Digital Technologies for Climate Change Mitigation and Adaptation: Evidence from the European Union

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ABSTRACT

This paper demonstrates that digital sustainability inventions have started to emerge but constitute few of the EU27's inventions during 2001-2018. This is the case even though the region offers the greatest breadth of relevant technological specialisations, which currently concentrate primarily in transportation and energy sectors. Nonetheless, the analysis shows that the EU27 lacks specialisation advantages in some key ICT-related technologies, as well as in the top four climate change mitigation and adaption technologies associated with digital sustainability inventions. The paper outlines possible pathways for smart specialisation in digital sustainability technologies, including in renewable energies, transportation, and carbon capture storage, using existing or complementary specialisations as well as international

1. *Disclaimer*: This publication builds upon previous work funded by the European Commission [CT-EX2021D449586-101]. Where relevant we refer to the original source that has been published under the CC BY 4.0 licence. We include a link to code published in European Commission's official repository according to the procedure set by Commission Decision C(2021) 8759. Any views expressed in this publication solely reflect the position of the authors.

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collaboration. We also provide open access to SQL queries, which can be used to recreate the dataset of digital sustainability inventions.

KEYWORDS: Digital Technologies, Green Technologies, Digital Sustainable Technologies, Twin Transition, Smart Specialisation, Technology Space Analysis

JEL CODES: O33, O38, Q55

The European Union (EU) was among the first global players to present a long-term vision for climate neutrality. The Green Deal proposed a sustainable growth strategy, including dematerialising the economy and decoupling economic growth from resource use. The European Climate Law established a legally binding target of reaching net zero greenhouse gas emissions by 2050[2]. So far, the EU has cut its total emissions to nearly a quarter below their 1990 level, but progress has varied across sectors (Arregui *et al.*, 2020). Emissions from power and industry have fallen by about a third, buildings by a quarter, and agriculture by a fifth, while transport emissions have risen (*ibid.*).

The “green transition” refers to a fundamental shift in production and consumption patterns to enable us to live within planetary boundaries (Rockström *et al.*, 2009). A key structural transformation relates to transitioning from high to low-carbon-emitting energy sources . We have already witnessed the growth of renewable energy sources with dramatic reductions in the cost of generating electricity and increases in investment, capacity, and generation (Fouquet, 2019). Although renewable energies, resource-efficient innovations, and new, environmentally-friendly materials are central elements of “green growth”, alone they are not sufficiently far-reaching to sustain growth, as they do not lead to sufficient technical convergence in equipment, engineering, skills, or suppliers (Mazzucato, Perez, 2022; Perez, 2019).

In previous technological revolutions, a new energy source’s success and broad adoption were linked to complementarities with other technologies and industries . In the contemporary context, Perez (2016) argues that information communication technologies (ICTs) have “*the capacity to facilitate wide-ranging sustainable innovations to radically reduce materials and energy consumption while stimulating the economy*” in a possible shift towards green growth (p. 200). Since the 1970s, the ICT revolution advanced digital electronics, including the widespread diffusion of personal computers, mobile communication, and the Internet. Over the past two decades, we have witnessed the diffusion of commercial applications of artificial intelligence (AI), cloud computing, robotics, 3D printing, the Internet of Things (IoT), advanced wireless technologies, and more.

2. http://data.europa.eu/eli/reg/2021/1119/oj.

When analysing the relation between ICTs and energy or resource efficiency, we must differentiate between first-order, second-order and third-order effects (Hilty *et al.*, 2011). First-order effects develop directly from the use of ICTs, whose carbon footprint is growing as greenhouse gases (GHG) are released from all of its life cycle stages. Direct carbon emissions from ICTs are growing at a faster rate than global GHG emissions in general (Freitag, 2021). This trend could accelerate due to the increasing use of (1) big data, data science, and AI; (2) the IoT; and (3) blockchain and cryptocurrencies (*ibid.*). If ICT is an enabling technology that improves or can be substituted for processes in other sectors, it will generate second-order effects in the target sector (Hilty *et al.*, 2011). In energy generation and distribution, digital technologies enable efficient power transmission (Ishida, 2015; Collier, 2017). The deployment of digital technologies in other sectors of production can lead to energy efficiency, for example, in manufacturing, construction, and buildings (Nidumolu, 2009; Hosseini *et al.*, 2017; Sovacool, Furszyfer del Rio, 2020), transportation systems (Mohanty *et al.*, 2016; Bibri, 2018; Noussan, Tagliapietra, 2020; Adedoyin *et al.*, 2020), or in agriculture (Anser *et al.*, 2021). At the same time, however, resource decoupling – the reduction rate of use of primary resources (such as coal and oil) per unit of economic activity – may result in a growth rate of energy consumption of the whole system higher than the decoupling rate, counteracting the resource-saving effects of decoupling. Such third-order or rebound effects are strongest in the ICT sector itself (Koomey *et al.*, 2011).

Today, it is not clear whether ICT and digital technologies allow for efficiency improvements in other sectors and thereby facilitate emission savings bigger than ICT's own emissions and rebound effects (GeSI, 2015), or whether rebound effects are larger than efficiency gains (Court, Sorell, 2020). While the EU's Green Deal acknowledges ICT's first-order effects and commits to reducing them, the primary thrust of the EU climate strategy is to use ICT to enable emissions savings in other industries (Freitag, 2021). This explains why EU policies highlight the notion of the "twin transition", which refers to the potential of digital technologies enabling sustainability through increasing energy and resource efficiency (Amoroso *et al.*, 2021). A pre-condition for any second-order enabling effects of digital technologies in energy, ICT, and other sectors to materialize is the growth of so-called "digital sustainability technologies" (DSTs). They enable us "*to create, use, and regulate digital resources in order to maximize their value for our society today and in the future*" (Stuermer, 2014, p. 494).

The literature inquiring into the extent to which specialisation in green technologies can benefit from the opportunities of digital technologies in the EU is still scarce and primarily focused on a sub-national level of analysis (Bachtrögler-Unger *et al.*, 2023; Cicerone *et al.*, 2023). So far, we have limited evidence on the growth and structural pattern of digital sustainability technologies across a wider range of application sectors. Jindra and Leusin (2022) revealed recently that four main clusters of digital sustainability technologies have been emerging globally since the turn of the century: energy generation and data-related technologies, technologies related to the capture, storage, sequestration or disposal of GHG, technologies related to the processing of goods and domestic applications, and technologies related to transportation.

This paper replicates the main clusters of digital sustainability technologies identified by Jindra and Leusin (2022) and applies technology space analysis to a patent-based dataset (2001–2018) (see Section 2). Then, we analyse the revealed specialisation advantages of EU27 inventors in technologies relevant to the development of four clusters of digital sustainability technologies (see Section 3.1). Next, we investigate relatedness between the clusters and their specific technologies to learn whether, and how, they overlap (see Section 3.2). By considering the current specialisations of EU27 inventors and how these relate to other technologies, we obtain information about potential complementarities that are not yet deployed but which might eventually connect similar knowledge across clusters. Subsequently, we investigate the geography of digital sustainability technologies (see Section 3.3). We analyse the output and specialisations of EU27 inventors at the global level, consider how individual EU27 countries specialise in the relevant technologies linked to the four main clusters, and investigate how international co-inventions feed into the development process. Finally, we discuss our findings in the context of recent research on the "twining" of technologies and develop recommendations on policies to advance smart specialisation in digital sustainability technologies in the EU27 (see Section 4).

Data

Green or digital technologies on their own have been subject to research, and patent data has enabled these technologies to be identified in a variety of ways (see for example EPO, 2020[3]; Inaba, Squicciarini, 2017; León *et al.*, 2018; Haščič, Migotto, 2015; OECD, 2019; Sadowski *et al.*, 2016). So far, however, there is no blueprint for identifying digital sutainability technologies. We follow the method proposed in Jindra and Leusin (2022), which combines specialists' opinions, keywords, and classification-based approaches. We use

3. https://www.epo.org/en/news-events/in-focus/classification/classification/updatesYO2andY04S.

six distinct search modules to generate a joint dataset: Module 1 was entirely based on the Y section (Y02 and Y04) of the Cooperative Patent Classification (CPC)[4]. Module 2 searched patents with at least one digital and one sustainability keyword in their title or abstract. Modules 3 and 4 combined the use of keywords to proxy digital and AI-related technologies with the Y02 code as a proxy for sustainable technologies. Modules 5 and 6 applied International Patent Classification (IPC) codes identified as typical for digital technologies to collect patents classified under the Y02 sustainability tag. We provide the SQL queries to recreate each of these modules as well as the R code used to create the subsequent analysis fron an an open access repository[5].

