Export	0.144**	-0.004	0.020	-0.035	0.216**
	(0.028)	(0.026)	(0.026)	(0.025)	(0.026)
Familyowned	0.142**	0.153**	0.118**	0.103**	0.119**
	(0.029)	(0.029)	(0.028)	(0.028)	(0.028)
Financecap	0.129**	0.076**	0.036	0.086**	0.015
	(0.025)	(0.024)	(0.023)	(0.023)	(0.024)
Highgrowth	0.085**	0.015	0.040	-0.017	0.112**
	(0.030)	(0.028)	(0.028)	(0.027)	(0.028)
Localisation	0.057	0.103**	0.007	0.025	0.063+
	(0.035)	(0.035)	(0.034)	(0.033)	(0.034)
Oldfirms	0.061*	0.057*	0.101**	0.137**	0.014
	(0.025)	(0.023)	(0.023)	(0.022)	(0.024)
Skillshortage	0.047+	0.076**	0.063**	0.061**	-0.000
	(0.026)	(0.024)	(0.023)	(0.023)	(0.024)
Size	0.039**	0.015+	0.032**	0.067**	0.016*
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Urban	-0.034	-0.037	-0.066**	-0.109**	-0.015
	(0.025)	(0.023)	(0.023)	(0.022)	(0.023)
Wald Chi^2	1777.9 (68)	3138.6 (67)	2981.1 (68)	2364.8 (68)	2262.8 (68)
Pseudo R^2	0.12	0.17	0.16	0.12	0.13
Observations	16,051	16,049	16,051	16,051	16,051

Probit models. Average marginal effects are reported. Robust standard errors in parentheses, ** p<0.01, * p<0.05, + p<0.1. Constant, sector and country dummies are included but not reported.

Source: European Commission (2020), own estimations.

A comparison of the role of digitalisation strategies for eco-innovations with respect to other innovations (Table 4) shows that digitalisation activities and nearly all types of innovation activities are highly correlated, but *smart* (marginal effect 45.2%) sensors or smart devices are especially important for eco-innovation. The use of *robot*s (38.2%) is crucial for process innovations. Concerning further control variables, financial capabilities are most important for eco-innovations (12.9%). The marginal effect of *family-ownership* (14.2%) is disproportionately high for eco-innovations compared with other innovation activities. High growing firms (*highgrowth*) seem to be more likely to realise other innovations. The highest marginal effect (21.7%) of this variable is estimated for general process innovation whereas the marginal effect for eco-innovation only amounts to 8.5%. Interestingly, older (*oldfirms*, 6.1%) founded before 2000 and bigger (*size*, 3.9%) firms are more likely to realise eco-innovations compared with other innovations.

Table 4: Digitalisation and different types of innovation

Correlates	Dependent variables					
	Eco-innovations	Product innovation	Process innovation	Organisational innovation	Sales innovation	Social innovation
AI	0.144**	0.211**	0.166**	0.126**	0.161**	0.102*
	(0.044)	(0.042)	(0.044)	(0.045)	(0.044)	(0.044)
Bigdata	0.237**	0.203**	0.180**	0.249**	0.245**	0.277**
	(0.034)	(0.033)	(0.035)	(0.035)	(0.034)	(0.034)
Cloud	0.082**	0.165**	0.099**	0.236**	0.197**	0.159**
	(0.026)	(0.025)	(0.027)	(0.028)	(0.027)	(0.027)
Highspeed	0.130**	0.144**	0.128**	0.097**	0.184**	0.160**
	(0.027)	(0.026)	(0.028)	(0.029)	(0.027)	(0.028)
Robot	0.186**	0.180**	0.382**	0.103*	-0.017	0.170**
	(0.042)	(0.041)	(0.041)	(0.044)	(0.044)	(0.043)
Smart	0.452**	0.227**	0.233**	0.131**	0.143**	0.250**
	(0.027)	(0.026)	(0.028)	(0.029)	(0.028)	(0.028)
Export	0.144**	0.343**	0.190**	0.155**	0.113**	0.039
	(0.028)	(0.026)	(0.028)	(0.030)	(0.028)	(0.029)
Familyowned	0.142**	0.069*	0.068*	0.061+	0.054+	0.023
	(0.029)	(0.028)	(0.030)	(0.031)	(0.030)	(0.030)
Financecap	0.129**	0.045+	0.099**	0.051+	-0.046+	0.054*
	(0.025)	(0.024)	(0.026)	(0.027)	(0.026)	(0.026)
Highgrowth	0.085**	0.204**	0.217**	0.191**	0.150**	0.145**
	(0.030)	(0.028)	(0.030)	(0.030)	(0.029)	(0.030)
Localisation	0.057	0.093**	0.053	0.039	0.051	0.032
	(0.035)	(0.034)	(0.035)	(0.037)	(0.036)	(0.036)
Oldfirms	0.061*	-0.003	-0.013	-0.060*	-0.018	-0.015
	(0.025)	(0.024)	(0.026)	(0.027)	(0.025)	(0.026)
Skillshortage	0.047+	0.009	0.028	0.041	-0.041	-0.041
	(0.026)	(0.024)	(0.026)	(0.028)	(0.026)	(0.027)
Size	0.039**	-0.006	0.008	0.058**	-0.038**	-0.001
	(0.008)	(0.008)	(0.009)	(0.009)	(0.009)	(0.009)
Urban	-0.034	0.040+	-0.044+	0.054*	0.073**	0.013
	(0.025)	(0.024)	(0.026)	(0.027)	(0.025)	(0.026)
Wald Chi^2	1777.9 (68)	1779.5 (68)	1727.6 (67)	1238.4 (67)	1322.4 (68)	1546.1 (68)
Pseudo R^2	0.12	0.10	0.12	0.09	0.09	0.11
Observations	16,051	16,051	16,049	16,049	16,051	16,051

