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**Working Paper**

## A critical review of the digital and green twin transitions: Implications, synergies and trade-offs

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# A Critical Review of the Digital and Green Twin Transitions. Implications, synergies and trade-offs.

JRC Working Papers Series on  
Labour, education and Technology  
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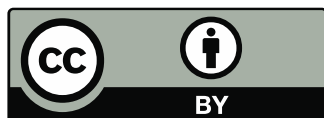
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# A Critical Review of the Digital and Green Twin Transitions

## Implications, synergies and trade-offs

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### Abstract

The working paper explores the complex relationship between the digital and green transitions and analyses how these two transformations, although independent, influence each other. It discusses the potential positive effects of digitalisation in the fight against climate change, such as improved efficiency and coordination of production and the dematerialisation of goods and services. However, the paper also highlights the risk of significant backlash due to the existence of rebound effects, as well as the potential negative consequences of digitalisation for the environment, including the high-energy consumption associated with digital technologies, the generation of e-waste, and the environmental impact of cryptocurrencies and artificial intelligence. Finally, the paper analyses the current state of adoption of the two transitions in companies, showing that although digitisation is more common, a significant percentage of companies are implementing both transitions, especially among large companies.

**Keywords:** Twin transitions, Digital Transition, Energy Transition, e-waste,

**Joint Research Centre reference number:** JRC140036

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## Executive summary

This working paper analyses the interactions between two major processes taking place today, the digital transition and the energy/green transition, known as 'twin transitions'. Although these processes are occurring simultaneously, they have different characteristics, objectives, drivers and actors. The digital transition, driven mainly by businesses, consumers and markets, started before the green transition and focuses on the use of digital technologies to increase productivity and economic growth. On the other hand, the green transition, originally led by governments, aims to decarbonise economic activity and mitigate climate change.

It is important to emphasise that there are two different ways of looking at and thinking about the twin transitions. According to the first, the digital and green transitions are largely independent processes that just happen to be happening more or less simultaneously, although the former started much earlier. From the second perspective, the digital transition is an integral part of the green transition, to the extent that it is seen as a key element for the success of the green transition. It is this second perspective, the digital transition as instrumental to the green transition, that is adopted in this paper. Although with a major difference in relation to mainstream thinking on the subject, as it is considered that the digital revolution has both positive and negative implications for the green transition.

The digital transition can contribute to the green transition in two main ways. The first is through its ability to generate and manage information flows and optimise processes. The second is through its contribution to the dematerialisation of goods.

With regard to the first axis, the paper examines the positive impact of the digital transition on the green transition in the following areas:

- Agriculture: Digital technologies can optimise the use of resources in agriculture through precision farming. This involves the collection and analysis of real-time data on soil conditions, weather and crop needs, enabling the precise application of water, fertilisers and pesticides.
- Energy: Digitalisation can optimise the management of the electricity grid, enabling the efficient integration of variable renewable energy sources such as solar and wind. Smart meters and connected devices can adjust energy consumption in real time based on the availability of renewable energy, reducing the need for fossil fuel power generation.
- Passenger transport: Digitalisation facilitates the development of autonomous vehicles, intelligent transport systems and shared mobility platforms. These innovations can optimise routes, reduce congestion and promote carpooling, leading to a reduction in energy consumption and greenhouse gas emissions.
- E-commerce: The digitisation of commerce eliminates the need for personal transport of customers to and from the store (although the energy footprint of this depends on the type of transport used: private car vs. public transport), as well as the energy consumption of the physical store. It has also been suggested that e-commerce can extend the life of products through second-hand and resale applications (e.g. ebay). On the negative side, as an example of the complexity of the twin transition, e-commerce involves much higher packaging intensity and more frequent returns, as well as the electrical footprint of data transfer associated with online shopping.

The dematerialisation and virtualisation axis is explored through the following case studies:

- Teleworking: teleworking reduces the need for daily commuting, reducing fuel consumption and emissions associated with transport.
- Paperless office: Digitisation of documents and the use of online communication platforms can significantly reduce paper consumption in offices.
- E-books: E-books can replace printed books, reducing the demand for paper, ink and the printing and transportation processes associated with the production of physical books.
- Streaming music: Streaming music has largely replaced CDs and other physical media, leading to a reduction in the production of physical discs and their packaging

However, the digital transition also presents environmental challenges due to its high demand for energy and resources which could hinder the green transition. Among the specific negative implications of some of the new digital technologies (or their applications) the working papers focus on the following:

- **Cryptocurrencies:** The process of mining cryptocurrencies, especially Bitcoin, consumes huge amounts of energy, which generates a considerable carbon footprint. Importantly, the use of cryptocurrencies as a means of payment remains limited, which calls into question their usefulness in the face of high environmental cost.
- **Data centres:** Cloud-based data storage and processing, driven by the exponential growth of digital information, requires ever-increasing data centre infrastructure, which implies considerable energy consumption. Despite improvements in energy efficiency, the growth of the sector continues to increase energy and water demand.
- **Artificial intelligence (AI):** Training and running AI models, especially those that generate content, is energy intensive. Developing more efficient AI models and choosing renewable energy sources are crucial to minimise their environmental impact.
- **Electronic waste:** The increase in the production and use of electronic devices generates a considerable volume of electronic waste (e-waste), which poses challenges for its management and recycling.