The adopted strategy uses the Y section of the CPC as the main reference. The CPC scheme, launched in 2013, combines algorithm-based identification with specialists' opinions (Angelucci *et al.*, 2018). The Y02 code refers to technologies or applications for climate change adaptation and mitigation (USPTO, 2021). Alternative approaches to identify "green technologies" include the OECD ENV-TECH classification or the IPC Green Inventory by WIPO (see Favo *et al.*, 2023 for a discussion), which are exclusively based on classification-based selection. In contrast, the "Y" scheme offers an additional quality filter by using specialists' opinions, thereby reducing false positives compared to purely classification-based selections (Angelucci *et al.*, 2018). Important for our purpose, the "Y" code Y04 tags "ICTs having an impact on other technology areas". The "Y" scheme is preferable for identifying technologies that combine sustainability and a digital component (Jindra, Leusin, 2022)[6].

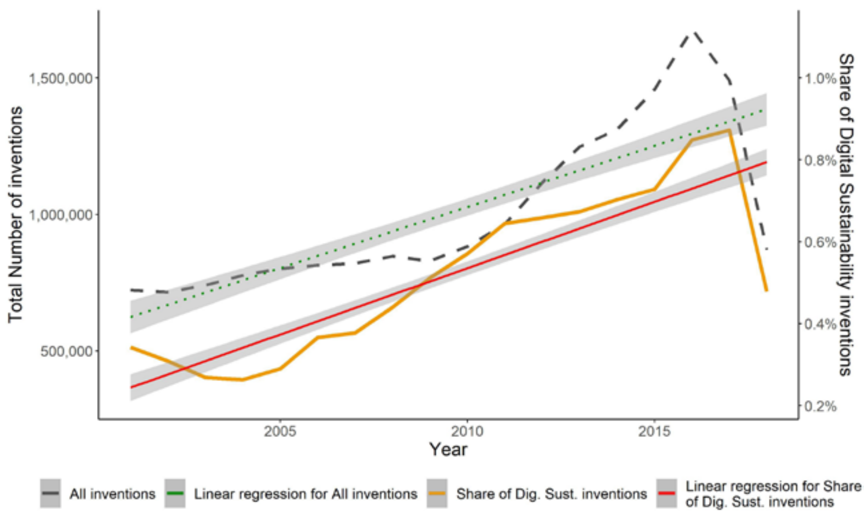
The Y04 code covers digital technologies but, at the same time, it introduces a bias towards digital technologies related to electric power, since this code refers exclusively to "Systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management or usage, *i.e.*, smart grids". Therefore, the adopted strategy extends the search by using keywords related to "digital technologies" and applying International Patent Classification (IPC) codes identified as typical for "digital technologies", to collect patents classified under the Y02 sustainability tag. This

4. https://www.uspto.gov/web/patents/classification/cpc/html/cpc-Y.html.
5. https://code.europa.eu/rentofr/twin-patents.
6. OECD ENV-TECH and Y-classifications yield a similar output, while the patent recall of the latter is about 31% lower. 82.5% of the patents classified in the Y scheme are also found in the ENV-TECH dataset, since 3 out of 9 modules of latter are based on Y codes. The OECD ENV-TECH adds codes in 'Environmental Management' (Module 1), 'Water-Related Adaptation Technologies' (Module 2), and 'Biodiversity Protection and Ecosystem Health' (not yet available Module 3). 29.5% of all patents from ENV-TECH Modules 1 or 2 are also found in the Y tag. In the Y selected dataset, there is a greater variety of IPC subclasses and better coverage of digital technologies linked to fields of 'Digital communication', 'Computer technology', and 'Telecommunications' (Jindra, Leusin 2022, pp. 57-61).

improves especially the coverage of “Climate change mitigation technologies in the production or processing of goods” as well as “Climate change mitigation technologies ICTs aiming at the reduction of their own energy use”.

Applying the search strategy to PATSTAT (Version 2019a) we identified 319,243 patent applications associated with digital sustainability technologies (1990 to 2018). To avoid double-counting, we used only 168,353 priorities[7] registered from 2001 to 2018. 65.5% of all identified digital sustainability priority filings between 2009 and 2018. The registration of new digital sustainability priority inventions has increased slightly faster than the global registration rate of new priorities patents, especially between 2005 and 2011 (see Figure 1). In 2018, the share of new digital sustainability priority inventions reached about one per cent of all new priorities registered globally.

***Figure 1* – Total number of inventions registered and share of digital sustainability inventions (2001-2018)**



Source: Authors’ calculations.

We find most digital sustainability priorities in “Climate change mitigation technologies in the production or processing of goods” (Y02P), “Climate change mitigation technologies in ICT” (Y02D), “Reduction of GHG emissions, related to energy generation, transmission or distribution” (Y02E), and “Climate change mitigation technologies related to buildings” (see Table 1). “Climate change mitigation technologies related to transportation” (Y02T) and

7. A priority patent is the 1st application filed to protect an invention. In case, the same patent is registered in other patent offices, the subsequent registrations are called non-priorities, constituting a patent family linked through the priority filing. From the identified 319,243 digital sustainability patents, 194,440 are priorities. 168,353 from these were registered in the 2001-2018 period considered.

"Technologies for adaptation to climate change" (Y02A) occur less frequently, "Climate change mitigation technologies related to wastewater treatment or waste management" (Y02W) rarely and "Capture, storage, sequestration of GHGs" (Y02C) (0.1%) hardly at all during the observation period.

Table 1 **– Occurrences and share of Y02 subclass in priority digital sustainability patents (2001-2018)**

Code	Description	Number of occurrences	Share
Y02P	Climate change mitigation technologies in the production or processing of goods	49,391	28%
Y02D	Climate change mitigation technologies in information and communication technologies aiming to reduce their own energy use	32,829	19%
Y02E	Reduction of greenhouse gas emissions related to energy generation, transmission or distribution	31,885	18%
Y02B	Climate change mitigation technologies related to buildings, e.g. housing, house appliances or related end-user applications	30,973	18%
Y02T	Climate change mitigation technologies related to transportation	16,468	9%
Y02A	Technologies for adaptation to climate change	12,222	7%
Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	2,991	2%
Y02C	Capture, storage, sequestration or disposal of greenhouse gases	90	0%

Source: Adapted from Jindra and Leusin (2022).

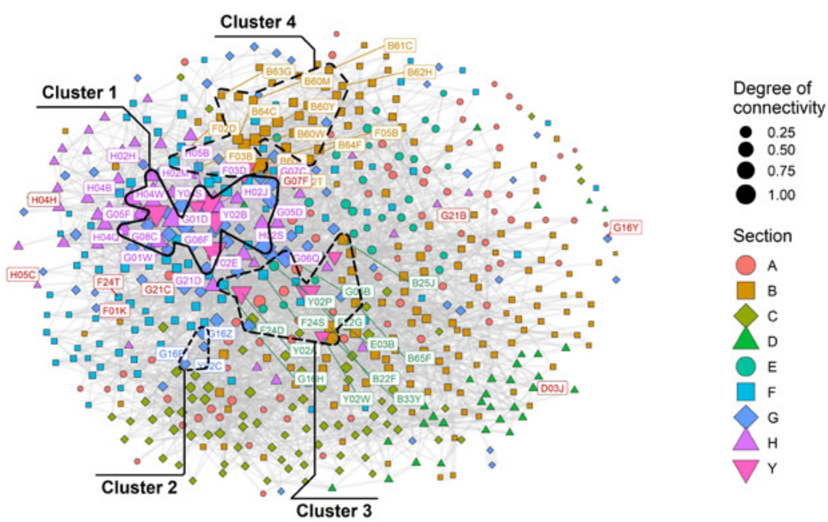
To process information about EU27 inventors, we followed de Rassenfosse *et al.* (2019) and assigned patents to countries by using inventors' addresses. From the 168,353 digital sustainability inventions classified as priority patents (2001–2018), we found information on the inventors' location for 103,366 priorities and used full counting to determine where the invention was made.