Probit models. Average marginal effects are reported. Robust standard errors in parentheses, ** p<0.01, * p<0.05, + p<0.1. Constant, sector and country dummies are included but not reported.

Source: European Commission (2020), own estimations.

The results for the *sustain*ability index also show significant marginal effects for all digitalisation variables (Table 5). Once again, the highest marginal effect is estimated for *smart* devices and intelligent sensors (20.4%). Interestingly, *family-owned* and *old*er *firms* are more likely to reach high values of the sustainability index. This result also holds for more *export*-oriented firms. Furthermore, economic success (*highgrowth*) and high financial capabilities (*financecap*) are also correlated to sustainability activities.

Table 5: Digitalisation and sustainable behaviour of firms

Correlates	Dependent variable: Sustainability index
AI	0.044**
	(0.013)
Bigdata	0.105**
	(0.010)
Cloud	0.147**
	(0.010)
Highspeed	0.134**
	(0.009)
Robot	0.070**
	(0.013)
Smart	0.204**
	(0.009)
Export	0.033**
	(0.010)
Familyowned	0.068**
	(0.009)
Financecap	0.038**
	(0.009)
Highgrowth	0.052**
	(0.010)
Localisation	0.032**
	(0.011)
Oldfirms	0.025**
	(0.009)
Skillshortage	0.031**
	(0.009)
Size	0.030**
	(0.003)
Urban	-0.022*
	(0.009)
Wald Chi^2 (68)	10373.93
Pseudo R^2	0.10
Observations	16,051

Negative binomial model. Average marginal effects are reported. Robust standard errors in parentheses, ** p<0.01, * p<0.05, + p<0.1. Constant, sector and country dummies are included but not reported.

Source: European Commission (2020), own estimations.

5. Summary and policy recommendations

Digitalisation activities of firms can promote their sustainable behaviour, but a higher electricity consumption of digital devices can also lead to negative effects. Positive effects might result from the use of intelligent sensoring systems accompanied by material and energy savings or the reduction of meetings in presence by video conferences leading to less travel and commuting activities. The paper analyses the importance of different digitalisation fields (AI, machine learning, pattern recognition, cloud-computing, use of robots, automation of processes in construction or design, smart devices or sensors, big data analytics, highspeed infrastructure and blockchain technologies) for sustainability actions such as eco-innovations, recycling, material and energy savings or sustainable products. Furthermore, the importance of digitalisation measures for different innovation activities are explored. The empirical analysis is based on firm data of the recent Eurobarometer 486/2020 of the European Commission. The econometric results show that all considered digitalisation measures are positively correlated to eco-innovation activities. The highest marginal effect is estimated for smart devices including intelligent sensors and smart thermostats e. g. leading to energy savings. The analysis of different environmentally relevant sustainability actions shows the highest marginal effects for AI and big-data and robot for sustainable products and services. Smart devices and intelligent sensors are especially important for material and energy savings but also recycling activities profit from digitalisation strategies, e. g. the use of robots might reduce the high labour intensity of recycling activities, smart sensors can improve the recyclability of plastic waste. A comparison of the role of digitalisation strategies for eco-innovations with respect to other innovations shows that digitalisation activities and nearly all types of innovation activities are highly correlated but smart sensors or smart devices are especially important for eco-innovation whereas the use of robots is crucial for process innovations.