### *Main findings*

After exploring the complex relationship between the digital and green transition, highlighting the opportunities, challenges and contradictions inherent in this process, the following are some of the most relevant conclusions that emerge from the analysis:

- **Digitalisation is not a panacea for sustainability:** While digital technologies offer powerful tools to optimise processes, improve efficiency and facilitate dematerialisation, their net environmental impact is a complex and controversial issue. The high energy demands of data centres, the manufacture of electronic devices and the management of e-waste represent significant environmental challenges that need to be carefully addressed.
- **Rebound effect can offset environmental benefits:** Despite improvements in energy efficiency and reduced resource use per unit of output, the increased accessibility and reduced costs driven by digitisation can stimulate an increase in overall consumption, partially offsetting the initial environmental benefits. It is crucial to understand and address this rebound effect to ensure that the digital transition genuinely contributes to sustainability.
- **Dematerialisation through digitisation is a selective process:** While digitisation has facilitated dematerialisation in areas such as teleworking, the paperless office and the consumption of music and books, it has also driven the growth of e-commerce, which in turn has increased the demand for packaging and transport. Digitalisation does not lead to uniform dematerialisation across sectors, and some of its effects may even result in increased demand for materials and energy.
- **The need for a holistic and strategic approach:** Addressing the challenges of the twin transition requires a holistic approach that considers both the opportunities and risks associated with digitisation. Strategies must go beyond the simple adoption of digital technologies and consider their impact on consumption patterns, energy demand, resource management and waste generation.
- **The crucial role of the public sector:** Governments play a key role in steering the twin transition, setting ambitious targets, creating sound regulatory frameworks, incentivising innovation in sustainable technologies and managing the environmental impacts of digitisation. Public-private collaboration is essential to harness the potential of the digital transition for sustainability and mitigate its potential negative effects.
- **The importance of research and innovation driven by the public interest:** It is essential to invest in research and innovation to develop more energy-efficient digital technologies, explore renewable

energy sources to power digital infrastructure, reduce water consumption and optimise e-waste recycling processes and better understand the complex interactions between digitisation and sustainability.

## Conclusions

The interaction between digital and green transition is complex and multifaceted. Digitalisation offers opportunities to move towards sustainability, but also presents environmental challenges that need to be addressed. It is crucial to consider the net impact of the digital transition on the fight against climate change, weighing its benefits and drawbacks. The development of digital technologies must be accompanied by strategies to minimise their environmental footprint, such as the use of renewable energy, energy efficiency and responsible e-waste management and be informed by the question of what for?

**The public sector has a key role to play in steering both transitions.** Government policies should incentivise innovation and the adoption of digital technologies that contribute to environmental sustainability. At the same time, it is necessary to establish regulations that limit the environmental impact of the digital transition, promoting energy efficiency, the use of renewable energies and the responsible management of e-waste.

"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair (...)"

Charles Dickens (1859), *A Tale of two Cities*



## **1 Introduction.**

We live in strange times. The economic success of the Industrial Revolution and the subsequent difficulties in combating climate change have put humanity on a path of potential climatic self-destruction. Yet just over half of US adults, 54%, see climate change as a major threat, with a significant difference according to political affiliation, as this percentage rises to 78% among Democrats and falls to 23% among Republicans.<sup>1</sup> On this side of the Atlantic, public opinion is more reassuring: according to the April-May special Eurobarometer 538 on the subject, 77% of respondents consider climate change to be a very serious problem, nine percentage points more than in June 2011. In any case, EU citizens seem to suffer from a kind of dissonance, believing that national governments, which they consider to be responsible (along with the EU) for tackling climate change, are not doing enough (2/3 of respondents), although they are responsible for electing such governments.

At the same time, high-income countries are grappling with changes in production processes linked to the now ubiquitous digital technologies, which are seen by many, rightly or wrongly, as a threat to their jobs. In 2012, for example, 70% of respondents to a Eurobarometer opinion poll thought that "robots are taking people's jobs" (Eurobarometer 382, 2012). From a global perspective, and focusing on the current hype, AI, according to IPSOS (2023), 57% of working adults under the age of 75 believe that AI will change the way they do their job, 36% believe that AI will replace their current job, and only 32% (21% in the US or 20% in Germany) believe that the use of artificial intelligence will improve the job market in the next 3-5 years.

