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Mapping the Scientific Base for SDGs and Digital Technologies

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Contents

Contents i
Abstract 1
Acknowledgements 2
1 Introduction 3
2. Data and methods 8
3. The global scientific landscape 13
    3.1 Scientific research in the SDGs-DTs knowledge space 13
    3.2 The geography of SDGs, DTs and SDGs-DTs scientific knowledge creation 18
4. SDGs, DTs, and SDGs-DTs publications in the European Union 21
    4.1 SDGs, DTs, and SDGs-DTs scientific performance of EU MSs 21
    4.2 SDG, DT and SDGS-DTS scientific performance of EU regions 24
5 Conclusions 31
References 32
List of abbreviations and definitions 35
List of boxes 36
List of figures 37
List of tables 38
Annexes 39
    Annex 1. Additional Figures and Tables 39

Abstract

In 2015, the UN General Assembly adopted the "2030 Agenda for Sustainable Development" containing 17 Sustainable Development Goals (SDGs) to achieve a sustainable, fair, and inclusive future for people worldwide by 2030. With less than 10 years left, Science, technology, and innovation (STI) are among the key enablers for the achievement of the 2030 Agenda's ambitions. This report provides first evidence of the emergence of scientific research that jointly studies SDGs and Digital Technologies (DTs). The combination of SDGs and DTs in scientific research is a recent development that has surfaced over the past ten years and is rapidly expanding. The growth is driven by scientific advancements in research jointly addressing SDG7 (Affordable and clean energy) and Internet of Things, and SDG13 (Climate change) and artificial intelligence. While China and the United States are the major players in scientific research in these domains, the European Union as a whole produces more scientific publications than any single country, including China and the United States, in the SDGs and SDGS-DTs domains, while China leads with regards to DTs. Yet, fully realizing the potential of EU scientific research for sustainable development requires improvements in the integration of national research systems enabling the exploitation of scale and scope economies that Member States cannot achieve in isolation.

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1 Introduction

Sustainability has become a moral imperative over the last few years. Sustainability can be understood as the result of a balanced articulation of three pillars: social, economic, environmental – including good governance (Griggs et al., 2013; Sachs, 2015). The Sustainable Development Goals (SDGs) formulated in 2015 by the United Nations (UN) General Assembly set an ambitious target to achieve a sustainable, fair, and inclusive future for people worldwide by 2030 (UN General Assembly, 2015).

The SDGs build on decades of work by countries and the UN (TWI2050, 2019) and are an unprecedented attempt to close the sustainability gap through a focus on the main ecological, social, and economic challenges that humanity faces. The 17 SDGs, which are shown in Figure 1, and the 169 associated targets of the "2030 Agenda for Sustainable Development" provide a shared blueprint for peace and prosperity for people and the planet. They represent an urgent call for action by all – developed and developing – countries in a global partnership.

With less than 10 years left, a growing number of policy initiatives are being put in place to make sure the goals are met (Sachs et al., 2019; TWI2050, 2019). Science, technology, and innovation (STI) are unquestionably among the key enablers for the achievement of the 2030 Agenda's ambitions. In particular, digitalization holds great promise for sustainable transformation.

Figure 1. *SDGs icons in the UN 2030 Agenda*

Source: https://SDG.un.org

Digital transformation (or transition) refers to the economic and societal effects of digitization and digitalization (OECD, 2019).[1] This study considers a broad spectrum of interconnected digital technologies, each differing in scope, life cycle, and degree of adoption and diffusion – that is, a *digital ecosystem*. The ecosystem is more complex, much stronger, and more functional than its components given that the latter interoperate with and complement one another. In this report, the digital ecosystem is inspired by the OECD taxonomy (2019, p.18) and includes the following technologies: *Additive Manufacturing*; *Artificial Intelligence (AI)*; *Blockchain*; *Big Data*; *Computing Infrastructures*; *Internet of Things (IoT)*; and *Robotics*. Box 1 in Section 2 provides a comprehensive description of these seven macro-components.

Despite an emerging literature, the nexus between digital transformation and sustainable development remains poorly explored and understood. Indeed, knowledge on the topic is based primarily on case studies, expert opinion, and anecdotes (see, e.g., Seele and Lock, 2017; del Río Castro et al., 2020; Ordieres-Meré et al., 2020; Vinuesa et al., 2020; Onyango and Ondiek, 2021). Against this background, growing efforts are made to map the development of digital technologies and knowledge through publication and patent statistics (European Commission, 2018; WIPO,

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[1] Digitization is the conversion of analogue data and processes into a machine-readable format. Digitalization is the use of digital technologies and data as well as interconnection that results in new or changes to existing activities.

2018; Baruffaldi et al., 2020). Similar initiatives have also been undertaken to map the SDGs (Purnell, 2022). Methodological details, search queries, and reports have been made available to the research community. Yet, less explored remains the *SDGs-Digital nexus*. An important part of the discussion on digital and sustainable transformations occurs in mediums such as grey literature and social media, but there is a general lack of in-depth and systemic analysis. This gap motivates the present study.

This report focuses on *scientific knowledge*, captured through publications in peer-reviewed journals and conference proceedings. Scientific knowledge is an important driver of technological innovation (see, among the many, Trajtenberg et al. 1997, Murray 2002, Fleming, and Sorensen 2004, Caraça et al. 2009, Dosi and Grazzi 2010). First, it guides research and development (R&D) efforts – e.g., by reducing trial-and-error and thus the time required for the development and deployment of new technologies. Second, a strong knowledge base provides opportunities for the recombination of existing knowledge. As such, it is the driving force behind new (valuable) ideas. Empirical research on the emergence of technological change confirms this role of science, showing a strong link between major scientific advances and new technologies in various domains such as ICT (Mazzucato 2014), semiconductors (Dibiaggio et al. 2014), biotechnology (Magerman et al. 2015) and wind turbines (Lacerda 2019).

In the ongoing scientific debate, the convergence of digitalization and sustainability is perceived as a winning combination, yet not exempt from challenges. Technological optimists claim that some technologies at the core of the digital transformation are fundamental drivers of disruptive change, much like the structural changes caused by previous technological revolutions such as the telegraph, the steam engine, or the electric motor (Brynjolfsson and McAfee, 2014).

Digital transformation is creating some essential preconditions for sustainability, but it is also undermining it. On the one hand, some technologies such as deep learning and smart sensors offer opportunities to decouple wealth creation from resource consumption, pollution, and ecosystem degradation (Vinuesa et al., 2020). Science can benefit from AI and big data, as these technologies have been shown to help human scientists in the process of experimentation and discovery (Bianchini et al., 2022a). Recent evidence also suggests that some digital applications further environmental governance by reducing energy production and consumption, water consumption, and material use (Nishant et al., 2020). The benefits are expected to be high also for developing or less developed economies. For instance, some governments could effectively tailor sustainable development strategies for education and health care through e-government and big data initiatives, as shown by selected case studies in Cambodia, Colombia, Egypt, Ghana, Kenya, the Philippines, and Tunisia (Elmessah and Mohieldin, 2020).

On the other hand, there are also some dark sides of digitalization. AI technology often requires massive computing centers, which are energy-demanding and thus responsible for a high carbon footprint (Jones, 2018; Bianchini et al., 2022b). In addition, new digitally driven configurations of the economic, social, political and cultural systems may disempower individuals and amplify inequalities (O'Neil, 2016); undermine democracy and inclusiveness (Zuboff, 2019); change labor markets (Acemoglu and Restrepo, 2020); and lead to uncontrolled human-enhancement (Bostrom, 2017).

This study provides first evidence on the emergence of scientific research that jointly studies SDGs and digital technologies (DTs) and assess the EU performances compared to other economies.[2] Scientific activity has steadily increased over the past decade (Table 1). The growth of science is a well-documented fact: "*[a]n exponential growth in the volume of scientific literature … a trend that continues with an average doubling period of 15 years*" (Fortunato et al., 2018).[3] This report finds analogous trends, with Web of Science (WoS) publications growing by 75% between 2010 and 2021. Yet, the digital and SDGs domains grew even faster during this period. In particular, the volume of scientific outcome related to SDGs has increased by about 450% and the volume of outcomes related to DTs by 750% (Table 1).[4]

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[2] This study and its results are part of a larger effort that the European Commission Joint Research Centre (JRC) is taking to provide a better understanding of sustainable development and an evidence-based implementation of the SDGs. The KnowSDGs, for example, provides semantic analysis of the policy initiatives of the Commission and their links to the 2030 Agenda and the SDGs (Borchardt et al., 2022). In addition, it builds on the knowledge and initiatives that have been produced in the context of the initiatives and studies on text mining and NLP methods.

[3] Yet, it would be naïve to equate the growth of the scientific literature with the growth of scientific ideas. Research shows that while the number of research efforts, researchers and publications is growing exponentially, their research productivity is in sharp decline. This finding seems to hold true across scientific domains, industries, and products (Bloom et al., 2020).

[4] As aforementioned, SDGs have been formally formulated by the UN in 2015 following the 2012 resolution A/RES/66/288 entitled "The Future We Want" released following the Rio+20 conference. The exponential growth in SDGs-related topics can therefore be partly linked to the growing interests in topic related to sustainability following UN actions.

Table 1. *Publications on SDGs, DTs and SDGs-DTs fields in Web of Science (WoS), 2010-2021*

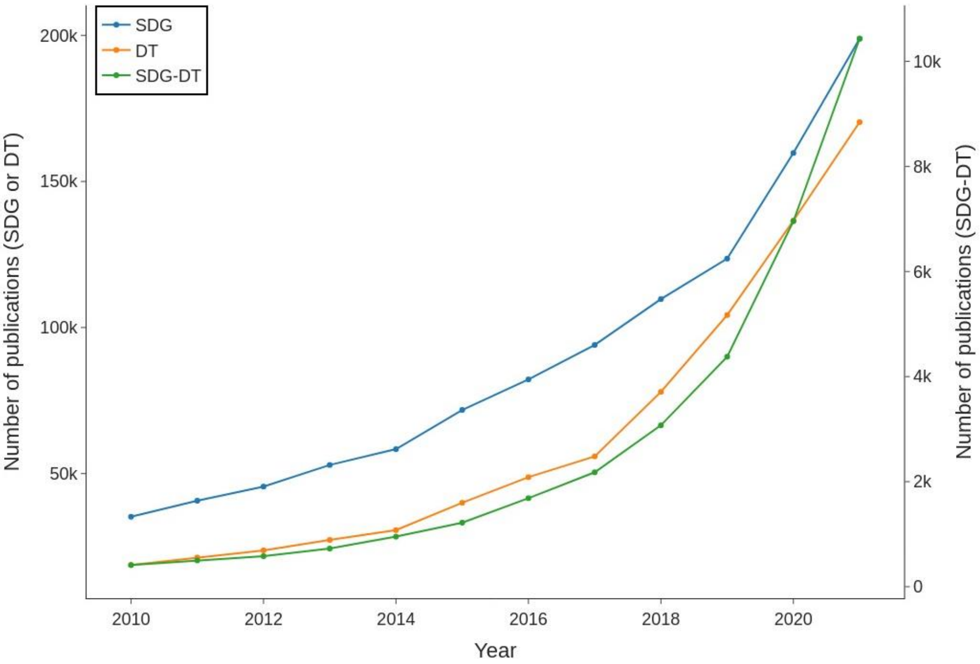
	Number of publications				**% of WoS pub**			**% of SDGs-DTs pub**	
	WoS	**SDGs**	**DTs**	**SDGs-DTs**	**SDGs**	**DTs**	**SDGs-DTs**	**SDGs**	**DTs**
2010	1,492,307	35,230	18,704	413	2.36	1.25	0.03	1.17	2.21
2011	1,582,442	40,706	21,277	501	2.57	1.34	0.03	1.23	2.35
2012	1,672,428	45,554	23,706	581	2.72	1.42	0.03	1.28	2.45
2013	1,756,550	52,954	27,289	726	3.01	1.55	0.04	1.37	2.66
2014	1,850,940	58,370	30,654	953	3.15	1.66	0.05	1.63	3.11
2015	2,086,391	71,801	40,014	1,219	3.44	1.92	0.06	1.70	3.05
2016	2,191,399	82,249	48,769	1,685	3.75	2.23	0.08	2.05	3.46
2017	2,274,353	94,043	55,880	2,178	4.13	2.46	0.10	2.32	3.90
2018	2,322,148	109,737	77,977	3,073	4.73	3.36	0.13	2.80	3.94
2019	2,519,145	123,587	104,257	4,378	4.91	4.14	0.17	3.54	4.20
2020	2,558,445	159,744	136,630	6,957	6.24	5.34	0.27	4.36	5.09
2021	2,614,139	198,883	170,309	10,433	7.61	6.51	0.40	5.25	6.13
% change 2021-2010	75.2	464.5	810.5	2,426.2	222.5	420.8	1,233.3	348.7	177.4

Notes: "WoS" is shorthand for "Web of Science"; "pub" for "publications"; "SDGs" for "Sustainable Development Goals"; and "DTs" for "Digital Technologies". Source: JRC calculations on WoS data.

Publications jointly related to SDGs and DTs, which are the main focus of the analysis, show in turn an even more pronounced growth rates (2426%), especially in recent years. This sharp increase is due to the fact that scientific output at the intersection between SDGs and the recent DTs selected in this report was nearly non-existent ten years ago. In 2021, by contrast, there were more than 10,000 contributions worldwide (

Figure 2).

Figure 2*. Recent evolution of scientific research in SDGs, DTs and their intersection, 2010-2021*



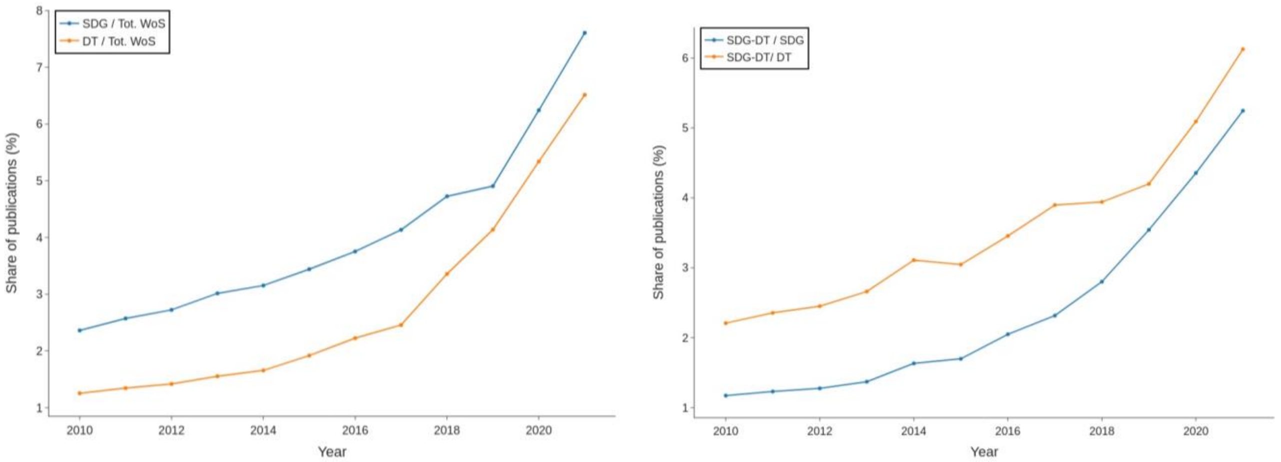
Source: JRC calculations on WoS data.