All in all, strengthening the digitalisation of the economy seems to be benign for a sustainable development but, from a policy perspective, there are still barriers and deficits. The free information flow across value chains promoting a sustainable circular economy is still hindered by many legislative burdens (Hedberg and Šipka 2020) so that the whole potential of digitalization cannot be used. "Better coordination and exchange of information in value chains can enhance transparency while creating the basis for smart circular applications, like improved product environmental footprints and digital product passports." (Hedberg and Šipka 2020:5). Furthermore, policy should give more incentives to invest in digitally enabled processes that explicitly promote sustainable solutions. On the other side, regarding the "dark side" of digitalisation connected with a higher energy and electricity consumption, political decision-makers should make more efforts for new requirements and financial support for energy-efficient and circular electronic devices and software solutions. A sustainability oriented public procurement might also be a relevant policy tool (e. g. Chatzistamoulou 2023) to realise the twin transition of digitalisation and sustainability.

References

Ahmadova, G., Delgado-Márquez, B. L., Pedauga, L. E., Leyva-de la Hiz, D. I. (2022): Too good to be true: The inverted U-shaped relationship between home-country digitalization and environmental performance. Ecological Economics 196,107393, https://doi.org/10.1016/j.ecolecon.2022.107393.

Appiah-Otoo, I., Acheampong, A. O., Song, N., Chen, X. (2022): The impact of information and communication technology (ICT) on carbon dioxide emissions: Evidence from heterogeneous ICT countries. Energy & Environment, https://doi.org/10.1177/0958305X221118877.

Axenbeck, J., Niebel, T. (2021): Climate Protection Potentials of Digitalized Production Processes: Microeconometric Evidence? ZEW Discussion Papers 21-105, Mannheim.

Axenbeck, J., Berner, A., Kneib, T. (2022): What drives the relationship between digitalization and industrial energy demand? Exploring firm-level heterogeneity. ZEW Discussion Papers 22-59, Mannheim.

Bitcom (2021): Klimaeffekte der Digitalisierung. Studie zur Abschätzung des Beitrags digitaler Technologien zum Klimaschutz. https://www.bitkom.org/sites/main/files/2021-10/20211010_bitkom_studie_klimaeffekte_der_digitalisierung.pdf.

Cameron, A. C., Trivedi, P. K. (2009): Microeconometrics Using Stata. Lakeway Drive: Stata Press.

Cattani, L., Montresor, S., Vezzani, A. (2022): Look where they are! Firms' eco-innovation and Industry 4.0 technologies in urban and rural areas. GSSI (Gran Sasso Science Institute) Discussion paper No.2022-06, L'Aquila.

Chauhan, C., Parida, V., Dhir, A. (2022): Linking circular economy and digitalisation technologies: A systematic literature review of past achievements and future promises. Technological Forecasting & Social Change 177: 121508.

Chatzistamoulou, N. (2023): Is digital transformation the Deus ex Machina towards sustainability transition of the European SMEs? Ecological Economics 206: 107739.

Cicerone, G., Faggian, A., Montresor, S., Rentocchini, F. (2022): Regional artificial intelligence and the geography of environmental technologies: does local AI knowledge help regional green-tech specialization? Regional Studies, DOI: 10.1080/00343404.2022.2092610.

Denicolai, S., Zucchella, A., Magnani, G. (2021): Internationalization, digitalization, and sustainability: are SMEs ready? A survey on synergies and substituting effects among growth paths. Technological Forecasting and Social Change 166: 120650, https://doi.org/10.1016/j.techfore.2021.120650.

European Commission (2020): Flash Eurobarometer 486 (SMEs, Start-ups, Scale-ups and Entrepreneurship). GESIS Datenarchiv, Köln. ZA7637 Datenfile Version 2.0.0, Brussels https://doi.org/10.4232/1.13639.