The aim of this paper is to examine in detail the implications of these two processes of change, often referred to as the "Twin Transition". Indeed, in just a few years, the term "twin transition", which refers to the simultaneous process of technological change driven by the digital revolution and the substitution of fossil fuel-based energy by other renewable energy sources (mostly based on wind and solar power) and other changes aimed at reducing the environmental impact of economic activity, has become a buzzword. A search on Google yields over a hundred million entries under the term. Of course, the term has different meanings for different audiences. From one perspective, the twin or dual transition simply refers to the simultaneous occurrence of two major socio-economic transitions, the digital transition and the energy transition. From another, more complementary and policy-oriented perspective, the term refers to the existence of synergies between the two transitions that could contribute to the success of the green transition and the fight against global warming. That is, the digital transition as a facilitating tool and strategy for the green transition.

To this end, the paper is divided into the following sections. Section two reviews the different meanings or understandings of the twin transitions mentioned above and specifies the approach taken in the paper. Section three briefly introduces the reader to some theoretical concepts that may be useful in analysing the multidimensional impacts of the digital transition on climate change and the environment. Against this background, section four explores the potential positive effects of the digital transition on the green transition as a tool to facilitate the energy and environmental transition. In contrast, the following section analyses how the digital transition could be another nail in the coffin of environmental sustainability due to its high energy and material requirements. Before concluding our analysis of the twin transition, section six reviews the existing evidence on firms' practices with respect to the digital-green transition to assess whether both paths are being taken simultaneously. Finally, section seven attempts to summarise the evidence presented in the paper and the main conclusions drawn from the analysis.

## **2 Meanings of the Twin Transition.**

As noted above, the first interpretation of the twin transition is based on the recognition that the process of adoption of digital technologies by firms, governments and consumers, and the need to develop a green transition to limit global warming, are simply two separate processes that happen to be occurring simultaneously. As changes in production technologies (whether digital or energy generation

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<sup>1</sup> Fortunately, the concern is much greater among younger adults (Lewandowski, et al., 2024).

technologies) are rarely Pareto improving, and can have negative impacts on firms and workers, the coincidence in time of the two processes of change has been a major cause for concern. This is the approach taken, for example, by the Eurochambres Twin Transition Survey (Eurochambres ,2022), which collects information on digital and green investments by Europeans companies and the barriers to digitalisation and greener business models they face from a fully segmented perspective.

From this perspective, the twin transition simply refers to two parallel overarching processes occurring simultaneously, albeit with their own characteristics, objectives, drivers, actors and rationales. Table 1 presents the main characteristics of the digital and green transitions, looking at four different dimensions of such transitions: timing, goals and rationale, actors and current situation.

Table 1. Differences between the digital and green transitions

	Digital transition	Green transition
<b>Timing</b>	Ongoing since the 1970's and 1980 's (Solow's productivity paradox, Moore's Law)	1990 First IPCC Assessment Report, Kyoto Protocol in 1997, 2006 Stern <i>Review on the Economics of Climate Change</i> , Paris Agreement 2015, "Green New Deal" (T. Friedman, 2007*)
<b>Aims/ rationale</b>	Use of digital technologies and development of new products for business reasons (increase in productivity, market share, profits and survival rates)	Reducing global warming through a change in energy sources (mainly wind and solar renewable energy) and the promotion of the circular economy.
<b>Actors</b>	Mostly private, with public support (research -ARPANET-, funding -Next Generation EU-, etc.)	As a response to an unintended consequence of the working of markets (global warming), the green transition is being led and managed by governments (using a range of tools from regulation to incentives and public investment). However, the private sector also has an important role to play the development of new technologies to increase the efficiency and reduce the cost of renewable energy technologies, as well as in the adoption of greener production processes and the greening of workplaces
<b>Current situation</b>	In 2022, 70% of all EU businesses reached a basic level of digital intensity. The share for SMEs was 69%, around 20 percentage points below the EU 2030 target. For large businesses it stood at 98% (Eurostat, Digital Intensity by size class of enterprise)	The chance of global near-surface temperature exceeding 1.5°C above preindustrial levels for at least one year between 2023 and 2027 is more likely than not (66%). It is unlikely (32%) that the five-year mean will exceed this threshold. (WMO Global Annual to Decadal Climate Update: a synthesis report for 2023–2027)

(\*) T. L. Friedman (2007): "The Power of Green", *New York Times Magazine*, April 15

Source: Autor's elaboration.