As a result of these different dynamics, the fraction of publications related either to SDGs or DTs grew from 3.6% in 2010 to 13.6% in 2021 (

Figure 3, panel a). While the volume of scientific research on SDGs kept larger than the one on DTs throughout the period, the faster growth of DTs-related scientific production implied a gradual tendency to close the gap in more recent years: the quantity of scientific research on SDGs almost doubled the one on DTs in 2010 (188%) and was 'only' 125% larger in 2021. Not only the number but also the share of SDGs-DTs-related publications grew in the period (

Figure 3, panel b). SDGs-DTs-related publications accounted in 2021 for 0.4%, 5.2% and 6.6% of, respectively, total WoS publications, SDGs related publications and DTs-related publications. This testifies the growing importance of this emerging knowledge domain in the scientific community.

***Figure 3**. Contribution of SDGs, DTs and joint SDGs-DTs research domains to scientific research, 2010-2021*



Panel a. SDGs and DTs scientific output as % of WoS scientific output

Panel b. SDGs-DTs output as % of SDGs and DTs scientific output

Source: JRC calculations on WoS data.

The remainder of this report is structured as follows: The next section describes the data and methods used for the identification of publications related to SDGs and DTs as well as the statistical methods applied. Section 3 provides insights into the diffusion of SDGs and DTs publications worldwide. Sub-section 3.1 focuses on the prevalence of all SDGs-DTs possible combinations, whereas sub-section 3.2 provides an overview of the main global players in SDGs, DTs and SDGs-DTs scientific domains. Section 4 zooms in the European Union (EU) at the national (Sub-section 4.1) and regional (Sub-section 4.2) levels, discussing Member States strengths and specialization. Finally, Section 5 concludes summarizing the main findings of the report while discussing possible avenues for future research.

2. Data and methods

The data in this report come from the Web of Science (WoS) Core Collection. WoS is a widely used data source for science mapping and analysis of the "science of science". The analysis considers all scientific articles published in peer-reviewed journals and conference proceedings (i.e., it excludes other types of publications such as, e.g., books, series, etc.). This approach introduces some heterogeneity in the coverage of different scientific disciplines depending on the type of outlet preferred by researchers in these disciplines. However, WoS coverage of journals and proceedings is sufficiently large to capture the dynamics of science more generally. For each publication, detailed information – i.e., title, keywords, abstract, year of publication, journal information, topical information, author, and institutional affiliations – has been collected.

To identify scientific output in SDGs and DTs domains the authors used a *keyword-based approach*. Queries searched for all publications over the period 2010-2021 containing at least one search term either in the title, the abstract, or among keywords. The use of search terms is not free of issues. In particular, as comprehensive as a set of search terms can be, it is impossible to cover all semantic variants of complex and multidimensional concepts, as those in this study, resulting in true negatives. Moreover, enlarging the set increases the likelihood of capturing publications not pertinent to the aimed search, resulting in false positives. Publications on the SDGs were identified using the search queries for "Mapping Research Output to the Sustainable Development Goals (SDG)". The project represents a comprehensive effort to map scientific output related to the 17 different SDGs. Originally developed for Scopus, the search queries are elegant constructions of keyword combinations, Boolean and proximity operators that have been adapted to WoS syntax.[5] Notwithstanding the partial overlapping of publications related to SDGs identified using different methods (Armitage et al., 2020), this approach emphasizes precision over recall (Purnell 2022), meaning that it privileges the minimization of false negatives (i.e., the erroneous inclusion of publications unrelated to SDGs) rather than false positives (i.e., the erroneous exclusion of publications related to SDG). The dataset is therefore constructed following a prudential attitude as it sacrifices the full coverage of SDGs-related publications in favour of including mostly publications with a high relevance to the SDG targets. The resulting dataset comprises almost 1.3 million publication records. Among the most frequent SDGs in the data, SDG13 (Climate action) accounts for about 22% of these whereas SDG3 (Good health and well-being), SDG6 (Clean water) and SDG14 (Life below water) covers about 10% each of the records. Among the less frequent, SDG1 (No poverty), SDG2 (Zero hunger), SDG8 (Decent work and economic growth), SDG9 (Industry, innovation, and infrastructure) and SDG10 (Reduced inequalities) account for just 2% each.

Figure 4 shows the trend of scientific research on the SDGs grouped into three macro-categories, namely "*Society*" (SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11), "*Economy*" (SDG8, SDG9, SDG10, SDG12, SDG17), and "*Environment*" (SDG13, SDG14, SDG16). First, it can be observed that the volume of publications on SDGs related to Society and Environment is about five times larger than the one of publications on SDGs related to Economy. Second, scientific output increased in every area. In particular, growth rates accelerated since 2015 onwards. The growth rates of scientific output related to Society and Environment showed the largest increases, widening the gap in volumes with scientific output on Economy-related SDGs. Finally, it is possible to notice a marked increase in the Society SDGs over the past two years, which can be partially explained by the surge of research on health (SDG3), especially after the arrival of the COVID-19 pandemic – see Section 3 for additional details.

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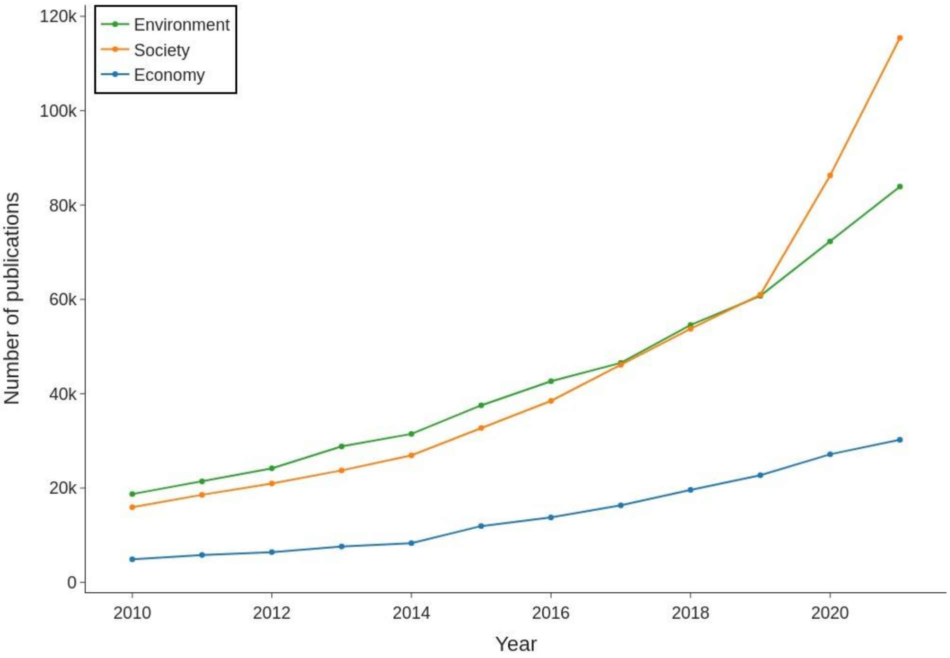
[5] As an example, queries related to SDG-1 (i.e., eradicate extreme poverty for all people everywhere), part I (reduce at least by half the proportion of people living in poverty by 2030) are: ("poverty line*") OR ("poverty indicator*"); ("poverty" OR "income") W/3 ("inequalit*"); and ("poverty") W/3 ("chronic*" OR "extreme"). The full list of keywords and queries is available as supplementary material.

Figure 4. *Scientific research in SDGs by SDGs category, 2010-2021*



Notes: the "Society" category includes SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11 and SDG17); the "Economy" category includes SDG8, SDG9, SDG10, SDG12, SDG17; the "Environment" category includes SDG13, SDG14 and SDG16. *Source*: JRC calculations on WoS data.

Digital publications were identified using a comprehensive list of search terms inspired by recent contributions on the mapping of advanced digital technologies (Van Roy et al., 2020; Martinelli et al., 2021; Bianchini et al., 2022b). The ongoing digital transformation is typically understood as the economic and societal effects of a homogeneous set of technologies, with a particular emphasis on AI (Di Vaio et al., 2020; Goralski and Tan, 2020; Truby, 2020; Vinuesa et al., 2020). While this somewhat simplistic view has its attractions, it is more appropriate to take a holistic view and consider a much broader spectrum of interconnected technologies, each differing in scope, life cycle, and degree of adoption and diffusion – that is, a digital ecosystem. Largely inspired by the OECD (2019, p.18) taxonomy, this study considers seven macro-categories composing the digital ecosystems: Additive Manufacturing; Artificial Intelligence; Blockchain; Big Data; Computing Infrastructures; Internet of Things; and Robotics.[6] Box 1 provides a short description of each technological class composing the digital ecosystem. Overall, the resulting dataset comprises of about 860 thousand records of which about half are related to AI and about 110 thousand to IoT and Robotics. The less represented technology is instead Blockchain (about 10 thousand publications), followed by Big data and Additive Manufacturing (about 50 thousand publications each).

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[6] Importantly, this is not the only taxonomy available. As an example, the European Commission Joint Research Centre produced a operational definition of artificial intelligence to be adopted in the context of AI Watch, the Commission knowledge service to monitor the development, uptake and impact of artificial intelligence for Europe (Samoili et al., 2020). Interestingly, this approach relies on both qualitative and quantitative approaches. Researchers applied natural language processing (NLP) methods to a large set of AI literature as well as carried out a qualitative analysis on 55 documents including artificial intelligence definitions from three complementary perspectives: policy, research, and industry. In addition, the Digital ecosystem analysis: DGTES 2022, allows mapping the digital ecosystem through a) the detection of players and activities that engage in a set of selected digital technologies, b) the identification of the interlinkages and relations resulting from shared activities, locations and technological fields.

Box 1. The components of the digital ecosystem

Additive Manufacturing: Additive manufacturing (AM), or 3D printing, is the computer-controlled production of three-dimensional objects achieved by depositing materials, usually in layers, with precise geometric shapes. A rapid prototyping system using photopolymer layers was first proposed in 1981 by Hideo Kodama (Nagoya Municipal Industrial Research Institute). Soon afterwards, it became possible to create complex models with the help of computer-aided manufacturing or computer-aided design (CAM/CAD) software. The procedure came to be known as stereolithography: a liquid resin material is polymerized with a high-precision laser to form each layer, and the process is said to be "additive" because the objects are built layer by layer. The first 3D printing machines only became a viable commercial product in the early 2000s, paving the way for the production of industrial parts on demand. Today, different AM processes are in use, each with specific standards. What characterizes these processes is that, unlike traditional manufacturing, they do not require machining or other techniques to remove surplus material. Moreover, AM processes can produce objects that present much finer details, and they tend to be more reliable, being capable of consistently achieving high quality results. 3D printed products can serve a variety of applications ranging from the automotive, healthcare, and aerospace industries to parts replacement.

Artificial Intelligence: The emergence of artificial intelligence (AI) as a fully-fledged field of research coincided with three important meetings: Session on Learning Machines in 1955 (Los Angeles); Summer Research Project on Artificial Intelligence in 1956 (Dartmouth); and Mechanization of Thought Processes in 1958 (London). The 1956 workshop is considered to mark the birth of AI. Today, AI unites a number of distinct, yet often intersecting, sub-fields including machine learning, computer vision, natural language processing (NLP), symbolic reasoning, knowledge representation, and many others. Recent definitions aim to be understandable, technically accurate, technology-neutral, and applicable to short- and long-term horizons. The following are representative: "Machines or agents that are capable of observing their environment, learning, and based on the knowledge and experience gained, taking intelligent action or proposing decisions" (European Commission, 2018); "An AI system is a machine-based system that can, for a given set of human-defined objectives, make predictions, recommendations or decisions influencing real or virtual environments" (OECD, 2019); "Machines that can become better at a task typically performed by humans with limited or no human intervention" (WIPO, 2019). Although establishing precise boundaries as to what constitutes AI is an ongoing subject of debate, there is a consensus on the methodological building blocks required to mechanize human intelligence (Russel and Norvig, 2020). They typically include the following four elements: machine learning, NLP, computer vision and speech recognition.

Big Data: The term 'big data' was introduced by computer scientist John Mashey in the 1990s, in reference to unusually large, heterogeneous data sets that were difficult to capture and process with the software then available. More specific definitions were provided in the early 2000s: "Big data is high volume, high velocity, and/or high variety information assets that require new forms of processing to enable enhanced decision making, insight discovery and process optimization" (Douglas Laney, 2001). Today, much the same as for AI, there is no clear consensus on what actually constitutes Big Data. Definitions often include (at least) three features, commonly referred to as the "3Vs of Big Data": that is, Volume or very large size; Velocity corresponding to the speed of data creation which should be in real-time or nearly real-time; and, Variety representing the heterogeneity of data sources (e.g., text from messages, images posted to social networks, readings from sensors). Other Vs have been added from time to time, such as Veracity (data quality), Value (value obtained from exploitation), and Variability (rate of change). For instance, De Mauro et al. (2015) propose that Big Data can be considered as a standalone term referring to those "Information assets characterized by such a High Volume, Velocity and Variety to require specific Technology and Analytical Methods for its transformation into Value", and as an attribute when denoting its peculiar requisites (e.g., "Big Data Technology" or "Big Data Analytics").

Blockchain: Blockchain is a distributed ledger technology (DLT) consisting of a list of records, called *blocks*, which are chained to one another using advanced cryptography. It constitutes a secure protocol where a network of computers collectively verifies a transaction before it can be recorded and approved; it provides an immediate, shared, and transparent exchange of encrypted data simultaneously to multiple parties. It therefore enables applications to authenticate ownership and carry out secure transactions for a variety of asset types (OECD, 2019). One of blockchain's most widespread application is for cryptocurrencies (e.g., Bitcoin, Ripple), but its use is starting to affect many other sectors, including agriculture, manufacturing, retail, healthcare, energy, transport, and the public sector.

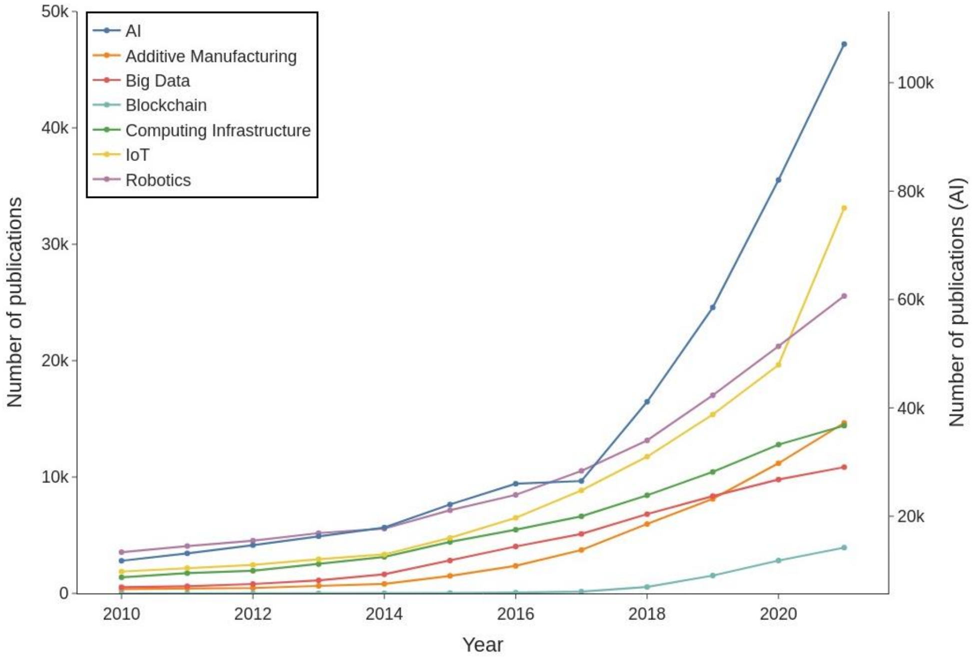
Computing Infrastructure: Computing infrastructures include those physical and virtual resources that support the flow, storage, processing, and analysis of data. An infrastructure can either be centralized within a data centre or decentralized and distributed in several data centres. Cloud computing encompasses the delivery of computing services – servers, storage, databases, networking, software, and analytics – over the Internet (i.e., the "cloud"). Cloud manufacturing embraces the application of cloud technologies to manufacturing, with widespread access, easy and on-demand IT services to support production processes and supply chain management. The concept of infrastructure-as-a-service (IaaS) dates back to the 1960s but became fully operational for users in the early 2000s. Recent technologies such as fog computing and 5G extend the benefits of IaaS, providing a far higher level of performance (high speed and low latency) than previous generations of computing and mobile communication systems. Furthermore, computational capabilities have undergone an astounding increase in recent decades, and this has been made possible by new computational approaches (many of which are still in an experimental phase) such as quantum computing.