European Commission (2022a): Digital Economy and Society Index 2022. Methodological Note, Brussels, https://digital-strategy.ec.europa.eu/en/policies/desi.

European Commission (2022b): Digital Economy and Society Index (DESI) 2022. Thematic chapters, Brussels, https://digital-strategy.ec.europa.eu/en/policies/desi.

Fuenfschilling, L. (2019): An institutional perspective on sustainability transitions. In: Boons, F., McMeekin, A. (eds.): Handbook of Sustainable Innovation, Edward Elgar, Cheltenham: 219-236.

Gaglio, C., Kraemer-Mbula, E., Lorenz, E. (2022): The effects of digital transformation on innovation and productivity: Firm-level evidence of South African manufacturing micro and small enterprises. Technological Forecasting & Social Change 182: 121785.

Greene, W. H. (2008): Econometric Analysis (6th Ed.). New Jersey: Pearson International.

Guaita Martínez, J. M., Puertas, R., Martín, R. M., Ribeiro-Soriano, D. (2022): Digitalization, innovation and environmental policies aimed at achieving sustainable production. Sustainable Production and Consumption 32: 92-100.

Guandalini, I. (2022): Sustainability through digital transformation: A systematic literature review for research guidance. Journal of Business Research 148: 456-471.

Guo, Q., Geng, C., Yao, N. (2022): How does green digitalization affect environmental innovation? The moderating role of institutional forces. Business Strategy and the Environment, DOI: 10.1002/bse.3288.

Hedberg, A., Šipka, S. (2020): Towards a green, competitive and resilient EU economy: How can digitalisation help? European Policy Centre. https://www.epc.eu/en/Publications/Towards-a-greencompetitive-and-resilient-EU-economy-How-can-digital~35bfc4.

Horbach, J. (2019): Determinants of eco-innovation at the firm level. In: Boons, F., McMeekin, A. (eds.) (2019): Handbook of Sustainable Innovation, Edward Elgar, Cheltenham.

Kemp, R., Pearson, P. (2008): Final report MEI project about measuring eco-innovation, Maastricht, www.merit.unu.edu\MEI.

Lange, S., Pohl, J., Santarius, T. (2020): Digitalization and energy consumption. Does ICT reduce energy demand? Ecological Economics 176: 106760, https://doi.org/10.1016/j.ecolecon.2020.106760.

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M., Scapolo, F. (2022): Towards a green and digital future. Publications Office of the European Union, Luxembourg, doi:10.2760/54, JRC129319.

Neligan, A. (2018): Digitalisation as Enabler Towards a Sustainable Circular Economy in Germany. Intereconomics 2018 (2): 101-106. DOI: 10.1007/s10272-018-0729-4.

Pan, H., Yang, J., Zhou, H., Zheng, X., Hu, F. (2022): Global value chain embeddedness, digital economy and green innovation—Evidence from provincial-level regions in China. Frontiers in Environmental Science 10:1027130. doi: 10.3389/fenvs.2022.1027130.

Rammer, C., Fernández, G. P., Czarnitzki, D. (2022): Artificial intelligence and industrial innovation: Evidence from German firm-level data. Research Policy 51 (7), https://doi.org/10.1016/j.respol.2022.104555.

Reddy, S., Reinartz, W. (2017): Digital Transformation and Value Creation: Sea Change Ahead. Value in the Digital Era. Vol. 9 (1): 11-17, doi 10.1515.

Rusch, M., Schöggl, J. P., Baumgartner, R. J. (2022): Application of digital technologies for sustainable product management in a circular economy: A review. Business Strategy and the Environment 2022:1-16.

Santoalha, A., Consoli, D., Castellacci, F. (2021): Digital skills, relatedness and green diversification: A study of European regions. Research Policy 50 (9): 104340, https://doi.org/10.1016/j.respol.2021.104340.

Schulte, P., Welsch, H., Rexhäuser, S. (2016): ICT and the Demand for Energy: Evidence from OECD Countries. Environmental and Resource Economics 63(1): 119-146.

Thanh Ha, L., Lan Huong, T. T., Thanh, T. T. (2022): Is digitalization a driver to enhance environmental performance? An empirical investigation of European countries. Sustainable Production and Consumption 32: 230-247, https://doi.org/10.1016/j.spc.2022.04.002.