As we can see, although the two process have parallels, there are many differences between them. First, the digital transition clearly precedes the green transition. In fact, we can say that when the first IPCC Assessment Report stated with certainty that "emissions resulting from human activities are substantially increasing the atmospheric concentration of greenhouse gases (...) These increases will strengthen the greenhouse effect, resulting on average in an additional warming of the Earth's surface" (IPCC, 1992, p. 52), the digital revolution was well under way. To give just a few examples of its development, in 1965 Gordon E. Moore (1929-2023), co-founder of Intel, predicted that the number of

transistors that could be crammed onto an integrated circuit would double every year, thereby increasing the computing power of the machine (Moore, 1965). Two decades later, Robert L. Solow (1987), winner of the Memorial Nobel Prize in Economics, argued in an article for the New York Times Book Review, in what has since become known as "Solow's Paradox", that "you can see the computer age everywhere but in the productivity statistics." By the end of the 1980s, computers were everywhere. The World Wide Web was opened to the public in the early 1990s, and by the end of 1994 there were more than 10,000 servers around the world. Obviously, the digital revolution is, to use a Trotskyist term, a permanent revolution that is still ongoing. Of course, we are talking about a process that is much more rooted in the economy than the green or energy transition. In fact, as Fouquet and Hippe (2022, p.16) show, at similar levels of economic development the communications transition seems to be faster than the energy transition.

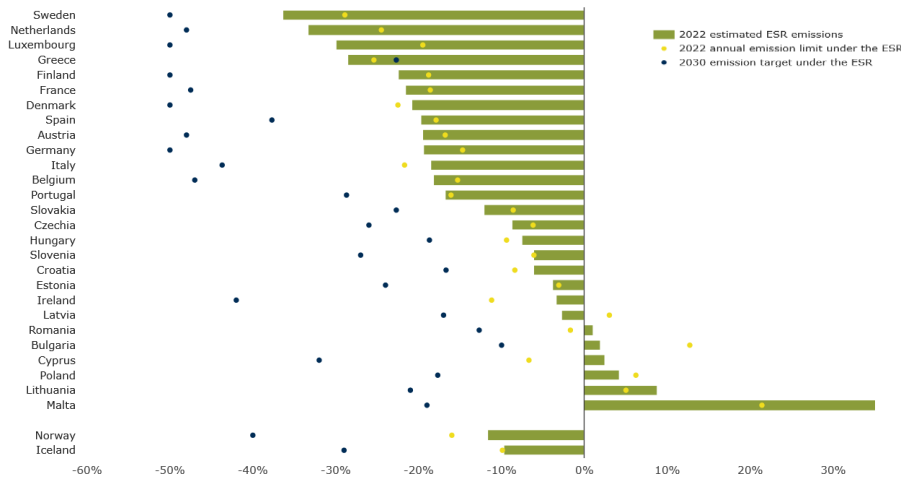
The two transitions also differ in their rationale. On the one hand, the adoption of digital technologies by businesses is driven purely by productivity and profit motives, to improve business performance. In contrast, the green transition is driven by the need to reduce global warming and to adapt production processes to the ecological limits of "Spaceship Earth", to use Kenneth E. Boulding's (1910-1993) apt metaphor.

The actors are also different. The digital transition, while supported by the public sector through public R&D, such as the Advanced Research Projects Agency (ARPA), set up by the US government in 1958, or direct funding to encourage firms to go digital, is primarily a private matter. Companies – and consumers – are the ones who decide when, how and how much to invest in digital technologies. By contrast, in its origins the green transition was primarily a public process. Governments, whether national or supranational, were the ones responsible for developing the policies that will (or will not) make it possible to limit global warming to the 1.5-degree threshold. In fact, the need for a green transition is the result of the failure of markets to properly account for all production costs, including those associated with greenhouse gas emissions. If markets had worked well, none of this would have been necessary, because the cost of global warming would have been included with the rest of the production costs of those processes that generate GHG emissions, reducing overall production and incentivising the development of non-polluting technologies. No wonder that extreme pro-market advocates, such as the President of Argentina, Javier Milei, abhor the idea of the existence of a global warming. To acknowledge the existence of anthropogenic global warming is to acknowledge the existence of market failures, in this case fatal failures. However, increased awareness of the costs of inaction and the development of incentives to reduce greenhouse gas emissions have led to an increased role for private actors, businesses and consumers, the former, for example, among other things (ILO, 2022), as key actors in the development of the new technologies behind the huge increases in efficiency in the production of renewable energy. In the words used by the ILO (2022): "Enterprises are increasingly recognized as crucial to a healthy environment and to making progress on climate change, as well as being key actors in achieving a just transition" (p. xvii)

Finally, the two transitions also differ in their level of accomplishment. Again, although the digital revolution is an ongoing process, with new developments, such as generative AI, happening from time to time, many of the objectives of the digital transformation are in the close to being accomplished, at least in high income countries. In contrast, the green transition is barely beginning. For example, according to *WMO Global Annual to Decadal Climate Update* (2023), the chance of global near-surface temperature exceeding 1.5°C above preindustrial levels for at least one year between 2023 and 2027 is more likely than not (66%). The seminal paper of Fouquet and Hippe (2022) on the twin transitions from a historical perspective confirms the higher speed of the communication and digitalisation transition vis à vis the energy (decarbonisation) transition: "the evidence suggests that twin transitions of the decarbonisation and digitalisation of economies are likely to experience a process of imbalanced structural transformation (with ICT continuing to forge ahead)" (p.1).