Internet of Things: The idea of connecting a physical object to the Internet can be traced back to 1982, albeit it became more pervasive in the 90s. Today, the Internet of Things (IoT) describes a large ecosystem of interconnected devices and services collecting, exchanging, and processing data to adapt dynamically to a given context (Atzori et al., 2010). The IoT comprises networks of physical objects (or "things") embedded with ambient sensors and dedicated software and connected via standard communication protocols. The underlying technologies needed to build an IoT device are semiconductor devices, sensors, and, more generally, micro-electromechanical systems (MEMS), and, of course, the Internet. When connected to each other, the network of "things" offers self-identification, localization, diagnostic status, data acquisition and processing capabilities. Data and information can, moreover, be collected from a wide variety of sources (e.g., industrial products, transport vehicles, etc.). The IoT allows objects to interact with other objects and, therefore, with people in an increasingly digitalized and automatized fashion.

Robotics: Robotics encompasses agents with different capabilities to substitute for humans and to replicate and automate human actions. Although robotics has a long, rich history of visionary insights, with inventions that intersected in various scientific domains – (information and mechanical engineering, computer science, etc.), the first commercial robots installed for industrial purposes did not appear until the 1960s. Yet, it was only in the 1980s that industries witnessed a massive deployment of (multitasking) robots aimed at automatizing the mass production of consumer and industrial goods. Modern, flexible robots, driven by machine learning systems, can interact with and self-learn from the environment while improving with experience. Robots find applications in various sectors of the economy: manufacturing, assembly and packing, transportation, earth and space exploration, surgery and patient healthcare, laboratory R&D, but also household chores. Industrial robots are often classified into various subgroups, depending on their anthropomorphic characteristics, the type of movements they can perform and the plane of action (e.g., horizontal, vertical, rotary). Among such subgroups, we typically find SCARA (Selective Compliance Assembly Robot Arm), articulated, Cartesian, dual arm robots and cobots (Nilsson, 2009; Russel and Norvig, 2020).

Figure 5 shows that AI technologies account for the large majority (57.9%) of digital publications in the 2010-2021 period. Among other digital technologies, robotics (16.7%) and IoT (14.9%) account for the largest fractions of digital publications, while blockchain shows the lowest percentage (1.2%). The predominance of AI among digital-related publications is the result of the strong growth experienced by scientific research on AI, especially since 2017 when its pace of change accelerated at a substantially larger rate than other digital technologies. Note that our categories are not mutually exclusive, that is, a paper can be assigned to more than one category (e.g., AI *and* robotics). A closer inspection of the sample suggests that 18.2% of publications on robotics and 15.1% on IoT are also co-classified as AI. This is not surprising given the general-purpose nature of artificial intelligence.

Figure 5. *Scientific research in DTs by component of the digital ecosystem, 2010-2021*



Source: JRC calculations on WoS data.

This report uses *fractional count*s to analyse scientific performance of countries and European Union (EU) regions. This involved geo-localizing each publication exploiting authors' affiliations – i.e., attributing a publication to a given country (or region) when the affiliation of at least one of its authors is located in that country (or region)[7]. To avoid making assumptions about the numbers of authors per publications across different countries (regions) and scientific domains, the contribution to any given publication of each country (region) is weighted by the number of authors (*n)*. A publication with *n* authors, each one located in different countries (regions), will contribute by 1/*n* to the scientific production of each country (or region). Note that multiple affiliations are counted only once when they are: (i) within the same country for the national-level analysis; and (ii) within the same region in the regional-level analysis.

For EU member states (MSs) we have also constructed Revealed Comparative Advantage (RCA) indexes which allow us to study country *specialization*. This index is defined as the ratio of two shares:

- the numerator is the share of each MSs research output in each scientific domain *d* considered in this report (i.e., DTs, SDGs, and DT-SDGs related publications) over each MSs total research output;
- the denominator is the share of EU-level research output in each aforementioned scientific domain *d* over EU-level total research output.

$$RCAd_{ms,\,d} = \frac{Share_{ms,d}/Tot_{ms}}{Share_{EU,\,d}/\;Tot_{EU}}$$

where:

RCAd_ms is the Revealed Comparative Advantage index of member state (ms) for scientific domain d;
Share_ms,d is the share of each MSs research output in scientific domain d;
Tot_ms is the total research output of each MS;
Share_EU,d is the share of EU-level research output in scientific domain d;
Tot_EU is the total research output of the EU.

The RCA index takes a value between 0 and infinity. An RCA index lower than 1 means that country *c* has comparatively less research output on scientific domain *d* than the EU, thus is *not* specialized (or *it is* under-specialized) in scientific domain *d*; when the RCA index is greater than 1, country *c* has - comparatively to its overall research - more research output on scientific domain *d* than the EU thus is specialized in scientific domain *d*; an RCA index equal to 1 means that country *c* has the same share of research output on scientific domain *d* as the EU thus is neither specialized nor under-specialized. The RCA index is calculated on the period 2010-2021.

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[7] In the geo-localization process at the regional level around 1% of publications are not identified.

3. The global scientific landscape

This section provides a global portrait of scientific output in SDGs, DTs and their combination by identifying the combinations of SDGs and DTs that are emerging globally as the most important and comparing the scientific performance of the European Union with other world economies.

3.1 Scientific research in the SDGs-DTs knowledge space

This sub-section discusses the prevalence of SDGs-DTs combinations in worldwide scientific production. Combinations were obtained by combining the two dataset described in the previous Section and selecting records appearing in both. **Figure 6** maps the scientific knowledge related to both SDGs and DTs in the 119 SDGs-DTs pairwise combinations obtained intersecting the 17 SDGs (horizontal axis) entering the UN 2030 Agenda for Sustainable Development with the 7 DTs composing the digital ecosystem.

First, AI plays a key role in driving the emergence of scientific research on SDGs-DTs domains, holding the largest number of publications worldwide and having a marked presence in 8 of the 10 SDGs-DTs combinations. Unlike other digital technologies composing the digital ecosystem, it finds applications in virtually all SDGs. This confirms the versatility of AI across a wide range of domains. The evidence suggests a role for AI as possible "enabling technology" or "emerging method of invention" or "general purpose technology" (Cockburn et al., 2019; Trajtenberg, 2019; Bianchini et al., 2022a), through which AI opens up '*the set of problems that can be feasibly addressed, and radically altering scientific and technical communities' conceptual approaches and framing of problems*' (Cockburn et al., 2019, p. 7). Among SDGs, AI is particularly prominent in SDG13 (Climate change), SDG11 (Sustainable cities and communities), SDG7 (Affordable and clean energy), and SDG3 (Good health and well-being).

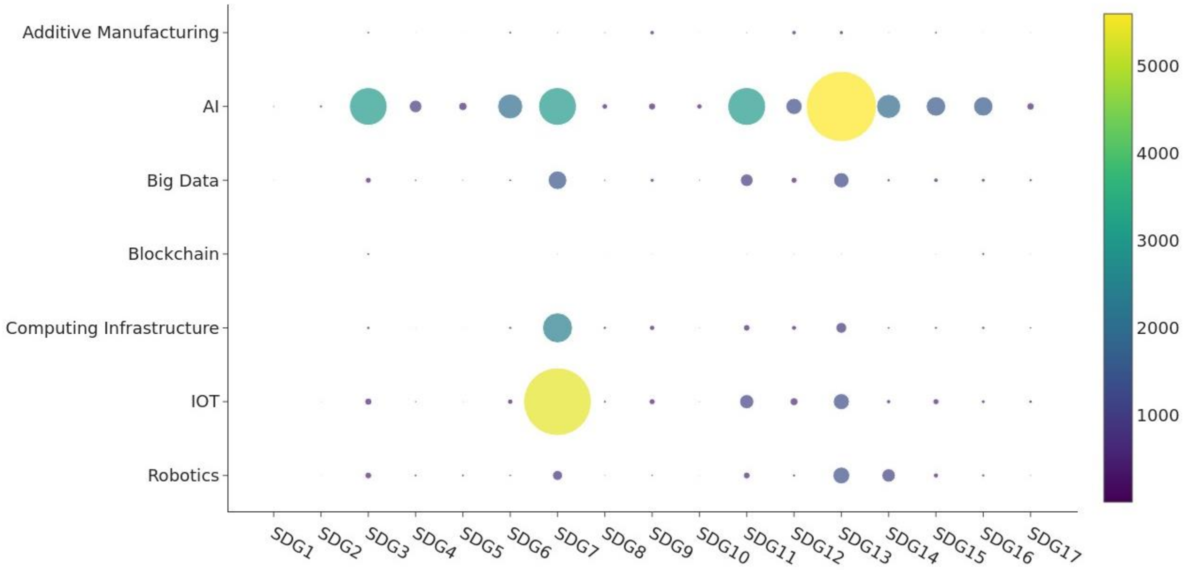

Figure 6. Scientific research in the SDGs-DTs knowledge space, 2010-2021

Source: JRC calculations on WoS data.

Other SDGs-DTs combinations account for fewer scientific publications, with the notable exception of the SDG7-IoT combination, which is the second largest combination after SDG13-AI. Interestingly, SDG7 is combined with a heterogeneous set of different digital technologies that, beyond IoT and, to a lower extent, AI, also include a sizable amount of scientific research on computing infrastructure and big data.[8] This suggests that recent scientific research related to energy production, distribution and consumption is exploring new paths of knowledge re-combinations with different intertwined digital technologies. Analogous evidence, yet with lower numbers, is observed for SDG11,

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[8] Figure A.1 in the Annex, which shows the shares of the different DTs in every SDG, confirms these patterns making that: i) AI is the most prevalent DT in all SDGs but in SDG7, for which IoT is the most prevalent DT; and ii) the distributions of DTs are typically very skewed with AI accounting for most of publications in all SDGs, but in the cases of SDGs 7, 8 and 9, which show more balanced distributions of DTs also covering IoT, big data and computing infrastructure.

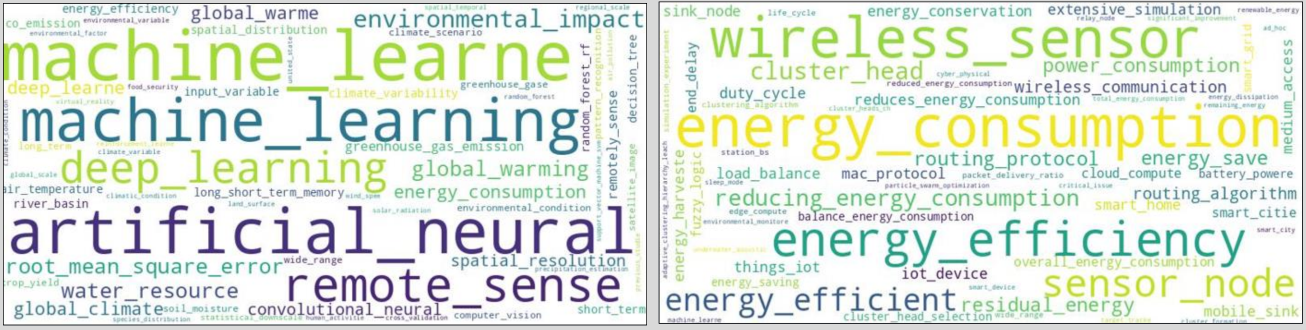
which beyond AI also include sizable research on big data and IoT, and SDG13, which beyond AI also include sizable research on big data, IoT, computing infrastructure and robotics. A more detailed analysis on the publication corpus is proposed in Box 2.

Box 2. Artificial Intelligence, IoT, and main application domains

We examine the most recurring bigrams in the abstracts of publications at the intersection of AI and SDG13 (important application domains.

Figure 7, panel a) and IoT and SDG7 (panel b) to gain a broader understanding of the most important application domains.

Figure 7. The most recurrent terms in publication abstracts



Panel a. AI and SDG13 (Climate Change)

Panel b. IoT and SDG7 (Affordable and Clean Energy)

Source: JRC calculations on WoS data.

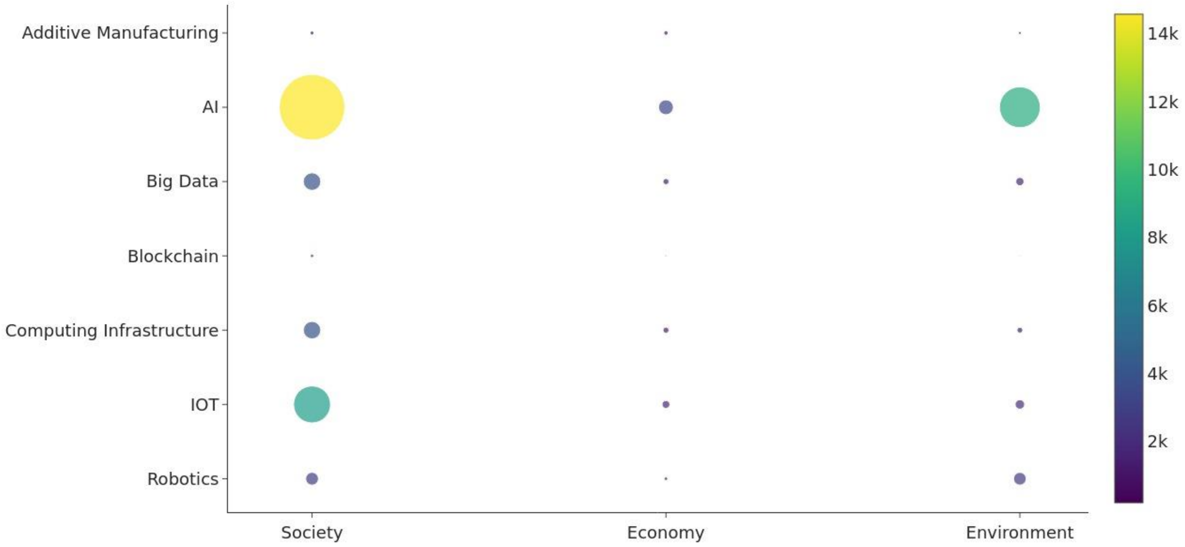
Most AI publications on SDG13 seem to deal with climate issues and environmental monitoring via machine learning (deep learning in particular). Beyond the over-representation of AI-related keywords, we see some recurring terms such as "*global warming*", "*global climate*", and "*water resources*", on the one hand, and terms such as "*remote sense*", "*environmental impact*", and "*satellite image*" on the other. This comes as no surprise since, in recent years, AI has shown great potential to address various environmental problems, although its net environmental return remains a controversial issue (see Bianchini et al., 2022b for an in-depth discussion). A closer reading of some of the publications in this intersection category suggests that researchers have made use of machine learning techniques to forecast environmental patterns – e.g., water scarcity, intense droughts, and flooding. Remote sensing is also a very important area of application. Here, AI techniques are used to process data and images acquired from sensors with the goal of extracting information about the environment and monitoring it over time.