Analysis

Clusters of Digital Sustainability Inventions and EU27 Specialisations

We used technology space analysis to identify technologies relevant to the development of digital sustainability inventions. This approach allows data-driven identification of relevant technologies without any ex-ante assumption about how they relate to each other (Breschi *et al.*, 2003). Similar technologies were placed closer to each other in a network visualisation; conversely, less similar technologies are situated farther from one another. We employed the Revealed Technology Advantage (RTA) Index (Soete, 1987) as a specialisation measure to determine technologies that are relatively frequently used to create digital sustainability inventions. The representation of the technology space combined with specialisations enabled us to visually identify clustered technologies. Additionally, we used these technologies' "Section" information to draw the limits between clusters of related digital sustainability technologies.

Figure 2 **– Technology Space of Digital Sustainability Technologies (2001-2018)**



Note: Specialisations that are not included in the four clusters are highlighted in red.
Source: Adapted from Jindra and Leusin (2022).

Of the 670 4-digit CPC codes in the technology space, 62 show at least one specialisation. Of these, 53 are placed relatively close to each other, whereas the remaining nine appear to be relatively disconnected. The 53 codes fall into four distinct clusters (see Figure 2): Cluster 1 is composed primarily of technologies from Sections H (Electricity) and G (Physics). Clusters 4 and 3 are very close to Cluster 1 but relatively distant from each other, and contain mainly technologies from Section B (Performing operations, transporting). Cluster 2, relatively distant from these three clusters, is composed primarily of technologies from Section G (Physics). Clusters 1 and

3 are by far larger than the other two clusters, and continuously expand in terms of total patents (see Table 2). We find that, on average, Clusters 2 and 4 combine a higher number of technologies per invention (measured by the average number of 4-digit CPC codes in their patents). This could indicate that their technologies are more complex and, thus, partially explain the smaller size of these clusters.

Muench *et al.* (2022) suggests agriculture as another possible focus sector for the integrated green and digital transitions. Agriculture-related technologies are primarily covered in Section A (Human necessities) of the CPC classification. However, we find that none of the A01 codes (directly related to agriculture) shows a specialisation in our technology space analysis, *i.e.*, the frequency of use of these codes to create digital sustainability technologies is still low. Most of the A01 codes appear in the technology space close to Cluster 3, indicating that they share technical similarities.

In Tables 3-6 below, we present each of the 53 main technologies according to the cluster to which they belong, indicate the growth of inventions over the three intervals, and display technologies in which EU27 inventors have a specialisation advantage in international comparison (*i.e.*, RTA> 1). We also calculate, separately, specialisations for the three distinct time intervals (2001-2006, 2007-2012, 2013-2018) to determine whether clusters expanded or contracted in terms of the number of specialisations over time.

Digital Sustainability Technologies in Energy Generation and Data-Related Technologies

Cluster 1 holds digital sustainability inventions related to *energy generation and data-related technologies*. We linked 24 CPC codes to this cluster (see Table 3), which takes the most central position in the technology space, besides showing the highest number of specialisations of all four identified clusters across all three intervals (21 in the 1st, 18 in the 2nd, and 17 in the 3rd interval). Cluster 1 includes three sustainability Y02 codes, namely "Climate change mitigation technologies related to buildings" (Y02B), "Climate change mitigation technologies in ICT" (Y02D), and "Reduction of GHG emissions, related to energy generation, transmission or distribution" (Y02E). The Y02E and Y02B codes, which refer to energy generation, transmission, or distribution, and end-user applications, respectively, appear strongly linked to CPC codes related to energy generation (*e.g.*, F03D, G21D, and H02S), transmission/distribution (*e.g.*, H04B, H02J, H02M, and Y04S), and in-house electric technologies (*e.g.*, G01D, F21W, H02H, and H05B). The Y02D code, which focuses on ICT technologies, appears most strongly linked to data processing and data transmission technologies (*e.g.*, G06F, G06Q, H04L, and H04W).

Table 2 – Summary statistics for the four identified clusters

Cluster	Avg. N. of 4 dig. CPC	Avg. Year Patents	Total No. Codes Cluster	No. Patents 2001–2006 (1st interval)	No. Patents 2007–2012 (2nd interval)	No. Patents 2013-2018 (3rd interval)	Total Patents	Growth from 1st to 2nd interval	Growth from 2nd to 3rd interval	Avg. Growth
1	3.2	2013.2	24	12,102	36,001	62,123	110,226	197%	73%	135%
2	4.1	2012.5	3	94	151	220	465	61%	46%	53%
3	2.4	2012.7	13	9,997	19,043	38,652	67,692	90%	103%	97%
4	3.9	2012.9	13	1,452	6,486	9,936	17,874	347%	53%	200%

Regarding the specialisations of EU27 inventors, we determined that EU27 inventors have a revealed specialisation advantage in 8 out of 25 Cluster 1 technologies, including "Transmission of digital information" (H04L), "Circuit arrangements or systems for supplying or distributing electric power" (H02J), "Wireless communication networks" (H04W), "Electric digital data processing" (G06F), and "Systems integrating technologies related to power network operation" (Y04S). Furthermore, we find high specialisation index values in less frequent ICT-related areas such as "Measuring" (G01D) and "Selecting" (H04Q). However, EU27 inventors lack specialisation in prominent ICT technologies such as "Climate change mitigation technologies in ICT" (Y02D) and "Data processing systems or methods" (G06Q).

In terms of low-carbon energy-related technologies, we find that EU27 inventors have a high specialisation advantage in "Wind motors" (F03D), a modest one in "PV-modules" but no specialisation in technologies related to "Nuclear power plants" (G21D). All three technologies appear with low relative frequency for digital sustainability inventions, especially compared to ICT-related fields.

Digital Sustainability Technologies in GHG Capture and Storage

The second cluster features technologies used to *capture, store, sequester, or dispose of GHGs* (Y02C). By far the smallest cluster, this basically has vanished over time, holding three specialisations in the 1st interval, two in the 2nd, and zero in the 3rd. Linked to it are two ICT technologies, namely "Bioinformatics" (G16B) and "ICT for specifically adapted application fields" (G16Z) (see Table 4). EU27 inventors hold a specialisation advantage in the cluster as a whole and "Bioinformatics" (G16B), but not in "ICT for specifically adapted application fields".

Digital Sustainability Technologies in the Processing of Goods and Domestic Applications

Cluster 3 is the only cluster that expands the number of relevant specialisations (8 in the 1st interval, 5 in the 2nd, and 11 in the 3rd). It shows the largest average growth of individual technologies deployed (see Table 5).

Cluster 3 can be linked to digital *sustainability inventions in the processing of goods and domestic applications*. It includes three Y02 subclasses, namely "Technologies for adaptation to climate change" (Y02A), "Climate change mitigation technologies in the production or processing of goods" (Y02P), "Climate change mitigation technologies related to wastewater treatment or waste management" (Y02W). Apart from Y02P, we find several other

Table 3 – **Technologies relevant to the deployment of digital sustainability inventions in Cluster 1**

CPC code	Cluster 1: Energy generation and data-related technologies	No. of occur.	1st – 3rd Interval	Specialis. EU27
Y02D	Climate change mitigation technologies in information and communication technologies [ICT], i.e. ICTs aiming at the reduction of their own energy use	32,829	118%	0.72
Y02E	Reduction of greenhouse gas emissions related to energy generation, transmission, or distribution	31,885	880%	0.59
Y02B	Climate change mitigation technologies related to buildings, e.g. housing, house appliances or related end-user applications	30,973	786%	0.68
Y04S	Systems-integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management or usage, i.e. smart grids	26,601	700%	1.07
G06F	Electric digital data processing	15,745	235%	1.16
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy	14,188	906%	1.77
H04L	Transmission of digital information, e.g. telegraphic communication	13,851	206%	1.84
H04W	Wireless communication networks	13,789	174%	1.53
G06Q	Data processing systems or methods specially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes; systems or methods specially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes, not otherwise provided for	13,278	484%	0.81
H05B	Electric heating; electric light sources not otherwise provided for; circuit arrangements for electric light sources, in general	3,744	903%	0.83
H04B	Transmission	3,367	99%	1.76
G01D	Measuring not specially adapted for a specific variable; arrangements for measuring two or more variables not covered in another subclass; tariff metering apparatus; measuring or testing not otherwise provided for	2,359	98%	5.17