From another perspective, Figure 1, which shows the evolution of progress towards the GHG emission targets under the Effort Sharing Regulation (ESR) of the EU Member States (plus Norway and Iceland) from 2005 to 2022, illustrates the long way to go to achieve the green transition. And we only focus on one aspect of the green transition, the energy transition and the reduction of greenhouse gas emissions, without taking into account other objectives related to the circular economy or the protection and restoration of biodiversity.

Figure 1. National progress towards greenhouse gas emission targets under the Effort Sharing Regulation



Compared to 2005 (%)

Source: European Environmental Agency (2023)

In summary, according to the first meaning, the twin transition is just a way of highlighting that two different processes of different nature, drivers and actors are taking place at the same time (or to be more precise, with some overlapping). This is important because, as two major societal changes, the digital and green transformations will have negative impacts on certain people and economic sectors, regardless of their overall positive impact. And the fact that both processes are overlapping to some extent may increase the overall negative impact of the changes.

The second perspective, without questioning the above narrative, goes beyond and argues that there are important interrelations between the digital and green transitions, and, in particular, that the digital revolution can be a major tool to facilitate the green transition. In the words of Morten Dæhlen (2024), head of *Centre for Computational and Data Science* at the University of Oslo, “the digital and green transitions are not parallel processes but transformations that affect each other deeply”.

This perspective has been widely adopted among international institutions. To name but a few, for UNESCO “With the term dual transition or twin transition, we refer to both the green and digital transition. Often these two ideas are combined not only because they are happening at the same time but also because, if managed well, they can potentially reinforce each other”.<sup>2</sup> This approach is shared by the World Economic Forum, according to which “Rather than treating digital and sustainability in isolation, a twin transition strategy combines these critical functions to unlock huge benefits in terms of efficiency and productivity”,<sup>3</sup> or the OECD: “Importantly, digital technologies could play an instrumental role in the effort to build a greener future. For example, smart grids can optimize energy distribution, street sensors coupled with connected vehicles can optimise transport and enable smart cities (...)”.<sup>4</sup>

This point of view emphasises two elements: the existing linkages between the digital and green transitions, mostly from the digital to the environmental domain, and the positive nature of this relationship, *i.e.* how digital technologies can contribute to the realisation of the green transition.

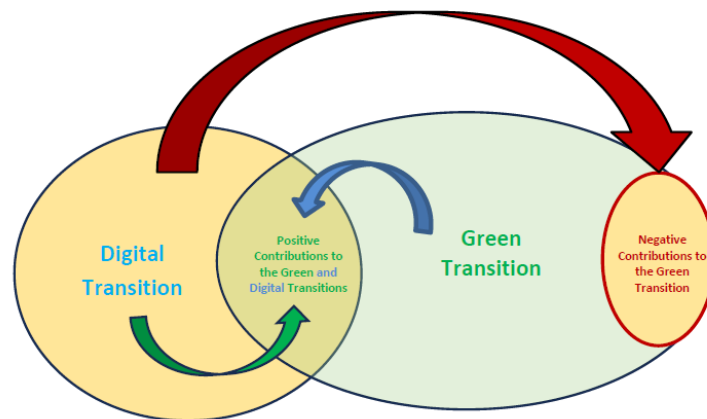
<sup>2</sup> UNESCO-UNEVOC (2023), Capacity building and strengthening of institutions through resilience building and greening TVET - online resource of the UNESCO International Centre for Technical and Vocational Education and Training.

<sup>3</sup> WEF (2022): *What is the 'twin transition' - and why is it key to sustainable growth?* Oct 26, 2022

<sup>4</sup> OECD workshop on “Start-ups and scale-ups for the twin transition: challenges and policy responses”, 19 March 2024, OECD, Paris.

However, this paper takes a slightly different approach to the twin transitions. In what follows, we add two further sources of interrelationship between the digital and green transitions. First, we analyse whether the digital transition could also complicate the green transition due to the high energy intensity of some of its processes, such as AI or cloud computing. Second, we consider whether the green transition could contribute to the digital transition in different ways. This slightly more nuanced perspective of the twin transitions is shown in Figure 2.