Regarding IoT publications related to SDG7, we identify some generic terms referring to energy, such as "*energy consumption*", "*energy efficiency*", and "*energy saving*". Most scientific work focuses on how to reduce the energy consumption of IoT devices (especially sensors) to improve their efficiency – i.e., use of less energy to perform the same task or produce the same result. One area of particular interest seems to be the design and implementation of energy-efficient wireless sensors – with terms such as "*wireless sensor*", "*wireless communication*", and "*sink node*". These sensors can find a variety of applications, ranging from precision agriculture to environmental monitoring to smart cities.

Interestingly, **Figure 6** also shows that in a number of SDGs and DTs there is limited digital-related scientific research, in particular in: SDG1 (no poverty), SDG4 (quality education), SDG5 (gender equality) SDG8 (decent work and economic growth), SDG9 (industry, innovation and infrastructure), SDG10 (reduced inequality) and SDG17 (partnerships for the goals) among SDGs, as well as in additive manufacturing and blockchain among digital technologies.

Taking a more aggregated perspective, Figure **8** shows that SDGs-DTs scientific research is particularly abundant in SDGs related to Society, with a strong role of AI and IoT and some non-trivial presence of research on big data, computing infrastructure and robotics. On the other extreme, SDGs-DTs research is scarce in SDGs related to the Economy. SDGs related to Environment take an intermediate position in terms of quantity of scientific production and exhibit a strong focus on AI. The particularly large quantity of research in Society-related SDGs is only partially driven by the number of publications falling in this category (539,947), as it is also confirmed by the comparatively high proportion of publications in the DTs-Society intersection (3.68% of all Society publications). By contrast, the absolute numbers of publications in the Economy (174,860) and Environment (522,870) SDGs categories drive the difference in the number of publications in the intersection with DTs, as Economy-DTs publications show a larger proportion of all Economy publications (2.80%) than the analogous proportion (2.32%) in the Environment category.

Figure 8. *SDGs-DTs scientific research by SDGs category, 2010-2021*



Notes: the "Society" category includes SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11 and SDG17); the "Economy" category includes SDG8, SDG9, SDG10, SDG12, SDG17; the "Environment" category includes SDG13, SDG14 and SDG16. Source: JRC calculations on WoS data.

Figure 9 shows the trend in scientific research of the most representative SDGs-DTs combinations.[9] Until 2018, scientific research on SDG7-IoT and SDG13-AI combinations has been of similar magnitude and displayed a similar upward trend, rising from less than 100 publications in 2010 to about 400 in 2018 (

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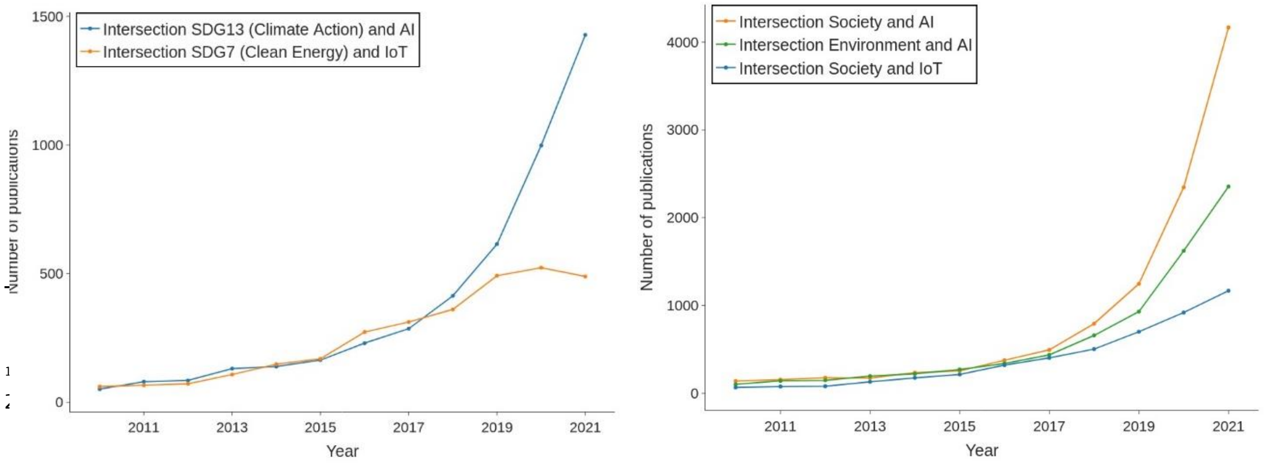
[9] As a cautionary note, at the present stage we are unable to ascertain whether digital technology serves as a support to the achievement of a given SDG (e.g., AI system for predicting extreme weather events) or is the very object of study in a given SDG area (e.g., quantifying datacenter energy consumption). A manual analysis of a random sample would seem to confirm that it is mostly the former case; however, a finer analysis would be needed to draw more robust conclusions.

Figure 9, panel a). It is only in 2019 that the trend showed a marked difference, with SDG13-AI research markedly accelerating its growth pace up to reach more than 1000 in 2021, and with SDG7-IoT on the contrary stagnating with about 500 publications per year between 2019 and 2021.

Differential trends in the most recent years are also observed when taking a more distant perspective by focusing on the combinations of SDGs macro-categories and DTs object of more intense research (

Figure 9, panel b). Scientific research on the Society-AI, Society-IoT and Environment-AI domains similarly rose from less than 100 publications each in 2010 up to about 400 publications each in 2017. Afterwards, the Society-AI domain showed the strongest increase, growing by 44% between 2020 and 2021[10], reaching more than 4000 publications in 2021, as compared to about 2500 in the Environment-AI domain and about 1200 in the Society-IoT one. The growth of the Society-AI combination is partially explained by the growing research in the SDG3 ('Good Health and Well-being')-AI combination that has been carried out in the wake of the COVID-19 pandemic (see Box 3). Overall, this evidence suggests, that AI has a key role in driving the recent growth of SDGS-DTS scientific knowledge development.

***Figure 9**. Trends in the most frequent combinations of SDG and DT*



nd

Panel a. The most studied SDGS-DTS combinations: SDG7-IoT and SDG13-AI

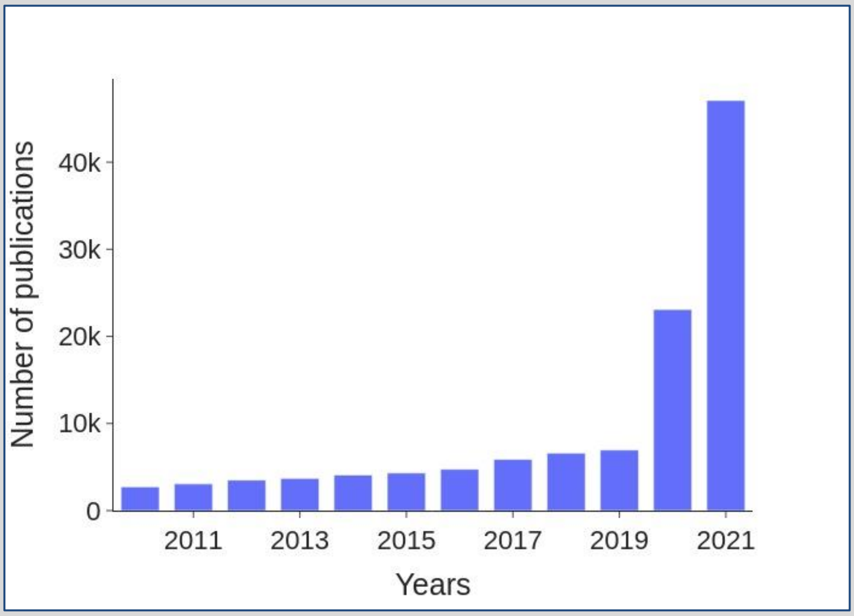
Panel b. The most studied combinations of SDG aggregate categories-DT: Society-AI, Society-IoT and Environment-AI

Notes: the "Society" category includes SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11 and SDG17; the "Environment" category includes SDG13, SDG14 and SDG16. Source: JRC calculations on WoS data.

Box 1. COVID-19 and scientific research

The early scientific response to the COVID-19 pandemic was a unique case of a global research effort toward a common goal. International scientific communities have brought together diverse expertise to assess the clinical and pathogenic characteristics of the disease and formulate therapeutic strategies. In this report, this phenomenon is captured by the large increase observed in 2020 and 2021 for publications related to SDG3 ('Good Health and Well-being') as shown in Figure 10.

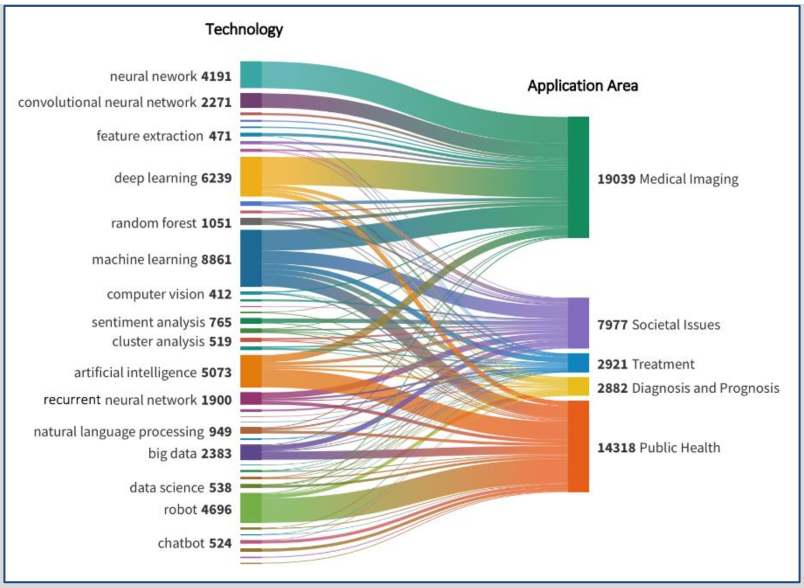
Figure 10. Number of publications in SDG3. Good Health and Well-being



Source: JRC calculations on WoS data.

In this context, AI has represented an effective solution to some of the challenges posed by COVID-19. Some studies confirm that AI tools have intervened at different stages of the pandemic, with applications in three main areas: molecular, clinical and social (Bulloc et al., 2020). Molecular applications included, e.g., protein structure predictions, drug repurposing, and drug discovery. Clinical applications involved, among others, autonomous and remote-controlled robots for telemedicine, image-based diagnosis, and hospital capacity planning. In the social realm, AI has found its place in two main domains: epidemiology and infodemiology. Concerning epidemiology, AI-based solutions have helped understand public policy interventions such as quarantine and social distancing, while for infodemiology, AI has helped combat information disorders and manage information overabundance (often intentionally deceptive).

Figure 11. Occurrence of AI keywords in the five COVID-19 application areas



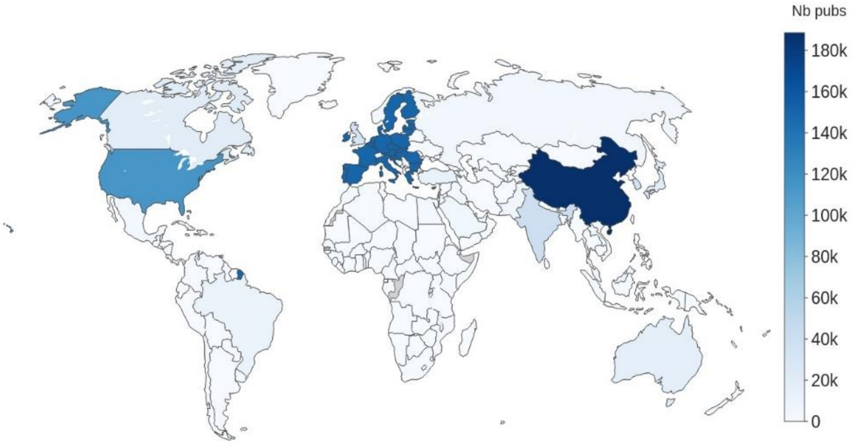
Source: Abbonato et al. (2022). Application areas are identified through topic modelling of publication corpus.

A recent bibliometric study on AI and COVID-19 confirmed the predominant role of machine learning techniques for medical imaging and public health, as shown in Figure 11 (Abbonato et al., 2022). A closer reading of the terms characterizing medical imaging suggests the massive use of deep learning models (e.g., CNN) to detect signs of COVID-19 from X-ray images and computed tomography (CT) scans. The trends described here may explain the recent upsurge in SDG3 papers discussed in this report.

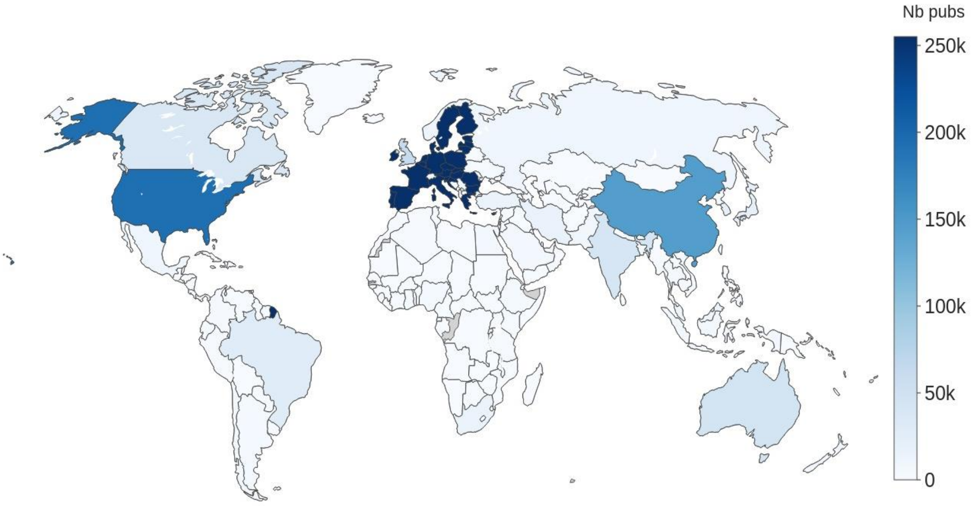
3.2 The geography of SDGs, DTs and SDGs-DTs scientific knowledge creation

This sub-section describes the main worldwide patterns of scientific production at the country level. Figure 12 maps world nations according to the number of publications in SDGs, DTs and their intersection between 2010 and 2021, while Figure 13 shows yearly trends for selected countries and the EU. The United States (US) is the world leader in SDG-related scientific research with about 194,000 publications, followed by China with about 145,000. Notice that the EU taken as a whole has more publications in the period – i.e., about 255,000 – with a growth rate comparable to the one of China. All other countries have much lower numbers of publications, with the United Kingdom (UK) showing the largest one (about 61,000), followed by Australia (46,000), Italy (37,000) and Germany (36,000).