CPC code	Cluster 1: Energy generation and data-related technologies	No. of occur.	1st – 3rd Interval	Specialis. EU27
G05D	Systems for controlling or regulating non-electric variables	1,743	922%	1.68
G08C	Transmission systems for measured values, control or similar signals	1,468	1120%	1.22
H02M	Apparatus for conversion between ac and ac, between ac and dc, or between dc and dc, or for use with mains or similar power supply systems; conversion of dc or ac input power into surge output power; control or regulation thereof	1,287	316%	2.20
H02S	Generation of electric power by conversion of infra-red radiation, visible light or ultraviolet light, e.g. using photovoltaic modules	1,264	2788%	1.05
F03D	Wind motors	1,158	617%	3.67
G07C	Time or attendance registers; registering or indicating the working of machines; generating random numbers; voting or lottery apparatus; arrangements, systems or apparatus for checking not provided for elsewhere	1,091	695%	3.28
H04Q	Selecting	917	75%	3.89
H02H	Emergency protective circuit arrangements	736	366%	1.96
G05F	Systems for regulating electric or magnetic variables	582	1335%	2.37
F21W	Indexing scheme associated with subclasses F21K, F21L, F21S and F21V, relating to uses or applications of lighting devices or systems	513	2394%	0.36
G01W	Meteorology	423	1104%	0.65
G21D	Nuclear power plant	265	224%	0.87

Source: Adapted from Jindra and Leusin (2022).

Table 4 **– Technologies relevant to the deployment of digital sustainability inventions in Cluster 2**

CPC code	Cluster 2: Capture, storage, sequestration or disposal of GHGs	No. of occur.	1st – 3rd Interval	Specialis. EU27
G16Z	Information and communication technology [ICT] specially adapted for specific application fields, not otherwise provided for	245	418%	0.71
G16B	Bioinformatics, i.e. ICT specially adapted for genetic or protein-related data processing in computational molecular biology	138	-11%	1.04
Y02C	Capture, storage, sequestration or disposal of greenhouse gases	90	106%	1.38

Source: Adapted from Jindra and Leusin (2022).

technologies directly linked to the production or processing of goods such as "Working metallic powder" (B22F), "Additive manufacturing" (B33Y), "Healthcare informatics" (G16H), and "Superheating of steam" (F22G). We find specific domestic applications, which include, apart from Y02A and Y02W, technologies such as "Solar heat collectors or systems" (F24S), "Gathering or removal of domestic or like refuse" (B65F), "Installations or methods for obtaining, collecting, or distributing water" (E03B), and "Domestic- or space-heating systems" (F24D).

Amongst the most frequently patented Cluster 3 technologies, EU27 inventors possess a specialisation advantage only in "Control or regulating systems" (G05B) and the region lacks specialisations in dominant technologies of this cluster, including "Climate change mitigation technologies in the production or processing of goods" (Y02P) and "Climate change mitigation technologies related to wastewater treatment or waste management" (Y02W). EU27 inventors show advantages relevant for deployment in less prevailing technologies such as "Additive Manufacturing" (B33Y), "Working metallic powder" (B22F), "Manipulators" (B25J), "Solar heat collectors" (F24S), and "Domestic – or space heating systems" (F24D).

Digital Sustainability Technologies in Transportation

Cluster 4 is related to *transportation* technologies and shows a decreasing number of relevant specialisations over time (9 in the 1st, 7 in the 2nd/3rd intervals).

This cluster has only one Y02 subclass, namely "Climate change mitigation technologies related to transportation" (Y02T) and it is the only cluster without any codes linked directly to ICT (see Table 6). A variety of technologies are linked to vehicles and engines for civilian and military use. Apart from Y02T, the cluster is dominated by technologies relating to "Propulsion of electrically propelled vehicles" (B60L), the category with the highest growth rate during the observation period, whereas technologies related to "Controlling combustion engines" (F02D) stagnated. Other transportation technologies linked to Cluster 4 include "Power supply lines" (B60M), "Conjoint control of vehicle sub-units" (B60W), "Controlling combustion engines" (F02D), "Locomotives" (B61C), "Offensive or defensive arrangements on vessels" (B63G), "Aeroplanes; helicopters" (B64C), "Ground or aircraft-carrier-deck installations" (B64F), or "Indexing scheme relating to wind, spring, weight, inertia or like motors, to machines or engines for liquids" (F05B).

We find that EU27 inventors possess specialisation advantages in all technologies associated with Cluster 4. This includes specialisation advantages in the dominant fields of "Climate change mitigation technologies

Table 5 – **Technologies relevant to the deployment of digital sustainability inventions in Cluster 3**

CPC code	Cluster 3: Processing of goods and domestic applications	No. of occur.	1st – 3rd Interval	Specialis. EU27
Y02P	Climate change mitigation technologies in the production or processing of goods	49,391	217%	0.46
G05B	Control or regulating systems in general; functional elements of such systems; monitoring or testing arrangements for such systems or elements	15,796	318%	2.03
Y02A	Technologies for adaptation to climate change	12,222	660%	0.28
Y02W	Climate change mitigation technologies related to wastewater treatment or waste management	2,991	407%	0.45
B33Y	Additive manufacturing, i.e. Manufacturing of three-dimensional [3-D] objects by additive deposition, additive agglomeration or additive layering, e.g. By 3-D printing, stereolithography or selective laser sintering	1,540	4869%	1.39
B22F	Working metallic powder; manufacture of articles from metallic powder; making metallic powder; apparatus or devices specially adapted for metallic powder	1,171	5989%	1.65
G16H	Healthcare informatics, i.e. Information and communication technology [ICT] specially adapted for the handling or processing of medical or healthcare data	909	50%	0.74
B25J	Manipulators; chambers provided with manipulation devices	678	283%	2.77
F24S	Solar heat collectors; solar heat systems	604	626%	1.50
F24D	Domestic- or space-heating systems, e.g. Central heating systems; domestic hot-water supply systems; elements or components therefor	438	597%	2.61
B65F	Gathering or removal of domestic or like refuse	404	888%	0.67
E03B	Installations or methods for obtaining, collecting, or distributing water	356	2655%	0.17
F22G	Superheating of steam	78	–	0.00

Source: Adapted from Jindra and Leusin (2022).

Table 6 **– Technologies relevant to the deployment of digital sustainability inventions in Cluster 4**

CPC code	**Cluster 4: Transportation technologies**	**No. of occur.**	**1st – 3rd Interval**	**Specialis. EU27**
Y02T	Climate change mitigation technologies related to transportation	16,468	583%	1.61
B60L	Propulsion of electrically-propelled vehicles; supplying electric power for auxiliary equipment of electrically-propelled vehicles; electrodynamic brake systems for vehicles in general; magnetic suspension or levitation for vehicles; monitoring operating variables of electrically-propelled vehicles; electric safety devices for electrically-propelled vehicles	7,663	849%	2.65
B60W	Conjoint control of vehicle sub-units of different type or different function; control systems specially adapted for hybrid vehicles; road vehicle drive control systems for purposes not related to the control of a particular sub-unit	1,351	263%	3.75
F02D	Controlling combustion engines	930	4%	6.16
F05B	Indexing scheme relating to wind, spring, weight, inertia or like motors, to machines or engines for liquids covered by subclasses F03B, F03D and F03G	825	367%	4.19
B60Y	Indexing scheme relating to aspects cross-cutting vehicle technology	597	1422%	1.25
B64C	Aeroplanes; helicopters	561	516%	3.18
F03B	Machines or engines for liquids	275	767%	1.94
B64F	Ground or aircraft-carrier-deck installations specially adapted for use in connection with aircraft; designing, manufacturing, assembling, cleaning, maintaining or repairing aircraft, not otherwise provided for; handling, transporting, testing or inspecting aircraft components, not otherwise provided for	155	808%	2.37
B60M	Power supply lines and devices along rails for electrically-propelled vehicles	118	1300%	2.77
B62H	Cycle stands; supports or holders for parking or storing cycles; appliances preventing or indicating unauthorized use or theft of cycles; locks integral with cycles; devices for learning to ride cycles	94	1750%	1.07
B61C	Locomotives; motor railcars	71	107%	1.28
B63G	Offensive or defensive arrangements on vessels; mine-laying; mine-sweeping; submarines; aircraft carriers	39	200%	2.77

Source: Adapted from Jindra and Leusin (2022).

related to transportation" (Y02T) and "Propulsion of electrically propelled vehicles" (B60L). Notably, an exceptional high index value for specialisation advantage is still associated with technologies "Controlling combustion engines" (F02D).