*Figure 2. The Twin Transitions*



Source: Author's analysis.

As we can see in Figure 2 the two spheres representing the *Digital Transition* (replacing analogue devices and technologies in production and consumption with digital ones) and the *Green Transition* (decarbonising society and reducing global greenhouse gas emissions and the environmental impact of economic activity) overlap, meaning that digital solutions could help to reduce global GHG emissions and dematerialise production, thereby facilitating the Green Transition. But there is another element in the picture that is often overlooked in the graphic metaphor. Digital technologies, like any other, use natural resources and require energy, thus contributing to the process of global warming and increasing the scale of the problem that the Green Transition aims to solve. This means that in addition to the intersection between the two transitions, which represents the positive contribution of the digital to the green transition, the "sweet spot" in the term used by PA (2022) in its *Twin Transition Playbook*, there is what we could call, by analogy, a "mean or sour spot" resulting from the energy-intensive (often very intensive) use of the newly developed digital technologies. Finally, we also consider the possibility that the Green Transition could provide incentives (from the demand side) for the development of new digital technologies.

Very little, if anything, has been said about the possibility that the decisions and actions taken by the public and private sectors, as well as by households, to move towards a green economy could contribute positively to the digital transition. This may seem surprising, since it could be argued that a major change in energy sources, such as renewable energy, will certainly stimulate the development and adoption of new technologies, including, logically, digital technologies. However, such a link is completely absent from the literature on the twin transitions.

We could think of two different reasons why the green transition could contribute to the digital transition. The first is that the process of decarbonising the economy, and the necessary development of new technologies to achieve this, could open up new areas and opportunities for the development of digital technologies, thus stimulating digital innovation. From this perspective, the green transition could stimulate the digital transition. Moreover, green technologies tend to be more digital than the technologies they replace. For example, most solar panels and battery systems come from the factory hyper-digitised and connected to the internet (and can be controlled from a mobile phone); something similar happens with electric vehicles, etc. The reason is the efficiency of digital to control any process, especially when it is complex and decentralised (like solar energy production).

The second is more opportunistic. Companies (and households) undergoing a process of transformation to reduce their environmental footprint could use this process of change to make changes in other areas of production. For example, a person renovating his or her house could use this as an opportunity to "domotise" the house: since we are going through a major construction work to insulate the house and install a heat pump, we might as well modernise other elements of the house installing digital devices and applications.

In any case, regardless of the interactions (positive and negative) between the digital and green transitions, the transformative processes behind each of them are different, have their own logic and have different socio-economic impacts. This is what makes the twin transitions a major economic and social challenge: two different sources of change, one largely driven by public policy, the Green Transition, aimed at correcting the negative environmental impacts of a growth process driven by market incentives that overlooked (often deliberately)<sup>5</sup> the environmental externalities of the production of goods and services, and the other, largely autonomous, resulting from the choices made by firms and people, although, like everything else, partly modulated by public policy and publicly funded R&D, in both cases with major social implications, operating simultaneously.

Before concluding this section, it is important to comment, if briefly, on one issue so far excluded from the analysis. Although as we have seen, the digital and green transitions are different processes, they share two important elements. First, both require significant increases in investment. Second, both could, in principle, have a major impact on the structure and level of employment. The simultaneity of the two transitions in time implies that the investment requirements for a successful transition will be even greater, as will the impact on employment resulting from their combined effect. Let's comment briefly on these two issues

Starting with investment, there are different estimates of the investment needs related to the green transition: Figure 3 shows four estimates of the annual investment needed in the EU to achieve the green transition (to bring GHG emissions in line with the 55% reduction target), together with the investment gap resulting from the comparison of estimated needs and actual investments. According to the European Commission, the estimated average investment needed to achieve the targeted GHG emission reduction is a hefty 764 billion per year, equivalent to 4.8% of EU GDP, and the annual investment gap (after discounting actual investments) is estimated at a further 3% of GDP in 2022. This brings the estimated total investment needs to almost 8% of EU GDP in 2022. The investment needed to reach the 90% reduction target by 2040 is even higher for the following decade, rising to just over 9%. The European Environmental Agency estimates the investment required to implement the European Green Deal in 522 billion per year from 2021 to 2030 (in addition to investments to around 92bn to improve the EU capacity to manufacture net-zero technologies).

From a global perspective, the estimated needs range from the \$3.5 trillion per year according to the Network from Greening the Financial System, a network of 123 central banks and financial supervisors, or the \$5.3 trillion per year (\$37 trillion in total by 2030) estimated by the Boston Consulting Group (2023), to the \$9.2 trillion per year for the next 30 years estimated by McKinsey (2022), an additional \$3.5 trillion above actual investment. According to the Global Landscape of Climate Finance 2023 (Buchner, et al., 2023), the annual climate finance needed through 2030 increases steadily from \$8.1 to \$9 trillion, and jumps to \$10 trillion per year from 2031 to 2050. In any case, even if we take the most modest estimates, we are talking about very relevant investment needs to face and enable the tectonic shift, in the worlds of BCG (2022), of the transition to a net zero energy future.