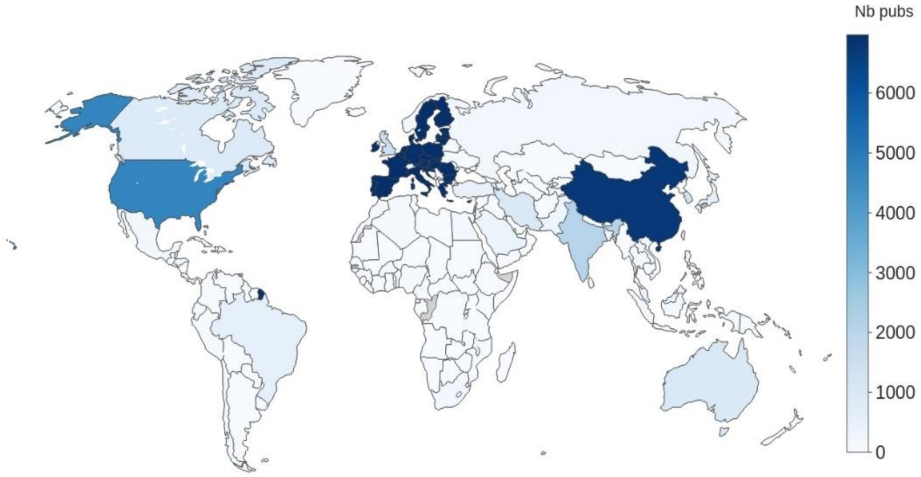
Figure 12. *Scientific publications in SDGs, DTs and SDGs-DTs knowledge domains in the world, 2010-2021*



Scientific research in SDGs

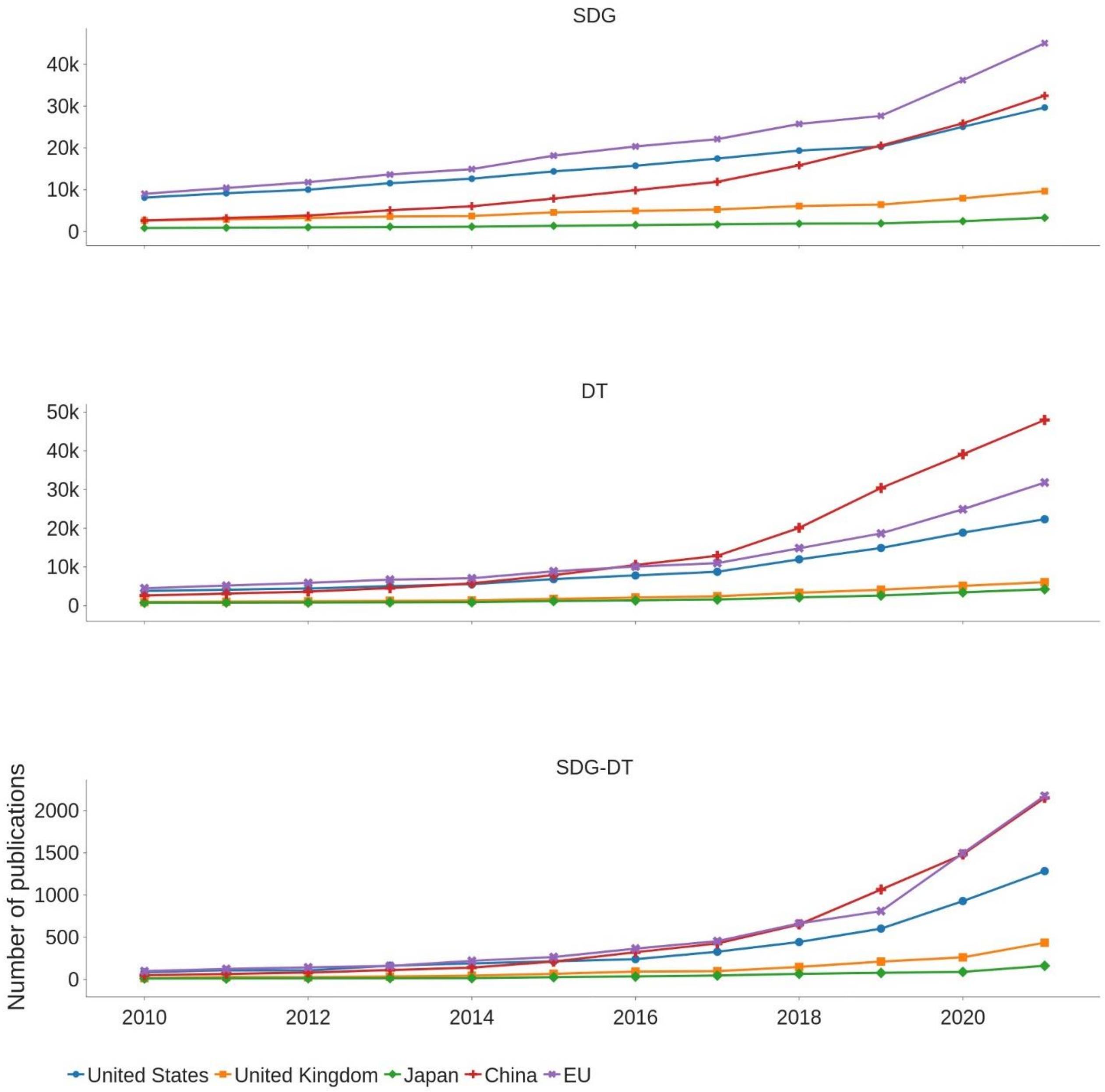


Scientific research in SDGs-DTs



Notes: Publications computed using fractional counting. Source: JRC calculations on WoS data.

Figure 13. Trends of scientific publications in SDGs, DTs and SDGs-DTs knowledge domains in selected countries and the EU, 2010-2021



Notes: Publications computed using fractional counting. Source: JRC calculations on WoS data.

China has the largest number of publications on DTs over the entire period (about 189,000). In the same years, the EU ranks second with about 150,000 publications, and the US occupies the third position with about 115,000 publications. The trends displayed in Figure 13 indicate that these differences were generated in the last years. A similar number of DTs-related publications (about 10,000) is recorded yearly up to 2017 in both China and the US as well as in the EU, while in 2021 China had more than 40,000 as compared to the EU and the US with about 30,000 and 20,000 respectively. Among other countries, South Korea and the UK show the largest number of DTs publications (respectively 33,000 and 31,000 over the entire period), followed by Germany and Italy (25,000 over the entire period).

Similarly, as in the case of SDGs, the EU as a whole leads in the production of scientific knowledge on SDGs-DTs (about 7,000 publications, roughly 21%), followed by China (6,500) and the US (5,000). The trends of the EU and China are very close across years, while the gap with the US accentuated since 2016. Among other countries, the UK has the largest number of SDGs-DTs publications in the period (about 1,500), followed by Italy, South Korea, Spain, Germany, and Australia (all approximately SDGs-DTs 1,000 publications).

The next section delves into the EU patterns by discussing SDGs-DTs scientific performance of EU MSs and regions.

4. SDGs, DTs, and SDGs-DTs publications in the European Union

This section studies the scientific performance of the EU Member States (MSs) and regions in SDGs and DTs fields.

4.1 SDGs, DTs, and SDGs-DTs scientific performance of EU MSs

The Section starts by zooming on the EU at the MSs-level. Figure 14 shows MSs' *strength* in DTs- and SDGs-related research defined as the research output, both in absolute terms (left) and normalized (right) by 2021 Gross Domestic Product (GDP) expressed in Purchase Power Standard (PPS). Unsurprisingly, the largest contributors in absolute terms to the creation of scientific knowledge are the biggest countries – i.e., France, Germany, Italy and Spain. Italy ranks first in the SDGs and SDGs-DTs domains (about 37,000 SDGs and 1,200 SDGs-DTs publications), while Germany is the European leader in the creation of digital knowledge (about 25,000 DTs publications).

The rankings change substantially when GDP-normalized values are considered. The maps on the right of Figure 14 shows MSs relative scientific performance obtained by deflating the number of publications by GDP expressed in PPS. These measures show that Portugal and Croatia are the best performers in SDGs-related scientific production; Slovenia, Greece and Cyprus in DTs-related scientific production; and Greece and Cyprus in the production of scientific publications covering both SDGs and DTs. On the other side of the ranking, Luxembourg, France and Germany are the worst performers in SDGs-related scientific research (normalized by GDP); Luxembourg, Ireland and France in DTs-related one; and Malta, France, Germany, Ireland and Luxembourg in scientific output combining SDGs and DTs research.

It is also interesting to discuss scientific specialization of EU MSs, as defined using the RCA index. **Figure 15** shows maps based on the scientific specialization of EU MSs in *selected* SDGs-DTs research domains. In particular, it focuses on broad domains obtained combining the SDGs-based classification in Economy, Environment and Society with the two most largely represented DTs categories, namely AI and IoT.[11] In the maps, MSs are assigned to three categories depending on the value of their RCA index: MSs with RCA larger than 1.25 are labelled as "specialized", those with RTA between 0.75 and 1.25 "not specialized" and those with RCA lower than 0.75 "under-specialized". The emerging picture suggests a highly heterogeneous EU landscape, with different MSs being specialized in different SDGs-DTs domains.

A few MSs are specialized in three of the selected domains:

- Greece in Economy-AI, Economy-IoT and Environment-IoT;
- Ireland in Economy-IoT, Environment-IoT and Society-IoT;
- Luxembourg in Economy-AI, Economy-IoT and Society-AI.

Several MSs are specialized in two domains:

- Belgium, Italy, Romania and Spain in Economy-IoT and Environment-IoT;
- Lithuania and Sweden in Economy-AI and Economy-IoT;
- Austria in Economy-AI and Environment-IoT;
- Bulgaria in Economy-IoT and Environment-AI;
- Denmark in Environment-AI and Environment-IoT;
- Latvia in Environment-IoT and Society-IoT;
- Slovakia in Economy-AI and Environment-AI.

Other MSs are specialized in one domain only; for the sake of brevity, we mention France in Environment-AI and Germany in Economy-IoT. A similar degree of heterogeneity is observed when focusing on under-specialization, as shown in **Figure 15**.

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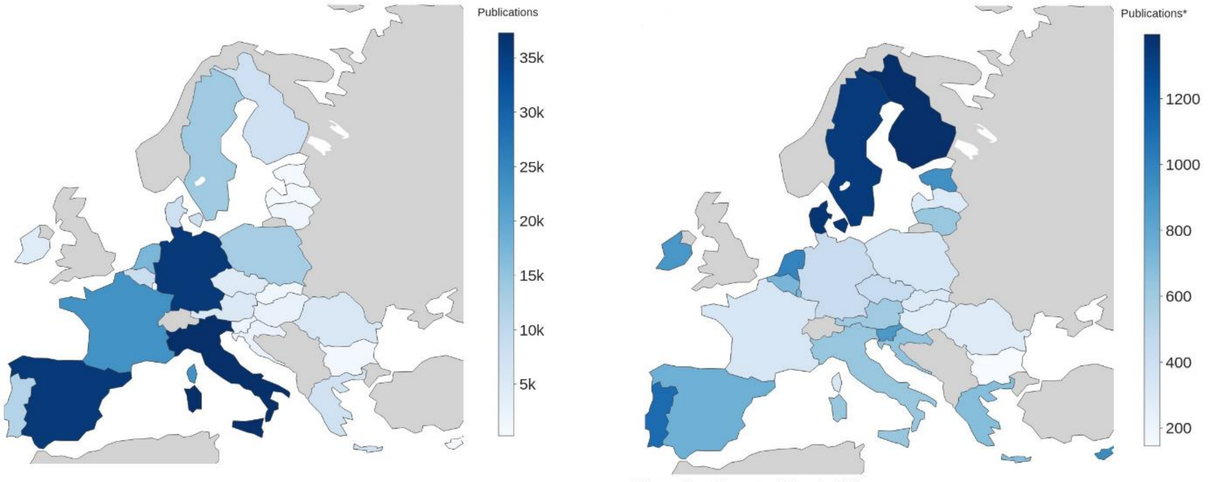
[11] These are 6 of the possible 21 domains given by the combination of the 3 SDGs categories (Economy, Environment and Society) with the 7 DTs (additive manufacturing, AI, big data, …).

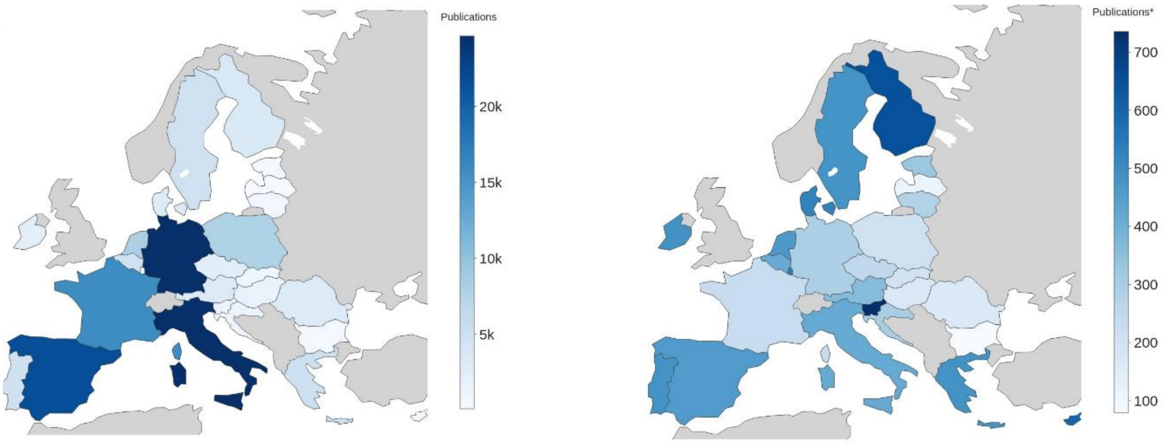
Figure 14. *Scientific research in SDGs, DTs and SDGs-DTs domains in EU Member States, 2010-2021*