WCED (World Commission on Environment and Development) (1987): Report of the World Commission on Environment and Development: Our Common Future, London, http://www.un-documents.net/our-common-future.pdf.

Table A1: Descriptive Statistics

Variables	Definition	Mean	SD
Sustainability			
Ecoinno	Innovation leading to less environmental emissions or re-source use, 1: yes, 0: no	.221	.415
Energysavings	Energy savings or renewable energy, 1: yes, 0: no	.505	.5
Recycling	Recycling, re-use of materials, 1: yes, 0: no	.598	.49
Reduceresource	Reduction of resource use, 1: yes, 0: no	.496	.5
Sustproducts	Sustainable products or services, 1: yes, 0: no	.32	.467
Sustain	Sustainability index (1-9)	4.13	2.68
Digitalisation			
AI	Artificial Intelligence, 1: yes, 0: no	.077	.266
Bigdata	Big Data Analytics (e. g. Data Mining), 1: yes, 0: no	.145	.352
Cloud	Cloud-computung, 1: yes, 0: no	.479	.5
Highspeed	High-speed infrastructure, 1: yes, 0: no	.337	.473
Robot	Use of robots, 1: yes, 0: no	.086	.28
Smart	Intelligent sensors or control techniques, 1: yes, 0: no	.278	.448
Control variables			
Export	Exports in foreign countries, 1: yes, 0: no	.325	.468
Familyowned	Predominantly family-owned, 1: yes, 0: no	.204	.403
Financecap	High financial capacities, 1: yes, 0: no	.365	.481
Highgrowth	Firm has grown by at least 30% since 2016, 1: yes, 0: no	.198	.399
Localisation	Firm located in an industrial area, 1: yes, 0: no	.129	.335
Oldfirms	Firm founded before 2000, 1: yes, 0: no	.472	.499
Skillshortage	Availability of staff with the right skills poor or very poor, 1: yes, 0: no	.367	.482
Size	Number of employees (ln)	2.332	1.511
Urban	Firm location in a big city, 1: yes, 0: no	.492	.5
Sector dummies	1: yes, 0: no		
Mining	Mining and quarrying	.005	.074
Manufacturing	Manufacturing	.195	.396
Electricity	Electricity, gas, steam and air conditioning	.006	.078
Water	Water supply, sewerage, waste management	.01	.101
Construction	Construction	.096	.295
Saletrade	Wholesale and retail trade, repair	.277	.447
Transport	Transportation and storage	.057	.231
Accomodfood	Accommodation and food service activities	.056	.23
Infocomm	Information and communication	.038	.192
Finance	Financial and insurance activities	.021	.143
Estate	Real estate activities	.023	.15
Techservice	Professional, scientific and technical support	.093	.291
Administ	Administrative and support service	.044	.205
Education	Education	.023	.151
Health	Human health and social work activities	.038	.191
Arts	Arts, entertainment and recreation	.017	.128
Country dummies	1: yes, 0: no		
FR	France	.031	.173
BE	Belgium	.031	.172
NL	Netherlands	.031	.172
DE	Germany	.031	.172

IT	Italy	.031	.172
LU	Luxembourg	.012	.11
DK	Denmark	.031	.172
IE	Ireland	.031	.172
GB	Great Britain	.031	.172
GR	Greece	.031	.172
ES	Spain	.031	.172
PT	Portugal	.031	.172
FI	Finland	.031	.172
SE	Sweden	.031	.172
AT	Austria	.031	.172
CY	Cyprus	.012	.11
CZ	Czech Republic	.031	.172
EE	Estonia	.031	.172
HU	Hungary	.031	.172
LV	Latvia	.031	.172
LT	Lithuania	.031	.172
MT	Malta	.012	.11
PL	Poland	.031	.172
SK	Slovakia	.031	.173
SI	Slovenia	.031	.173
BG	Bulgaria	.031	.172
RO	Romania	.031	.172
TR	Turkey	.018	.134
HR	Croatia	.031	.172
MK	Makedonia	.012	.11
RS	Serbia	.012	.11
NO	Norway	.018	.134
IS	Iceland	.012	.11
JP	Japan	.018	.134
US	USA	.031	.172
BR	Brazil	.021	.143
BA	Bosnia and Herzegovina	.012	.11
KM	Kosovo	.012	.11
CA	Canada	.031	.172