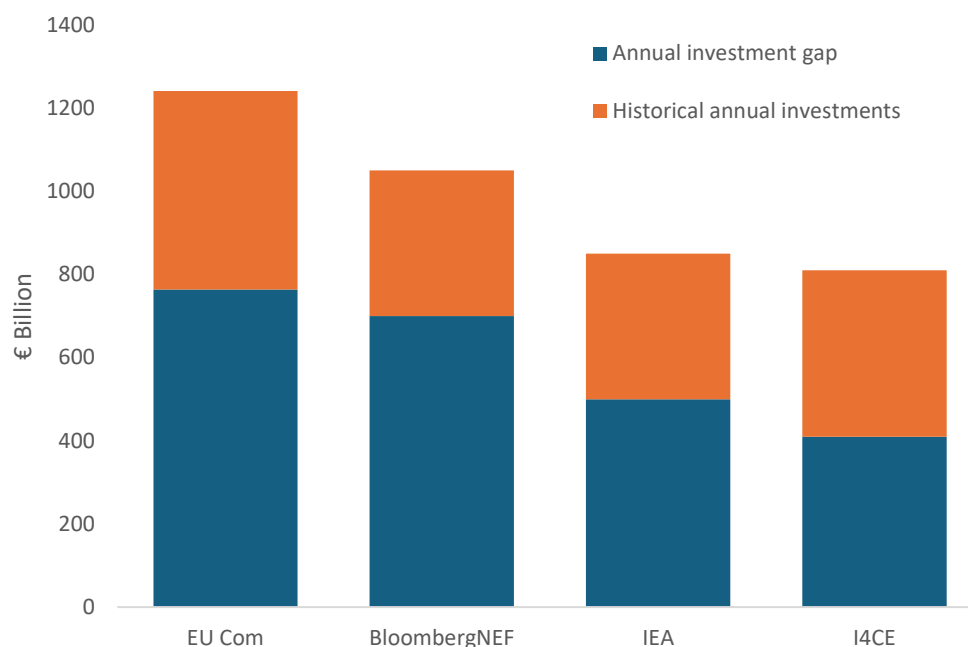
Compared to the investment needs for the green transition, the investment needs for the digital transition. According to the European Commission (EC, 2023) the EU will need a total additional investment of €125 billion per year to meet the EU's digital targets, on top of the average €46 billion

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<sup>5</sup> The 2024 Joint Staff Report of the US House Committee on Oversight and Accountability and the US State Senate Committee on the Budget titled *Denial, Disinformation and Doublespeak: Big Oil's Evolving Efforts to Avoid Accountability for Climate Change* shows that fossil fuel companies understood, at least since the 1960s, that burning fossil fuels causes climate change, while at the same time "they worked for decades to undermine public understanding of this fact and to deny the underlying science" (p.i), lobbying —either directly or through their trade associations— against pro-climate legislation and regulations.

per year invested over the 2014-20 period. In any case, these investment needs are estimated on the basis of the EU's current digital targets and obviously don't take into account future needs related to the digital economy, such as the current rapidly evolving developments in AI.

*Figure 3. Estimates of annual investment need required by the green transition*



Note: European Commission (EU Com), International Energy Agency (IEA), BloombergNEF, Institute for Climate Economics (I4CE)

Source: EIB (2024), p.11

In contrast, the available estimates of the impact of the green transition on employment are rather modest. For example, for the EU, estimates from different macroeconomic models of the impact of the 'Fit for 55' initiative (JRC-GEM-E3, E3ME and E-QUEST) suggest a small impact ranging from -0.3% to +0.5% by 2023. In this line, Alexandri et al. (2024), using a three-sector macroeconometric model for the EU with a rich labour market extension, find an overall modest positive impact on GDP and total employment of measures to reduce the use of fossil fuels in electricity generation and road transport, with the added benefit of making the employment structure slightly less polarised. Similar results are highlighted by García-García et al. (2020) in their comprehensive review of the employment impact of climate change policies. In any case, it is important to emphasise that, as discussed by Davide et al. (2024), there are important limitations to the mainstream methodology used to label jobs as green as opposed to brown, the starting point of most estimates of the impact of the green transition on employment.