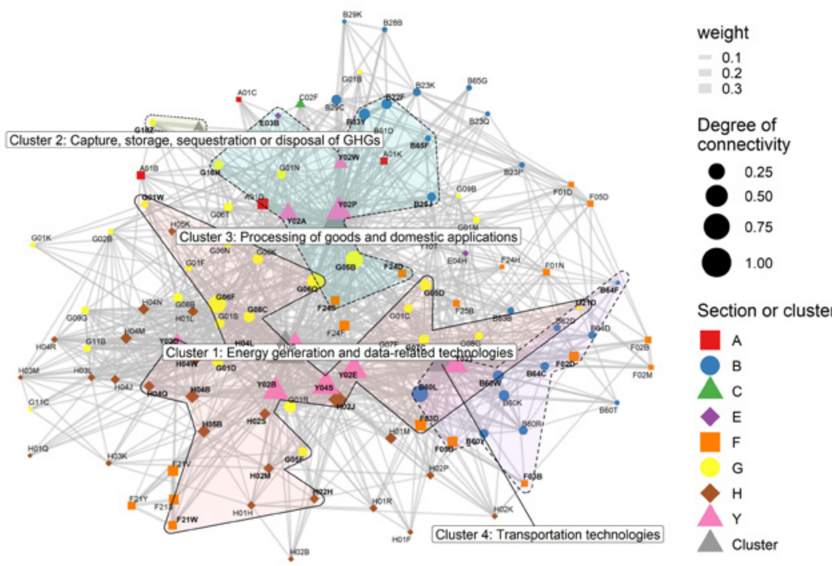
Summing up, our analysis demonstrates that EU27 inventors lack specialisation advantages in ICT technologies, most notably the ones from Cluster 1, like technologies for climate change mitigation and data processing systems or methods. Furthermore, EU27 inventors lack specialisation advantages in highly relevant sustainability technologies like climate change mitigation technologies in the production or processing of goods, climate change mitigation technologies related to wastewater treatment and waste management, as well as technologies for adaptation to climate change (all in Cluster 3). Similarly, we find a lack of specialisation advantages in ICT-related climate change mitigation technologies and mitigation technologies related to buildings, as well as technologies related to the reduction of greenhouse GHG emissions related to energy generation, transmission, or distribution (all from Cluster 1). In short, EU27 inventors had no specialisation in any of the top four climate change mitigation and adaption technologies (see Table 1) associated with digital sustainability inventions during the observation period. The EU27 dominates in terms of specialisation advantages relevant to digital sustainability advantages in transportation; however, from a global perspective, this cluster is relatively small and less directly linked with ICT or digital technologies.

Exploring Relatedness between Clusters of Digital Sustainability Technologies

Next, we focus on understanding the relatedness of the four identified clusters and their specific technologies. We created a code for each of the four clusters and used it to calculate new technology spaces. We used the 53 relevant technologies to link these cluster codes to each individual patent. For example, if a patent has the CPC codes B63G (from Cluster 4) and F22G (from Cluster 3), we linked the patent to these two clusters. This approach enables the measurement of relatedness between clusters due to their co-occurrence in patents. We excluded nodes with poor connectivity from the technology space to highlight the more relevant technologies (see Figure 3). Technologies very close to each other at the edges of clusters, especially those from the same CPC Section, are understood to be highly related to each other. We assumed that these technologies offer a way of connecting similar knowledge across clusters of digital sustainability technologies.

Cluster 1 ("Energy generation and data-related technologies") seems to be the most ubiquitous cluster, with more varied technologies. It has technologies that are closely related to both Cluster 3 ("Processing of goods and domestic applications") and Cluster 4 ("Transportation technologies"). In turn, these two clusters connect exclusively to Cluster 1. Finally, Cluster 2 ("Capture, storage, sequestration, or disposal of GHGs") is very isolated and does not connect to any other cluster of digital sustainability technologies. This implies that Cluster 2 is unrelated to the other clusters of digital sustainability inventions and follows its own development trajectory, while the evolution of the other clusters is interconnected.

Figure 3 **– Technology Space of Digital Innovation Technologies (2001-2018) with the main technologies and clusters highlighted**

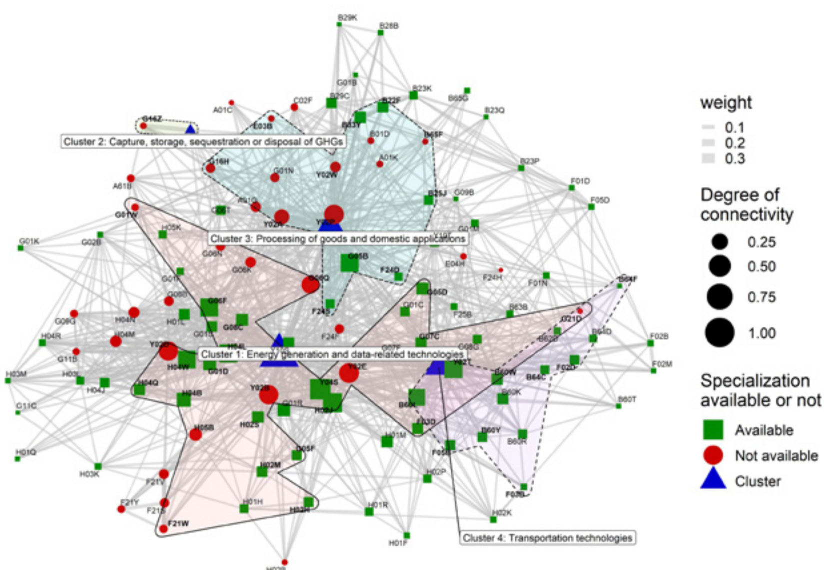


Note: The main relevant technologies from each cluster are shown in bold letters.
Source: Authors' calculations.

In terms of connecting technologies, we find that codes G06Q ("Data processing systems or methods, especially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes") and G05B ("Control or regulating systems in general") connect Clusters 1 ("Energy generation and data related technologies") and Cluster 3 ("Processing of goods and domestic applications"). Codes F03D ("Wind motors" from Cluster 1) and F05B ("Indexing scheme relating to wind, spring, weight, inertia or like motors, to machines or engines for liquids") connect Cluster 1 ("Energy generation and data related technologies") and Cluster 4 ("Transportation technologies"), respectively.

Figure 4 highlights the position of specialisations of EU27 inventors in the cluster-specific technology space shown in Figure 3. By displaying the existing specialisations of EU27 inventors previously discussed (see Tables 3–6) and how these relate to other technologies, we can identify potential complementarities that are not yet deployed in the development of digital sustainability inventions. This seems to be the case for technologies Y02E ("Reduction of GHG emissions, related to energy generation, transmission, or distribution"), Y02B ("Climate change mitigation technologies related to buildings, *e.g.*, Housing, house appliances or related end-user applications"), and G21D ("Nuclear power plant"). These technologies show no existing specialisation for EU27 inventors, but are highly complementary to the existing specialisations, which could facilitate their future development.

Figure 4 **– Technology Space of Digital Innovation Technologies (2001-2018) with specialisations of EU27 countries highlighted**



Source: Authors' calculations.

Other sustainable technologies, like Y02P ("Climate change mitigation technologies in the production or processing of goods"), Y02A ("Technologies for adaptation to climate change"), and Y02W ("Climate change mitigation technologies related to wastewater treatment or waste management"), also show no specialisation by EU27 inventors (see Tables 3–6), but they seem less related to existing specialisations of EU27 inventors, which could imply that greater efforts for their development are necessary. Finally, technologies with no specialisation advantages for EU27 inventors are partially surrounded by specialisations like Y02D ("Climate change mitigation technologies in ICT") and G06Q ("Data processing systems or methods, specially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes"). These technologies fall between the two categories discussed in this section.