SDGs



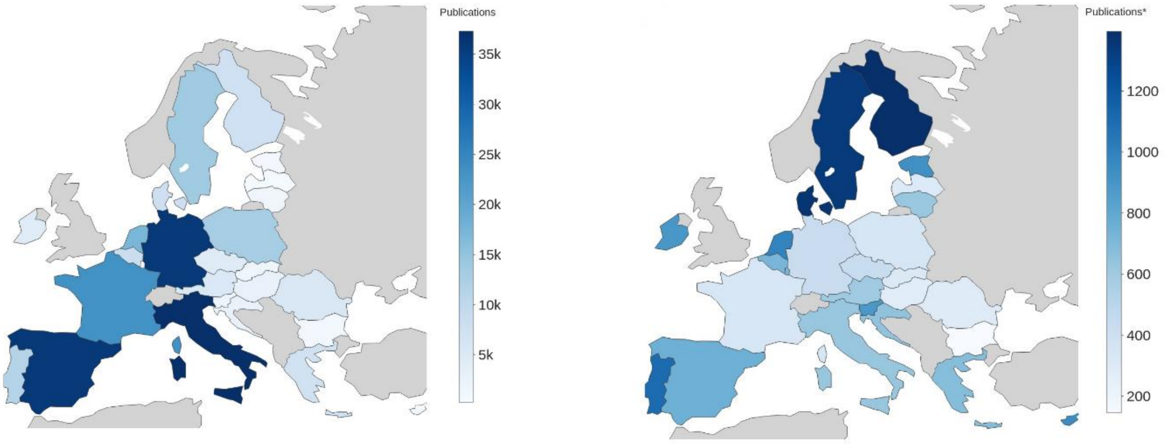
*Normalized by population in Million

DTs



*Normalized by population in Million

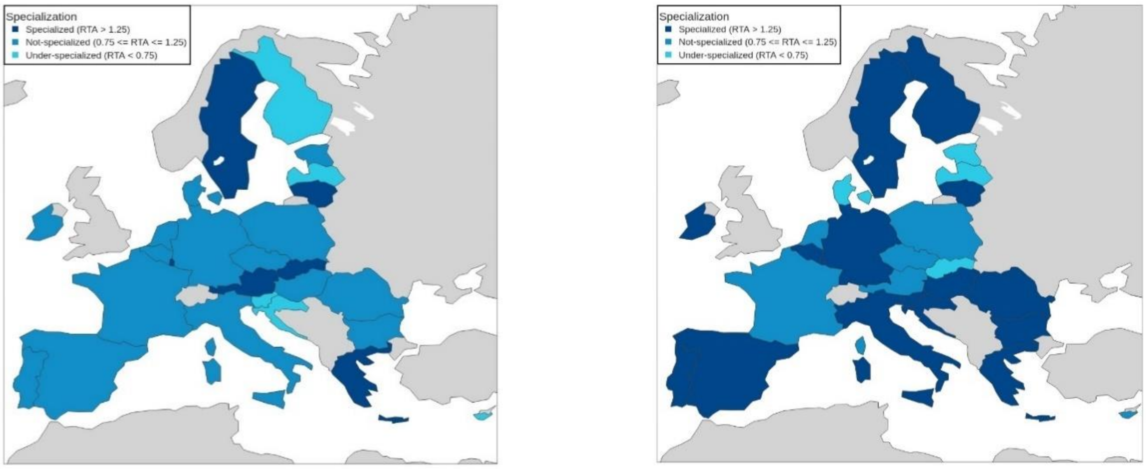
SDGs-DTs



*Normalized by population in Million

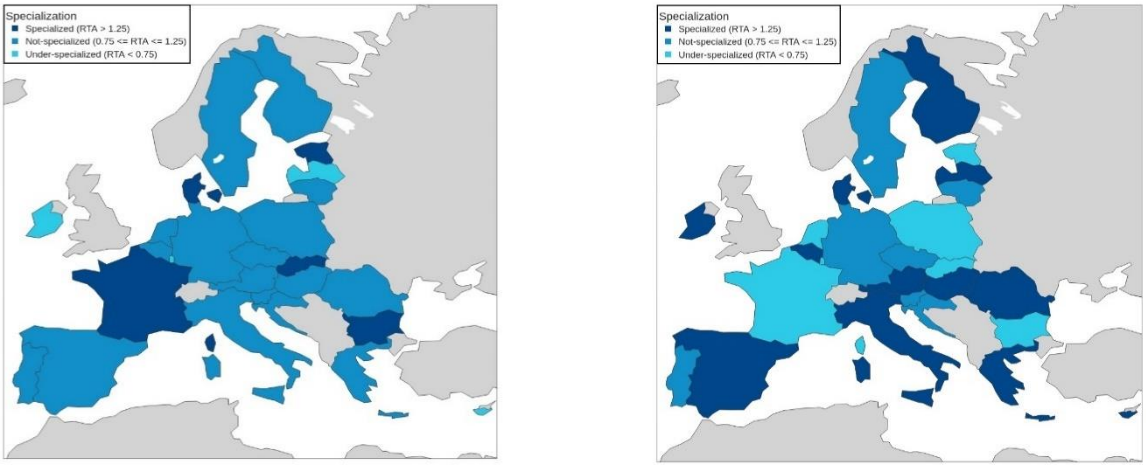
Notes: Publications computed using fractional counting. Left-hand side: pictures represent fractional counts; right-hand side: publications fractional counts normalised by 2021 population (in million). *Source:* JRC calculations on WoS and Eurostat data.

Figure 15. *Specialization of EU Member States in selected SDGs-DTs domains, 2010-2021*



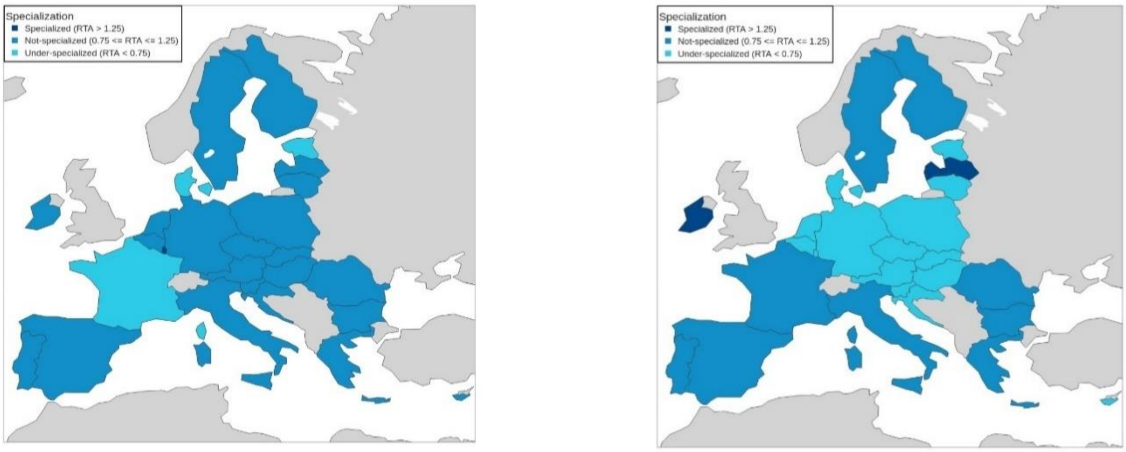
Economy-AI

Economy-IoT



Environment-AI

Environment -IoT



Society-AI

Society-IoT

Notes: RCA indexes computed using fractional counting. The “Society” category includes SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11 and SDG17); the “Economy” category includes SDG8, SDG9, SDG10, SDG12, SDG17; the “Environment” category includes SDG13, SDG14 and SDG16. *Source:* JRC calculations on WoS data.

4.2 SDG, DT and SDGS-DTS scientific performance of EU regions

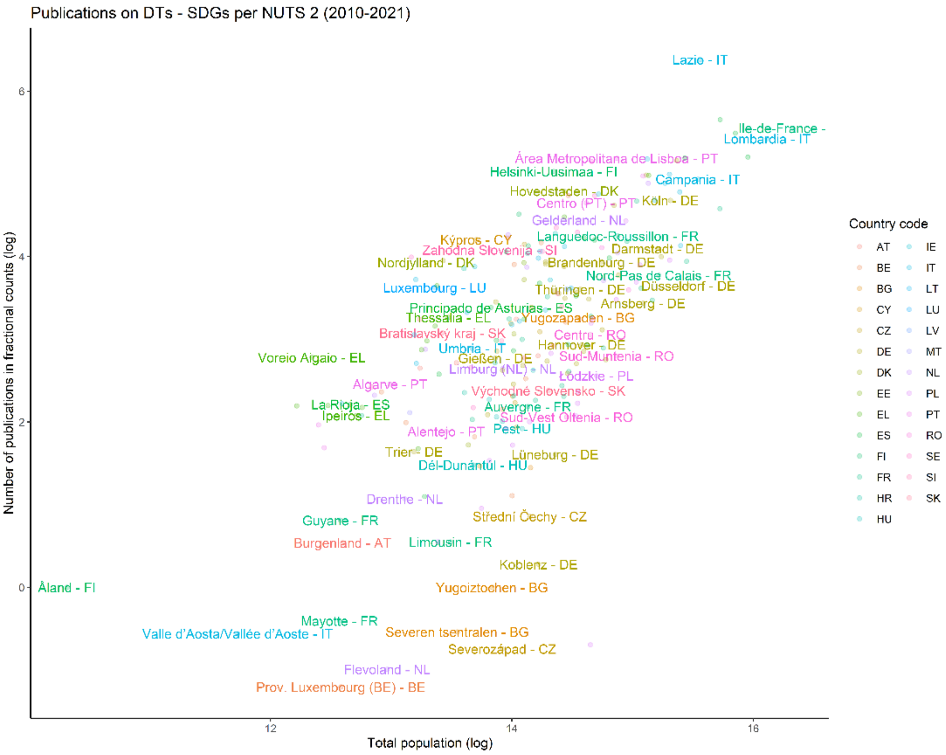
This sub-section studies the scientific performance of EU NUTS 2 regions in SDGs, DTs and SDGs-DTs fields. Similarly as in Section 4.1, we focus on what we defined as fractional counts and deflate the number of publications of each region NUTS-2 using their 2021 total population.

In absolute terms, the most scientific production comes from Cataluña (Spain) in SDGs and Île-de France (France) in DTs, with more than 10.000 publications since 2010. Other regions with large absolute numbers (more than 6.000) of publications are: i) in SDGs, Île-de France (France), Comunidad de Madrid and Andalucía (Spain), Lombardia and Lazio (Italy), Zuid-Holland (Netherlands) and Hovedstaden (Denmark); ii) in DTs, Comunidad de Madrid (Spain), Lombardia (Italy) and Oberbayern (Germany). As for the intersection SDGs-DTs, the highest amount of scientific knowledge comes from Lazio (Italy) with almost 600 publications, followed by Comunidad de Madrid and Cataluña (Spain) and Lombardia (Italy), with more than 200 publications.

Unsurprisingly, the weakest regions are instead among rural areas, some EU outermost and less populated regions such as Flevoland and Drenthe (Netherlands), Severen Tsentralen (Bulgaria), Prov. Luxembourg (Belgium), Valle d'Aosta (Italy), Burgenland (Austria) and Åland (Finalnd) where there are less 100 publications on SDGs or DTs since 2010.

Considering only absolute counts may be misleading. Indeed, more populated regions are expected to have more people working in the fields of education and R&D activities, leading to larger amounts of qualified human capital in any domain. Consequently, we also report a normalized indicator, in which all figures have been normalized by total regional population to get – at least partly – rid of scale effects. The positive correlation between (log-transformed) population and (log-transformed) number of publications in the three domains finds visual confirmations in the following chart figures (**Figure 16** for the SDGs-DTs intersection; and Figures A2 and A3 in Appendix for SDGs and DTs respectively).

Figure 16. *Correlation between scientific knowledge in SDGs-DTs fields and population for NUTS-2 regions, 2010-2021*



Notes: Number of publications computed using fractional counting. Population refers to 2021 regional population. *Source:* JRC calculations on WoS and Eurostat data.

When flagging the top-15 NUTS 2 regions by the number of publications across the three domains normalized by regional population (see the second column of **Table 2**, **Table 3** and **Table 4**), it emerges an interesting pattern: five regions from different countries are in the top-15 list of all SDGs, DTs and SDGs-DTs domains. Those regions are:

- Övre Norrland – SE
- Helsinki-Uusimaa – FI
- Bremen – DE
- Hovedstaden – DK
- Grad Zagreb – HR

Scientific production in the digital domain is evenly distributed across EU countries, having regions from 14 countries in the top 15. Only Denmark appears two times in the best 15 performing regions (Nordjylland and Hovedstaden). Geographical patterns are clearer if referring to SDG-related scientific production, where among the top 15 performers there are three Swedish (Övre Norrland, Östra Mellansverige, Stockholm), three Dutch (Gelderland, Utrecht, Groningen) and two Belgian regions (Prov. Vlaams-Brabant, Région de Bruxelles-Capitale). Observing publications in the intersection of digital technologies and SDGs, four countries appear two times among the best performers: Italy (Lazio, Provincia Autonoma di Trento), Finland (Helsinki-Uusimaa, Pohjois- ja Itä-Suomi), Denmark (Nordjylland, Hovedstaden) and Greece (Voreio Aigaio, Dytiki Elláda)

A high divergence emerges when flagging the worst-performing regions in the three domains. Six regions are in the bottom-15 list in all domains (Mazowiecki regionalny – PL, Severozápad – CZ, Vorarlberg – AT, Severen tsentralen – BG, Severozapaden – BG and Mayotte - FR). In most cases, however, being among the weakest regions in one domain is not associated to being among the weakest also in the others.

Table 2. *Top and bottom 15 NUTS 2 regions by number of publications in SDGs, 2010-2021*

NUTS 2 region	Publications	Publications by population (x 10000)
Top 15 NUTS 2		
Övre Norrland - SE	2,158.5	41.3
Bremen - DE	2,490.4	36.6
Hovedstaden - DK	6,435.3	34.7
Helsinki-Uusimaa - FI	4,995.8	29.3
Gelderland - NL	5,621.7	26.8
Utrecht - NL	3,453.8	25.4
Groningen - NL	1,475.9	25.1
Östra Mellansverige - SE	4,332.8	24.9
Grad Zagreb - HR	1,965.1	24.3
Stockholm - SE	5,532.4	23.1
Praha - CZ	2,983.0	22.3
Wien - AT	4,186.8	21.8
Prov. Vlaams-Brabant - BE	2,496.6	21.5
Région de Bruxelles-Capitale/ Brussels Hoofdstedelijk Gewest - BE	2,510.2	20.5
Algarve - PT	880.7	20.1
Bottom 15 NUTS 2		
Yuzhen tsentralen - BG	172.1	1.2
Ciudad de Ceuta - ES	9.2	1.1
Swietokrzyskie - PL	130.1	1.1
Sterea Elláda - EL	57.6	1.0
Severozápad - CZ	101.5	0.9
Åland - FI	2.3	0.8
Észak-Magyarország - HU	89.9	0.8
Yugoiztochen - BG	75.5	0.7
Mayotte - FR	13.5	0.5
Mazowiecki regionalny - PL	122.7	0.5
Burgenland - AT	12.6	0.4
Severen tsentralen - BG	28.6	0.4
Vorarlberg - AT	14.2	0.4
Drenthe - NL	15.8	0.3
Severozapaden - BG	11.3	0.2

Notes: Number of authors computed using fractional counting. Population refers to 2021 regional population. *Source:* JRC calculations on WoS and Eurostat data.

Table 3. *Top and bottom 15 NUTS 2 regions by number of publications in DTs, 2010-2021*

NUTS 2 region	**Publications**	**Publications by population (x 10000)**
Top 15 NUTS 2		
Provincia Autonoma di Trento - IT	1,615.9	29.8
Nordjylland - DK	1,408.3	23.9
Prov. Vlaams-Brabant - BE	2,629.1	22.6
Dytiki Elláda - EL	1,451.0	22.4
Övre Norrland - SE	1,099.8	21.0
Helsinki-Uusimaa - FI	3,374.9	19.8
Bremen - DE	1,236.5	18.2
Praha - CZ	2,353.6	17.6
Zahodna Slovenija - SI	1,735.1	17.3
Bucuresti-Ilfov - RO	3,921.3	16.9
Wien - AT	3,141.2	16.4
Hovedstaden - DK	2,933.7	15.8
Grad Zagreb - HR	1,258.4	15.6
Luxembourg - LU	955.7	15.1
Bratislavský kraj - SK	1,014.2	15.0
Bottom 15 NUTS 2		
Vorarlberg - AT	19.8	0.5
Åland - FI	1.3	0.4
Flevoland - NL	15.1	0.4
Pest - HU	47.9	0.4
Prov. Luxembourg (BE) - BE	10.7	0.4
Friesland (NL) - NL	18.0	0.3
Guyane - FR	8.0	0.3
Mazowiecki regionalny - PL	71.6	0.3
Severen tsentralen - BG	25.3	0.3
Martinique - FR	8.4	0.2
Severozápad - CZ	26.2	0.2
Zeeland - NL	7.1	0.2
Ciudad de Melilla - ES	1.2	0.1
Severozapaden - BG	6.9	0.1
Mayotte - FR	0.7	0.0

Notes: Number of authors computed using fractional counting. Population refers to 2021 regional population. *Source:* JRC calculations on WoS and Eurostat data.