Geography of Digital Sustainability Technologies from the EU27 Perspective

Output

Inventors from China account for approximately 52.8% of the digital sustainability patents identified. Japan, the US, South Korea, EU27, and other European (Non-EU) countries follow, with 16.3%, 11.6%, 8.0%, 6.2%, and 1.3% respectively.[8] When considering the share of digital sustainability patents compared to all patents created by a country, India and Israel lead, with 1.03% and 0.98% in in these technologies (see Annex Figure A1). China and the US follow, with 0.78% and 0.65%, respectively. For the EU27, digital sustainability inventions represent 0.41% of the total inventions. Thus, the EU27 rate is lower than the US rate, which might be partially related to the fact that the US is more specialised in ICT-related technologies, which have a higher propensity for being patented. India and Canada show several peaks in registrations of digital sustainability inventions, whereas Japan shows a very stable and low level. Most other regions/countries, including the EU27, show a steadily increasing trend over time (see Annex Figure A2). Nevertheless, the share of digital sustainability inventions constitutes across all countries a very small fraction of overall patenting, rarely exceeding one per cent after almost two decades of development.

International Comparison of Specialisation across Clusters of Digital Sustainability Inventions

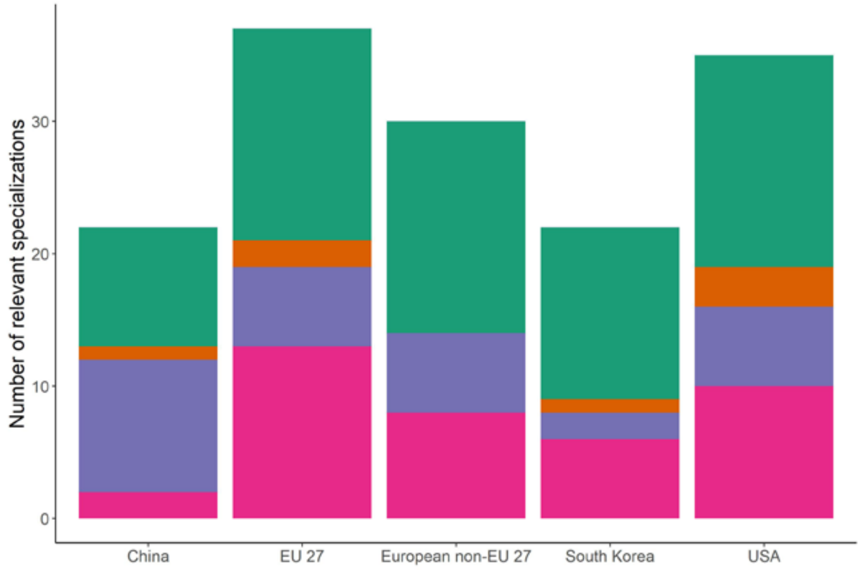
Next, we calculate the RTA of countries for all 4-digit CPC codes used at least once in a digital sustainability invention during the observation period. Analysis of the resulting 607 codes indicates that China leads in terms of number of specialisations, with 291 specialisations, followed by the US (214),

8. The performance by Chinese inventors should be treated with great caution, given the fact that our data source is priority patent applications. China saw a general shift in priority patent applications after the early 2000s driven by a change in the IPR framework and subsidies, which provided incentives for Chinese applicants to apply for protection only in China without subsequent extension from SIPO to other jurisdictions (Chen *et al*., 2016; Li, 2012; Dang, Motohashi, 2015).

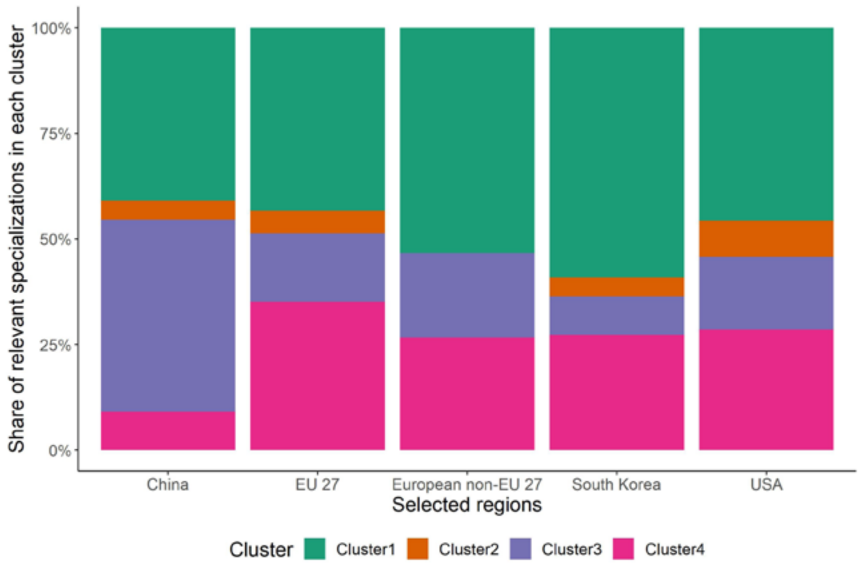
the EU27 (207), South Korea (200), other non EU27 European countries[9] (100), and Canada (66). We focus on these five countries/regions in the subsequent analysis, which looks at the specialisation advantages in technologies relevant to the main clusters. From these 53 technologies, the EU27, the US, and other European countries lead with 37, 35, and 30 specialisations, respectively, followed by China and South Korea with 22 specialisations each (see top panel of Figure 5). Thus, in international comparison, the EU27 region enjoys the greatest breadth of specialisation advantages in technologies that are relevant to the deployment of digital sustainability inventions.

EU27 and US inventors show a balanced distribution of specialisation advantages between Cluster 1 ("Energy generation and data related technologies") and Cluster 4 ("Transportation related technologies"), and EU27 inventors lead globally in Cluster 4 (see bottom panel of Figure 5). China has most of its specialisations in technologies associated with Cluster 3 ("Processing of goods and domestic applications") and South Korea's are centred in Cluster 1 ("Energy generation and data-related technologies"). Thus, economies differ from each other in terms of their potential to develop different types of digital sustainability inventions based on their existing specialisation profile.

***Figure 5* – Absolute and relative number of specialisations in each of the identified clusters (2001-2018)**



9. Andorra, Albania, Armenia, Azerbaijan, Bosnia and Herzegovina, Belarus, Switzerland, Faroe Islands, Georgia, Guernsey, Gibraltar, Greenland, Isle of Man, Iceland, Jersey, Liechtenstein, Monaco, Moldova, Montenegro, Former Yugoslav Republic of Macedonia, Norway, Serbia, San Marino, Ukraine, United Kingdom.



Source: Authors' calculations.

Investigating how individual EU27 countries specialise in the 53 relevant technologies, we find that France leads, followed by Germany, Italy, and Spain (see Annex Table A1). These four EU27 countries have the greatest breadth of specialisation advantages in technologies relevant to digital sustainability inventions. On the other side of the spectrum, we find EU27 members from the Baltics and Central Europe as well as Portugal and Greece. Scandinavia, Ireland, the Netherlands, Belgium and the Czech Republic are in the middle of the distribution. France has the most specialisations relevant to Cluster 1 ("Energy generation and data related technologies") and Cluster 4 ("Transportation related technologies"). In addition, it is the only EU27 country with a specialisation advantage in Cluster 2 ("Capture, storage, sequestration, or disposal of GHGs"). Spain has the most specialisation advantages relevant to deployment in digital sustainability technologies related to Cluster 3 ("Processing of goods and domestic applications").

We have demonstrated that EU27 as a region lacks specialisation advantages in ICT technologies such as "Climate change mitigation technologies in ICT" (Y02D) and "Data processing systems or methods, specially adapted for administrative, commercial, financial, managerial, supervisory or forecasting purposes" (G06Q) (see Table 3). These technologies seem only partially related to existing knowledge when assessed at the EU27 level (see Figure 4). Although we argue above that these technologies require relatively larger efforts to be developed in the EU, they constitute a main element for the advancement of digital sustainability inventions in Cluster 1 ("Energy generation and data related technologies") and could be furthered by individual EU27 countries that possess relevant specialisation advantages.

For example, Belgium, Finland, Ireland, Italy, the Netherlands, and Sweden show specialisation advantages in "Climate change mitigation technologies in ICT" (Y02D) and/or "Data processing systems or methods" (G06Q) (see Annex Table A2). Furthermore, Denmark is specialised in technologies related to the "Reduction of GHG emissions, related to energy generation, transmission, or distribution" (Y02E) and Belgium and Italy in "Climate change mitigation technologies related to buildings (Y02B) – both technologies have a key role in Cluster 1. Finally, it seems that France is the only European country with a specialisation advantage in "Nuclear power plants" (G21D) complementing wind and PV technologies as renewable energy sources in Cluster 1.