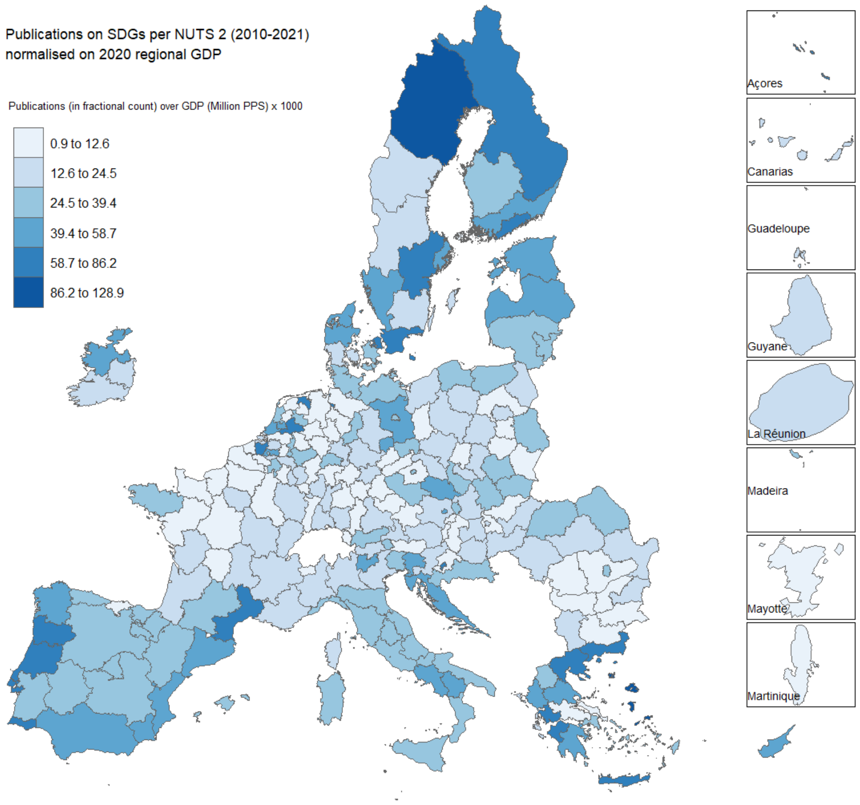
Table 4. *Top and bottom 15 NUTS 2 regions by number of publications in SDGs-DTs, 2010-2021*

NUTS 2 regions	**Publications**	**Publications by population (x 10000)**
Top 15 NUTS 2		
Lazio - IT	592.3	1.0
Övre Norrland - SE	54.3	1.0
Helsinki-Uusimaa - FI	153.0	0.9
Nordjylland - DK	50.9	0.9
Bremen - DE	52.1	0.8
Provincia Autonoma di Trento - IT	41.4	0.8
Bucuresti-Ilfov - RO	172.5	0.7
Hovedstaden - DK	120.6	0.7
Kýpros - CY	67.0	0.7
Pohjois- ja Itä-Suomi - FI	91.2	0.7
Voreio Aigaio - EL	16.2	0.7
Área Metropolitana de Lisboa - PT	179.5	0.6
Dytiki Elláda - EL	38.4	0.6
Grad Zagreb - HR	47.3	0.6
Luxembourg - LU	37.6	0.6
Bottom 15 NUTS 2		
Lüneburg - DE	5.0	0.0
Mayotte - FR	0.7	0.0
Mazowiecki regionalny - PL	0.5	0.0
Opolskie - PL	2.6	0.0
Prov. Luxembourg (BE) - BE	0.3	0.0
Prov. West-Vlaanderen - BE	3.0	0.0
Severen tsentralen - BG	0.6	0.0
Severoiztochen - BG	4.3	0.0
Severozápad - CZ	0.5	0.0
Strední Cechy - CZ	2.4	0.0
Sud-Vest Oltenia - RO	7.8	0.0
Swietokrzyskie - PL	5.6	0.0
Valle d'Aosta/Vallée d'Aoste - IT	0.6	0.0
Yugoiztochen - BG	1.0	0.0
Yuzhen tsentralen - BG	4.3	0.0

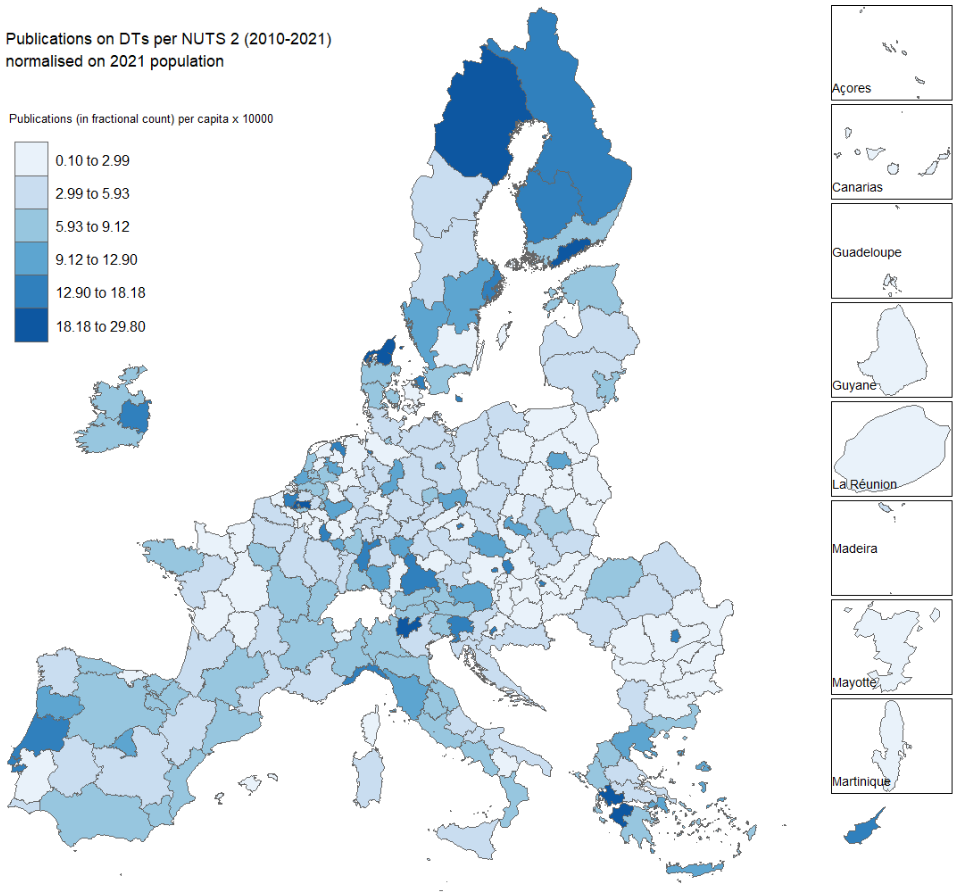
Notes: Number of publications computed using fractional counting. Population refers to 2021 regional population. Ciudad de Ceuta – ES, Ciudad de Melilla – ES, Vorarlberg – AT, Severozapaden – BG, Guadeloupe – FR and Martinique – FR have no publications and are not included in the table.
Source: JRC calculations on WoS and Eurostat data.

Figure 17 shows regional maps of scientific knowledge across the three domains normalised by 2021 total regional population. They visually confirm the evidence of an uneven distribution of publications in the three domains across European regions. While SDG-related scientific production is more concentrated in the northern EU regions (in particular within Sweden, Netherlands and Belgium), publications in DT-related knowledge are more distributed across EU regions.

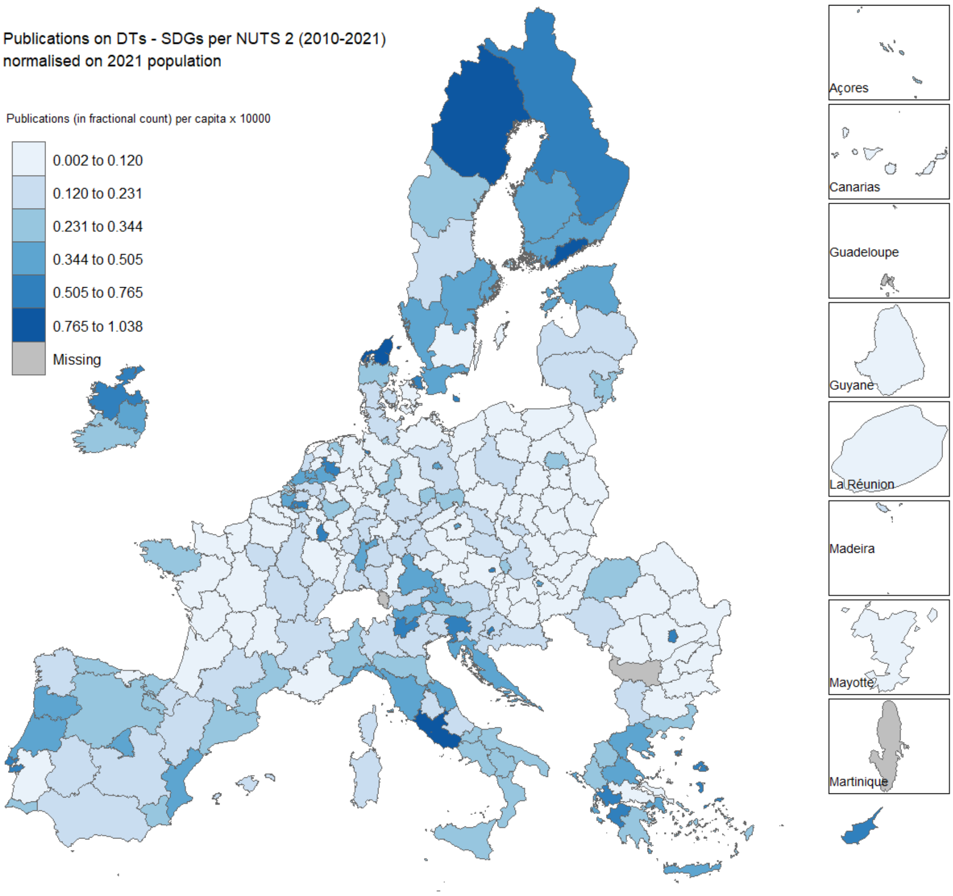
Figure 17. *Scientific strength of EU NUTS 2 regions in SDGs, DTs and SDGs-DTs, 2010-2021*



Publications on SDGs per NUTS 2 (2010-2021) normalised on 2020 regional GDP



Publications on DTs per NUTS 2 (2010-2021) normalised on 2021 population



Notes: Number of publications computed using fractional counting. Population refers to 2021 regional population. *Source:* JRC calculations on WoS and Eurostat data

5 Conclusions

This report provides the first evidence of the emergence of scientific research that jointly studies SDGs and DTs.

The combination of SDGs- and DTs-related in scientific research is a recent development that has surfaced over the past ten years and is rapidly expanding. This growth is mainly driven by scientific advancements on SDGs related to the Environment and Society (more than on those related to the Economy) and on AI and IoT. At a more granular level, the most studied SDGs-DTs combinations worldwide are SDG7 (Affordable and clean energy)-IoT and SDG13 (Climate change)-AI.

Unsurprisingly, China and the United States are major players in scientific research in the selected domains, with each country producing a large number of publications and holding a significant share of the global research output. Yet, the European Union as a whole produces more scientific publications than any single country, including China and the United States, in the SDGs and SDGS-DTs domains and closely follows China, which leads in terms of DTs publications. A closer look at knowledge productions across the European Union shows an uneven distribution across rural and urban areas. Nonetheless, no concentration patterns can be observed, as strengths in different topics (i.e., SDGs, DTs or a combination of the two) are evenly distributed across countries and European urban regions.

Scientific knowledge is well known to be an important driver of technological innovation (e.g., Rosenberg and Nelson 1994, Fleming and Sorensen 2004, Dosi and Grazzi 2010), as it guides research and development (R&D) efforts and indicates opportunities for knowledge recombination (Cassiman et al. 2004). The EU's strong scientific production in areas combining knowledge on both sustainable development and digital technologies, coupled with the strong ongoing EU policy efforts to promote the development, reinforcement, and diffusion of advanced digital technologies (such as the EU Digital Strategy), is likely to foster the opportunities for the creation of EU digital solutions enabling to approach the achievement of SDGs.

Yet, fully realizing the potential of EU digital research for sustainable development requires improvements in the integration of national research systems to exploit scale and scope economies that MSs cannot achieve in isolation. This is particularly important in research on advanced digital technologies, which is a domain whose development required solid infrastructures and specific capabilities, while being characterised by large investments worldwide. While having made some progress since the introduction of the European Research Area (ERA) in 2000, the EU scientific landscape appears fragmented (e.g., Chessa et al., 2013). This requires policy action. The EU shall, for instance, further promote the free movement of researchers, knowledge, and technology across its MSs, the harmonization of research policies and practices, and the coordination of research funding across different countries and industries – leveraging the European Research Council (ERC) to identify the priority areas. In addition, the EU shall encourage international collaborations with other leading players in the global research community as well as collaborations with economies that are less developed. By fostering international collaborations, the EU can bring in new ideas, technologies, and talented researchers from around the world, which will help to further strengthen and diversify the ERA.

This report is a first step toward the overall objective of providing a better understanding of the complex relationships between SDGs and DTs using the lens of science. Based on the collected data, a broad range of pathways can feed into future research to advance knowledge on the potential impact of emerging digital technologies on the different spheres of sustainable development. This carries important implications for the definition of strategies aimed at promoting research in the field.