International Co-Invention Patterns

Finally, we analyse international co-inventions, which indicates to what extent and how international collaboration feeds into the development of digital sustainability technologies in the EU27. International co-inventions are patents with inventors from at least two countries. We first consider digital sustainability priority patents for the 13 countries/regions with more than 100 digital sustainability priority patents (see Annex Table A3). We find an average of international co-inventions in digital sustainability inventions for all countries of 17.1%, which is higher than the corresponding share of international co-inventions in all priority patents (12%) during the observation period. This signals a higher propensity for international co-inventions for digital sustainability technologies and applies to all countries apart from China. For countries like India, Israel, and Canada, more than one-third of digital sustainability inventions were international co-inventions. For the EU27, about 10% of digital sustainability patents are based on international co-inventions, which is comparable to the US proportion (12%). All Asian countries show low rates of international co-inventions for all priority patents, including for digital sustainability inventions. In the development of digital sustainability technologies China has the lowest proportion (0.6%) of international co-inventions.

For the EU27, we find the highest share of international co-inventions in Cluster 1 (64.5%), followed by clusters 3 (26.0%), 4 (9.2%) and 2 (0.3%). Most EU27 international co-inventions are with co-inventors from the US (36.3%), followed by other countries (35.8%), European non-EU27 countries (24.9%) and less than 5.0% with with China. Although co-inventions of EU27 inventors with the US and China have a very different extent, the most frequent technologies developed via collaboration are similar. Most occur in Cluster 1 technologies, especially "Climate change mitigation technologies in ICTs" (Y02D) – a technology that is not only central to Cluster 1 but in which the EU27 lacks a specialisation advantage. EU27 inventors also frequently collaborate in the ICT-related technologies of Cluster 1, in which the region possesses a specialisation advantage: "Electric digital data processing" (G06F) in case of co-inventions with the US and "Transmission of digital information" (H04L) in case of co-inventions with China. We find the profile of co-inventions with European non-EU27 countries more broadly dispersed. The leading technologies are "Climate change mitigation technologies in the production or processing of goods" (Y02P) (Cluster 3) and "Systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management, or usage" (Y04S) (Cluster 1).

Discussion and Policy Implications

Our findings suggest that despite steady growth, digital sustainability inventions account only for a very small fraction (0.41%) of all inventions in the EU27. Thus, "twin technologies" are growing, but the integration of green and digital technologies proceeds slowly. This finding seems also to apply to scientific knowledge; Bianchini *et al.* (2023) documented that across the EU, "twin publication" accounted for about only one per cent in the early 2000s and rose to about three per cent of digital and six per cent of green publications at the end of the 2010s. Thus, the integration of digital and sustainable scientific knowledge as well as technologies has only been advancing to a limited extent. These empirical insights suggest caution as to how much digital technologies can enable second-order effects (Hilty *et al.*, 2011) in the wider economy, given that they are central to the EU's current climate strategy (Freitag, 2021), for example, reflected in the EU action plan on digitalising the energy system (COM, 2022).

Bachtrögler-Unger *et al.* (2023) find the European landscape of green and digital technologies is marked by high levels of concentration of key twin transition technologies in more developed regions, where more than 80% of twin transition technologies are invented. The researchers argue that the EU remains replete with unrealised potential to combine complementary regional technological capabilities, particularly by collaborating across national borders. This argument resonates with our finding that there seems to be a higher propensity for international co-inventions of digital sustainability technologies than other technologies. We find a rate of about 10% for the

EU27, which primarily has partners in the US and other European countries (hardly with China), and deals primarily with "Climate change mitigation technologies in ICTs", "Electric digital data processing", and "Transmission of digital information". Thus, international collaboration, primarily with the US, seem an important channel to foster the application of ICTs to climate change mitigation and adaption technologies in the EU27.

A number of inter-related dynamic market failures apply to the digital and green transitions, including scale economies, learning spillovers and network externalities (Geels *et al.*, 2021). They suggest that without public intervention to steer innovation and create new markets, the private sector is likely to underinvest in the range of assets necessary to generate higher productivity growth. A central strategy of long-run economic policy should be to ensure "smart green growth" (Mazzucato, Perez, 2023; Perez, 2019). The literature inquiring the extent to which specialisation in green scientific knowledge or technologies can benefit from the opportunities of the digital transformation is still scarce, and, as documented above, mainly focused upon the sub-national level of analysis (Bachtrögler-Unger *et al.*, 2023; Cicerone *et al.*, 2023). We extend this line of research by investigating the specialisation patterns of the EU27 – as a group as well as individual EU countries – for the main clusters of digital sustainability technologies following the methodology proposed by Jindra and Leusin (2022). The following discussion of findings and policy recommendations are embedded in the smart specialisation approach (Foray *et al.*, 2009), which emphasises relatedness, complexity, and regional diversification (Balland *et al.*, 2019), prioritisation (Panori *et al.*, 2022) and directionality as well as, more recently, an orientation towards sustainability (Miedzinski *et al.*, 2021).

Energy Generation and Data-Related Technologies

We find that the EU27 has specialisation advantages – in, among others, the transmission of digital information, electric data processing, circuit arrangements, and wireless networks – that are relevant for deployment in the cluster of energy generation and data-related technologies. This is crucial, since it is the most central cluster with a great variety of technologies, including some that connect to other domains of digital sustainability technologies in transportation, as well as in processing of goods and domestic applications. From our findings, we can highlight three particular characteristics:

First, the EU27 as a group lacks relevant specialisations in ICTs for climate change mitigation and data processing methods, which dominate this large cluster of digital sustainability inventions at the global level. At the level of individual EU27 countries, Belgium, Finland, Ireland, Italy, the

Netherlands, and Sweden show specialisation advantages. Furthermore, most international co-inventions by EU27 inventors take place in these specific ICT-related technologies, primarily with partners from the US. Thus, reinforcing country-level specialisations and international collaborations could be effective strategies for enhancing the EU's "twinning" in this central cluster of digital sustainability innovations.

Second, with respect to renewable energy technologies, we find that EU27 inventors have an advantage in wind and PV-modules but not in technologies related to nuclear power. Given that the EU's green taxonomy now includes nuclear energy, all three energy-related areas – wind, PV and nuclear – could benefit from a set of financial instruments that encourage investment[10] (EC, 2022). France, for example, could benefit from R&D and technology support targeting nuclear safety and waste management. At this stage, digital sustainability inventions in renewable energy occur much less frequently, compared to the ICT domains, which might indicate that direct take-up of digital technologies in inventions for renewable energies is slow.

Third, progress could be more impactful in technologies for GHG emissions related to energy generation, transmission, or distribution, as well as climate change mitigation technologies related to buildings. These are not only complementary to existing specialisations in the EU, but also two out of the top three technologies relevant for digital sustainability inventions in the energy-related domain, which the EU27 aspires to advance.

GHG Capture and Storage

Technologies associated with the capture, storage, sequestration, or disposal of GHG are part of an extremely small cluster of digital sustainability inventions; the cluster practically vanished during the observation period in terms of the number relevant specialisations (see Jindra, Leusin, 2022). We find this cluster to be isolated in the technology space of digital sustainability inventions. EU27 inventors, apparently driven by France, have a specialisation in the capture, storage, sequestration, or disposal of GHG. Global rates of carbon capture storage (CCS) deployment are far below those required by to store enough carbon to limit global warming to 1.5 °C to 2° C, according to model predictions (IPCC, 2023). CCS implementation faces various barriers, which could be reduced by policy instruments, greater public support and technological innovation (*ibid.*) Therefore, it might be appropriate for the EU to consider relevant barriers and to support digital sustainability inventions assisting CSS deployment.

10. http://data.europa.eu/eli/reg_del/2022/1214/oj.

Transportation

Most EU27 specialisations relate to the cluster of digital sustainability technologies in transportation. However, we know that this is only the third largest out of the four clusters, and it has contracted rather than expanded in terms of the number of relevant specialisations over time (see Jindra, Leusin, 2022). Although EU27 inventors developed specialisation advantages in climate change mitigation technologies in transportation and innovations in electric vehicles grew rapidly, EU27 inventors in international comparison are still heavily invested in stagnant technologies related to combustion engines.