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List of abbreviations and definitions

AI	Artificial Intelligence
AM	Additive Manufacturing
DLT	Distributed Ledger Technology
DT	Digital Technologies
ERA	European Research Area
EU	European Union
GDP	Gross Domestic Product
IaaS	Infrastructure-as-a-Service
IoT	Internet of Things
MS	Member State
NLP	Natural Language Processing
NUTS	Nomenclature des Unités Territoriales Statistiques
OECD	Organisation for Economic Co-operation and Development
PPS	Purchasing Power Standard
RCA	Revealed Comparative Advantage
R&D	Research & Development
SDG	Societal Development Goals
SDG1	No Poverty
SDG2	Zero Hunger
SDG3	Good Health and Well-being
SDG4	Quality Education
SDG5	Gender Equality
SDG6	Clean Water and Sanitation
SDG7	Affordable and Clean Energy
SDG8	Decent Work and Economic Growth
SDG9	Industry, Innovation and Infrastructure
SDG10	Reduced Inequality
SDG11	Sustainable Cities and Communities
SDG12	Responsible Consumption and Production
SDG13	Climate Action
SDG14	Life Below Water
SDG15	Life on land
SDG16	Peace and Justice Strong Institutions
SDG17	Partnerships to achieve the Goal
STI	Science, technology and innovation
UN	United Nations

List of boxes

Box 1. The components of the digital ecosystem 10

Box 2. Artificial Intelligence, IoT, and main application domains 14

Box 1. COVID-19 and scientific research 17

List of figures

Figure 1. SDGs icons in the UN 2030 Agenda 3

Figure 2. Recent evolution of scientific research in SDGs, DTs and their intersection, 2010-2021 6

Figure 3. Contribution of SDGs, DTs and joint SDGs-DTs research domains to scientific research, 2010-2021 7

Figure 4. Scientific research in SDGs by SDGs category, 2010-2021 9

Figure 5. Scientific research in DTs by component of the digital ecosystem, 2010-2021 12

Figure 6. Scientific research in the SDGs-DTs knowledge space, 2010-2021 13

Figure 7. The most recurrent terms in publication abstracts 14

Figure 8. SDGs-DTs scientific research by SDGs category, 2010-2021 15

Figure 9. Trends in the most frequent combinations of SDG and DT 16

Figure 10. Number of publications in SDG3. Good Health and Well-being 17

Figure 11. Occurrence of AI keywords in the five COVID-19 application areas 17

Figure 12. Scientific publications in SDGs, DTs and SDGs-DTs knowledge domains in the world, 2010-2021 18

Figure 13. Trends of scientific publications in SDGs, DTs and SDGs-DTs knowledge domains in selected countries and the EU, 2010-2021 20

Figure 14. Scientific research in SDGs, DTs and SDGs-DTs domains in EU Member States, 2010-2021 22

Figure 15. Specialization of EU Member States in selected SDGs-DTs domains, 2010-2021 23

Figure 16. Correlation between scientific knowledge in SDGs-DTs fields and population for NUTS-2 regions, 2010-2021 24

Figure 17. Scientific strength of EU NUTS 2 regions in SDGs, DTs and SDGs-DTs, 2010-2021 29

List of tables

Table 1. Publications on SDGs, DTs and SDGs-DTs fields in Web of Science (WoS), 2010-2021 5

Table 2. Top and bottom 15 NUTS 2 regions by number of publications in SDGs, 2010-2021 26

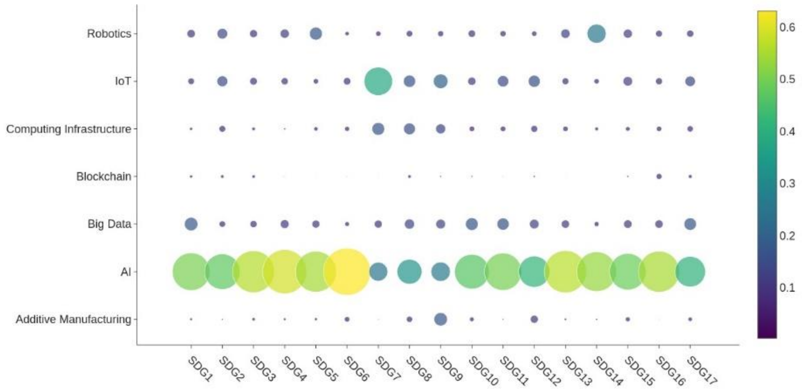
Table 3. Top and bottom 15 NUTS 2 regions by number of publications in DTs, 2010-2021 27

Table 4. Top and bottom 15 NUTS 2 regions by number of publications in SDGs-DTs, 2010-2021 28

Annexes

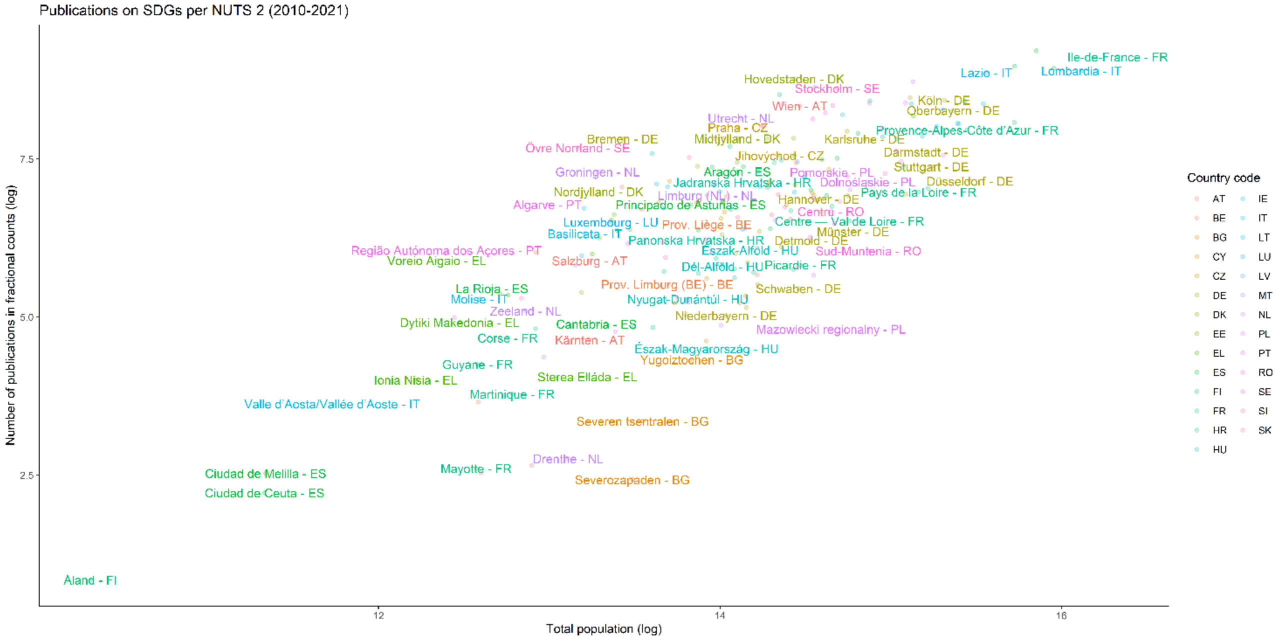
Annex 1. Additional Figures and Tables

Figure A1. *Shares of the different DTs in every SDG across the knowledge space, 2010-2021*



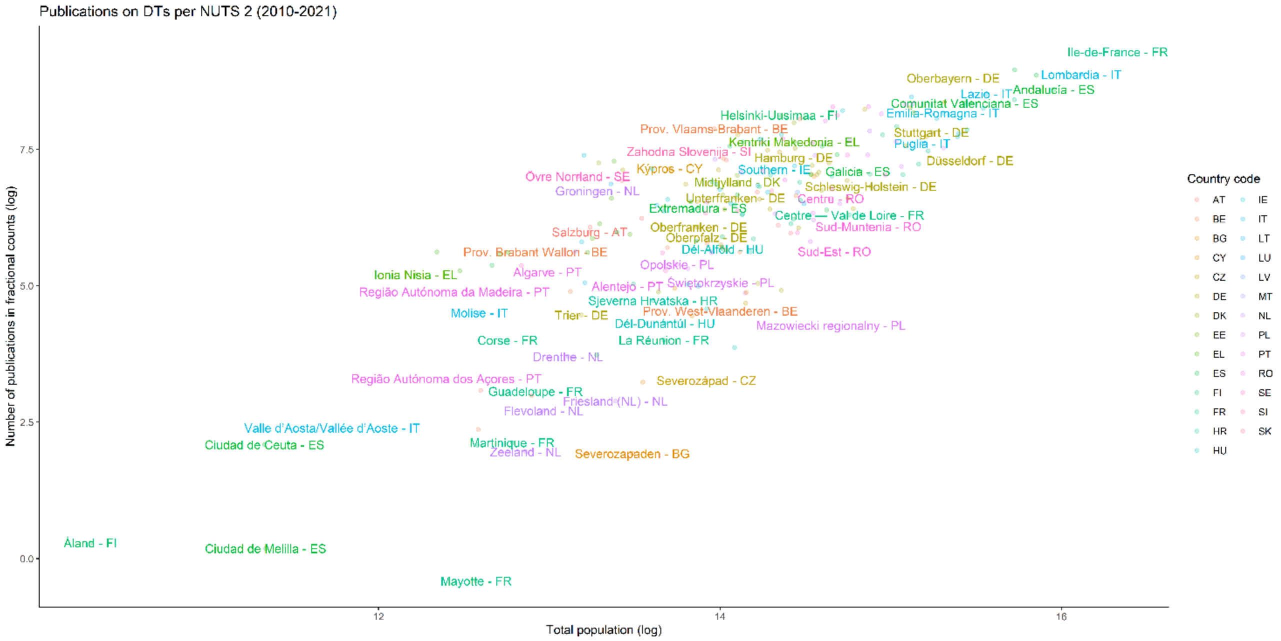
Notes: Source: JRC calculations on WoS data.

Figure A2. *Correlation of scientific knowledge in SDGs and population for NUTS 2 EU regions, 2010-2021*



Notes: Number of authors computed using fractional counting. Population refers to 2021 regional population. Source: JRC calculations on WoS and Eurostat data.

Figure A3. *Correlation of scientific knowledge in DTs and population for NUTS 2 EU regions, 2010-2021*



Notes: Number of authors computed using fractional counting. Population refers to 2021 regional population. Source: JRC calculations on WoS and Eurostat data.

Table A1. *Publications by EU and selected extra-EU countries, 2010-2021*

Country	**Number of publications**			**Number of publications by GDP**		
	SDGs	**DTs**	**SDGs-DTs**	**SDGs**	**DTs**	**SDGs-DTs**
EU Member States						
Austria	3236	5373	138	35.12	58.31	1.50
Belgium	4780	8372	182	40.44	70.82	1.54
Bulgaria	549	1009	25	37.86	69.54	1.69
Croatia	1225	2622	78	96.80	207.11	6.16
Cyprus	542	852	42	97.24	152.90	7.51
Czech Republic	2648	4619	108	49.88	87.01	2.03
Denmark	3078	7978	143	39.67	102.81	1.84
Estonia	439	1238	32	64.99	183.42	4.73
Finland	3615	7719	200	62.52	133.48	3.46
France	15854	23291	551	26.23	38.53	0.91
Germany	24570	36084	942	28.50	41.86	1.09
Greece	5161	7298	311	129.79	183.55	7.83
Hungary	1671	2768	85	52.46	86.91	2.68
Ireland	2429	4481	123	24.00	44.27	1.21
Italy	24648	37292	1220	59.79	90.46	2.96
Latvia	218	582	11	30.64	81.95	1.51
Lithuania	788	1752	40	65.33	145.24	3.34
Luxembourg	339	457	23	20.34	27.41	1.39
Malta	96	256	3	27.39	72.96	0.84
Netherlands	8149	17334	331	40.52	86.20	1.65
Poland	7937	13147	349	60.70	100.55	2.67
Portugal	4985	11420	295	101.23	231.88	6.00
Romania	3257	5699	211	69.69	121.93	4.52
Slovakia	1093	1734	42	49.48	78.51	1.88
Slovenia	1551	1863	60	133.63	160.49	5.21
Spain	21779	35876	1184	78.05	128.57	4.24
Sweden	4990	13918	244	39.77	110.94	1.94
EU	149627	255032	6974	44.07	75.12	2.05
Extra-EU countries						
Australia	17904	46271	972	55.09	142.39	2.99
Canada	20253	37206	902	53.71	98.68	2.39
China	188529	145200	6755	59.36	45.72	2.13
Israel	3376	4939	83	36.96	54.07	0.90
Japan	20909	19448	561	19.82	18.44	0.53
Norway	2617	9550	185	28.67	104.61	2.03
South Korea	32763	19411	1235	91.03	53.93	3.43
Switzerland	6294	9866	261	39.48	61.89	1.63
United Kingdom	30787	61206	1456	50.47	100.34	2.39
United States	114590	193488	4690	25.36	42.82	1.04

Notes: Number of publications computed using fractional counting. GDP refers to 2020 and is expressed in PPS, multiplied by 1,000,000.
Source: JRC calculatons on WoS data.

Table A2. *Revealed comparative advantages indexes of EU and selected extra-EU countries in selected SDGs-DTs domains, 2010-2021*

Country	**Economy-AI**	**Economy-IoT**	**Environment-AI**	**Environment-IoT**	**Society-AI**	**Society-IoT**
EU Member States						
Austria	1.42	0.92	1.07	2.10	0.81	0.64
Belgium	1.15	1.88	0.88	1.43	0.98	0.70
Bulgaria	1.04	1.62	1.30	0.00	1.07	1.12
Croatia	0.45	1.37	1.15	1.01	1.09	0.47
Cyprus	0.33	1.16	0.71	2.65	1.11	0.62
Czech Republic	0.95	1.18	0.97	0.91	0.93	0.55
Denmark	0.95	0.74	1.26	1.63	0.71	0.75
Estonia	1.08	0.51	1.64	0.46	0.51	0.65
Finland	0.60	2.92	0.98	1.57	0.75	1.10
France	0.82	1.07	1.34	0.74	0.75	0.87
Germany	1.15	1.32	1.25	0.85	0.85	0.55
Greece	1.31	1.46	0.92	1.49	0.94	0.88
Hungary	0.82	1.62	0.96	1.46	1.10	0.61
Ireland	1.12	1.53	0.71	2.17	0.96	1.28
Italy	0.77	1.55	0.85	1.54	0.82	0.95
Latvia	0.49	0.00	0.53	3.14	0.89	2.45
Lithuania	1.31	1.34	1.14	0.79	0.87	0.49
Luxembourg	1.49	1.74	0.60	0.00	1.62	0.07
Malta	0.00	0.00	0.20	0.00	1.53	0.38
Netherlands	1.21	0.79	0.97	0.41	1.08	0.54
Poland	1.13	0.94	1.10	0.56	1.08	0.53
Portugal	1.17	1.39	0.90	1.02	0.86	0.82
Romania	1.05	2.10	0.79	1.92	0.82	1.07
Slovakia	2.27	0.44	1.44	0.15	0.85	0.33
Slovenia	0.64	1.82	1.08	0.91	1.21	0.53
Spain	1.08	1.64	0.91	1.54	0.89	0.92
Sweden	1.30	1.69	0.90	1.15	0.86	0.98
Extra-EU countries						
Australia	0.80	0.98	1.14	1.24	0.83	0.67
Canada	0.80	0.85	1.20	0.81	1.07	0.84
China	1.00	0.72	0.99	0.86	1.07	1.23
Israel	0.21	0.00	1.01	0.14	1.34	0.58
Japan	0.60	0.61	0.98	0.93	0.88	0.83
Norway	1.05	0.54	1.28	0.45	0.69	0.65
South Korea	0.85	1.16	0.93	1.29	0.96	1.52
Switzerland	0.98	1.08	0.85	0.98	0.98	0.81
United Kingdom	1.10	1.37	0.86	0.99	0.95	0.89
United States	0.84	0.62	1.05	0.90	1.02	0.76

Notes: RCA indexes computed using fractional counting. The "Society" category includes SDG1, SDG2, SDG3, SDG4, SDG5, SDG6, SDG7, SDG11 and SDG17); the "Economy" category includes SDG8, SDG9, SDG10, SDG12, SDG17; the "Environment" category includes SDG13, SDG14 and SDG16. Source: JRC calculatons on WoS data.

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