Our findings reflect the transition in the transportation sector. The EU has missed its targets for reducing GHG emissions in this sector (Arregui *et al.*, 2020). Even with currently planned measures in the EU member states, domestic transport emissions will not drop below their 1990 level until 2029, at the earliest. Therefore, road transport generates the highest proportion of overall transport emissions, and international transport emissions (aviation and maritime) are projected to continue increasing[11]. If take-off and renewable energy sources can meet the additional electricity demand of electric vehicles, then a substantial share of the transport sector could be low-carbon within 30 years (Fouquet, Hippe, 2022). Arguably, the potential of e-mobility becomes transformative when synergised with digital technologies. This could be possible by advcing "twinning" soluations such as Intelligent Traffic Management Systems (ITMS), Vehicle-to-Grid (V2G) platforms, E-Mobility as a Service (eMaaS), or Digital Twins for urban mobility planning.

Processing of Goods and Domestic Applications

Finally, digital sustainability technologies in goods processing and household applications is the second largest cluster globally, and the only one that expands over time in terms of the number of relevant specialisations (see Jindra, Leusin, 2022). We find that for this cluster, EU27 inventors lack relevant specialisation advantages in climate change mitigation technologies in the production or processing of goods, wastewater, buildings and reduction of GHG, as well as technologies for adaptation to climate change. However, EU27 inventors possess specialisation advantages in smaller areas such as additive manufacturing, working metallic powder, solar heat collectors or domestic – and space heating systems. Given that this domain of digital sustainability inventions is expanding rapidly, there is a risk that the EU27 will fall behind. Enhancing existing and complementary specialisations in relevant technologies is the appropriate policy direction.

11. https://www.eea.europa.eu/ims/greenhouse-gas-emissions-from-transport.

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Appendices

Figure A1 – Share of digital sustainability priority patents in total priority patents by country (2001-2018)

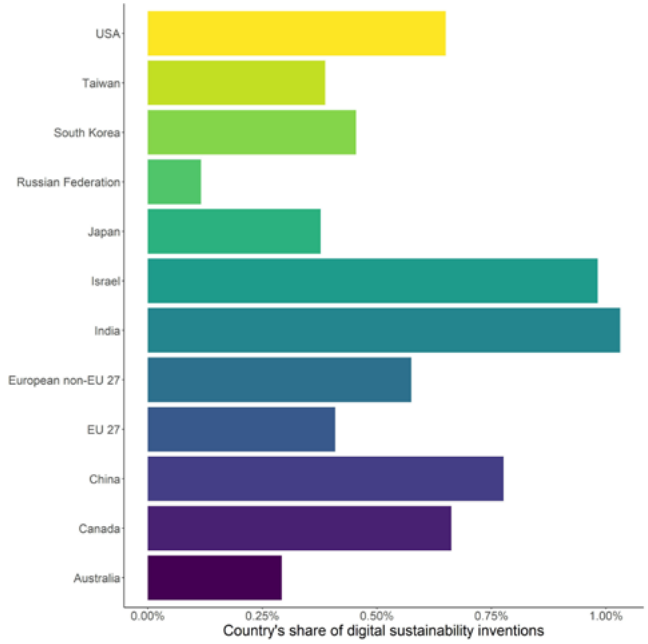

Figure A2 – Relative number of digital sustainability patents registered by top 8 leading regions (2001-2018)

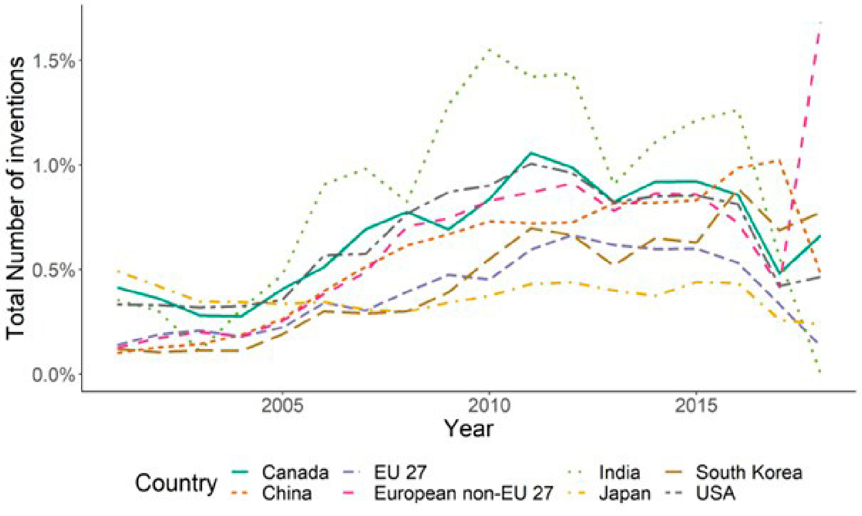

Table A1 – **Total number of specialisations in the identified relevant technologies for individual EU27 countries**

Country name	**N. Relevant Spec.**	**N. Spec. Cl. 1**	**N. Spec. Cl. 2**	**N. Spec. Cl. 3**	**N. Spec. Cl. 4**
France	33	17	1	4	11
Germany	27	12	0	6	9
Italy	27	14	0	6	7
Spain	26	13	0	8	5
Sweden	20	10	0	4	6
Netherlands	16	12	0	2	2
Denmark	15	11	0	3	1
Ireland	15	11	0	4	0
Belgium	14	10	0	2	2
Austria	12	9	0	1	2
Finland	12	11	0	1	0
Czech Republic	11	6	0	3	2
Greece	10	4	0	3	3
Portugal	8	6	0	2	0
Poland	7	5	0	1	1
Hungary	6	6	0	0	0
Romania	5	2	0	2	1
Slovenia	5	3	0	2	0
Bulgaria	4	2	0	1	1
Luxembourg	3	2	0	1	0
Latvia	3	1	0	2	0
Estonia	2	2	0	0	0
Slovakia	2	0	0	2	0

Table A2 – **Country-specific specialisations in relevant technologies from Cluster 1 that are missing at the EU27 level**

CPC Code	Description (abbreviated)	BE	DE	DK	ES	FI	FR	IE	IT	NL	SE
F21W	Indexing relating to uses or applications of lighting devices or systems	0	0	0	0	0	0	0	0	0	0
G01W	Meteorology	0	0.36	0	8.88	0	0.8	0	0	0	0
G06Q	Data processing systems or methods	1.54	0.83	0.86	0.89	1.02	0.69	1.64	1.45	0.54	0.5
G21D	Nuclear power plant	0	0.65	0	0	0	2.88	0	0	0	0
H05B	Electric heating	0	0.75	0.7	1.25	0.74	0.68	1.79	1.32	2.96	0
Y02B	Climate change mitigation technologies related to buildings	1.02	0.55	0.91	0.78	0.38	0.72	0.78	1.03	0.94	0.27
Y02D	Climate change mitigation technologies in ICTs	1.49	0.45	0.52	0.42	2.26	0.79	1.48	0.63	1.42	1.72
Y02E	Reduction of GHG emissions, related to energy gen., transmis., or distribution	0.36	0.48	1.74	0.99	0.31	0.54	0.42	0.5	0.49	0.16

Table A3 – **International co-inventions for all priorities and digital sustainability priorities by country (2001-2018)**

Country	Total (All priorities)	No. Int. co-inventions (All priorities)	%	Total (Dig. Sust. Inventions)	Int. Co-Inventions (Dig. Sust. Inventions)	%
India	65,592	24,646	37.60%	676	310	45.90%
Israel	43,806	9,806	22.40%	430	154	35.80%
Canada	124,521	28,310	22.70%	825	278	33.70%
European non-EU*	236,884	60,069	25.40%	1,363	382	28.00%
Australia	76,555	8,908	11.60%	224	43	19.20%
Taiwan	154,390	16,071	10.40%	598	92	15.40%
United States of America	1,889,782	175,993	9.30%	12,284	1,472	12.00%
Brazil	67,477	2,757	4.10%	189	20	10.60%
European Union (EU27)	1,606,190	104,625	6.50%	6,573	678	10.30%
Russian Federation	411,003	12,070	2.90%	477	38	8.00%
South Korea	1,858,856	32,011	1.70%	8,452	200	2.40%
Japan	4,567,299	28,898	0.60%	17,238	135	0.80%
China	7,168,418	48,999	0.70%	55,674	311	0.60%