By contrast, estimates of the impact of the digital revolution on employment are much more numerous and, at least some of them, quite alarming. Two elements stand out when reviewing the estimates of the impact of the digital revolution on employment. The first is the wide range of estimates depending on the methodology used. For example, the well-known and seminal paper by Frey and Osborne (2013) concludes that 47% of US jobs have more than 70% probability of being replaced by machines by 2030. Similar results are obtained by Bowles applying the same methodology to European countries, with 54% of jobs at risk for the EU, ranging from 47% in Sweden to 62% in Romania. On the other hand, estimates by Arnz et al. (2016), based on the idea that capital replaces specific tasks performed by workers, but less often full jobs (considered as a bundle of tasks), estimate a much lower share of jobs at risk, 9% in the OECD. Second, most analyses focus on the jobs at risk due to the introduction of new digital technologies, without providing a parallel estimate of the jobs created by these technologies.

Interestingly, the small but growing body of work looking at the impact of AI on employment (e.g., Georgieff y Hyee, 2021; Felten, et al., 2019) points, at least so far, in the same direction: a small negative impact at the most.

In order to better present the arguments behind the different relationships between the digital and green transitions captured in Figure 2, as mentioned in the introduction, we will examine each of the interactions separately, leaving the overall view for the last section of the paper. Before doing so, however, the next section briefly reviews the theoretical concepts needed to better understand the nature of the relationship between technological (digital) change and the environment.

### **3 A (very) simple model of the impact of the digital revolution on the environment and GHG emissions.**

In order to see the different ways in which technological change, in this case the new digital technologies, can have an impact on greenhouse gas emissions and, more generally, on the environment, in this section we will present a series of very simple relationships, which will nevertheless help us to organise the debate on the dual transition that will take place in the next two sections.

According to the well-known Commoner-Ehrlich equation (Ehrlich and Holden, 1971), the environmental impact,  $EI$ , of economic activity can be expressed as the product of total population,  $P$ , production per capita,  $Ypc$ , and the environmental impact per unit of production,  $T$ .<sup>6</sup>

$$(1) EI = P \cdot Ypc \cdot T$$

Figure 4 shows an example of the role of these variables in the evolution of total global CO<sub>2</sub>. In this case, the variable  $T$  of equation (1) has been decomposed in two: the energy intensity of GDP and the carbon intensity of energy.

The figure shows that in the first and last decades analysed, the 1970s and 2000s, the growth in GDP per capita was the main component in explaining the growth in CO<sub>2</sub> emissions, while the reduction in the energy intensity of GDP acted as a partially offsetting force.

Equation 1 can be easily transformed to capture the role of the sectoral composition of the economy in explaining variable  $T$ , the environmental impact per unit of output.

$$(2) EI = P \cdot Ypc \cdot (\sum t_i s_i)$$

Where  $t_i$  is the environmental impact per unit of output of sector  $i$ , and  $s_i$  is the share of output of sector  $i$  in total output ( $Y$ ).

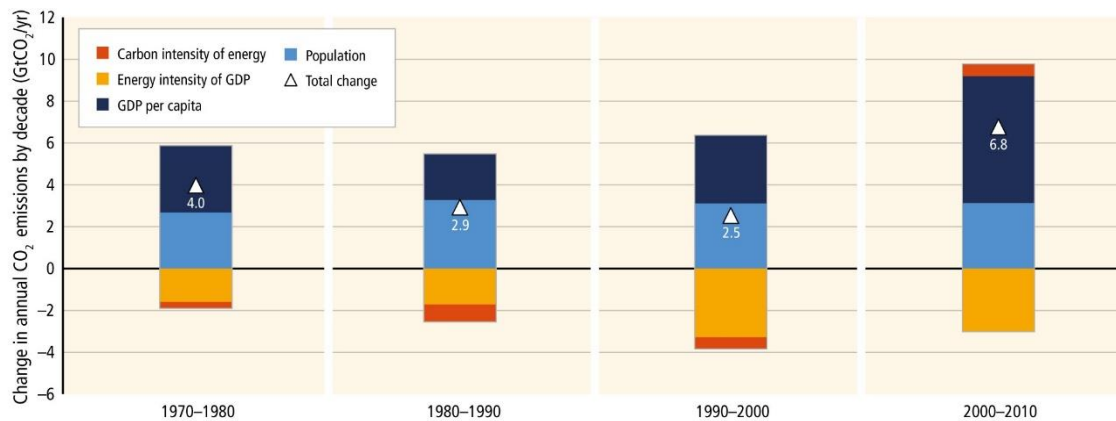
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<sup>6</sup> There are many versions of this identity, one of them is the Kaya Identity (Kaya and Yokobori, 1997) that focuses in the factor affecting global emissions of CO<sub>2</sub>: population growth, per capita economic activity, energy intensity, and carbon intensity of energy consumption.

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Figure 4. Decomposition of the change in total global CO<sub>2</sub> emission from fuel combustion by decade.



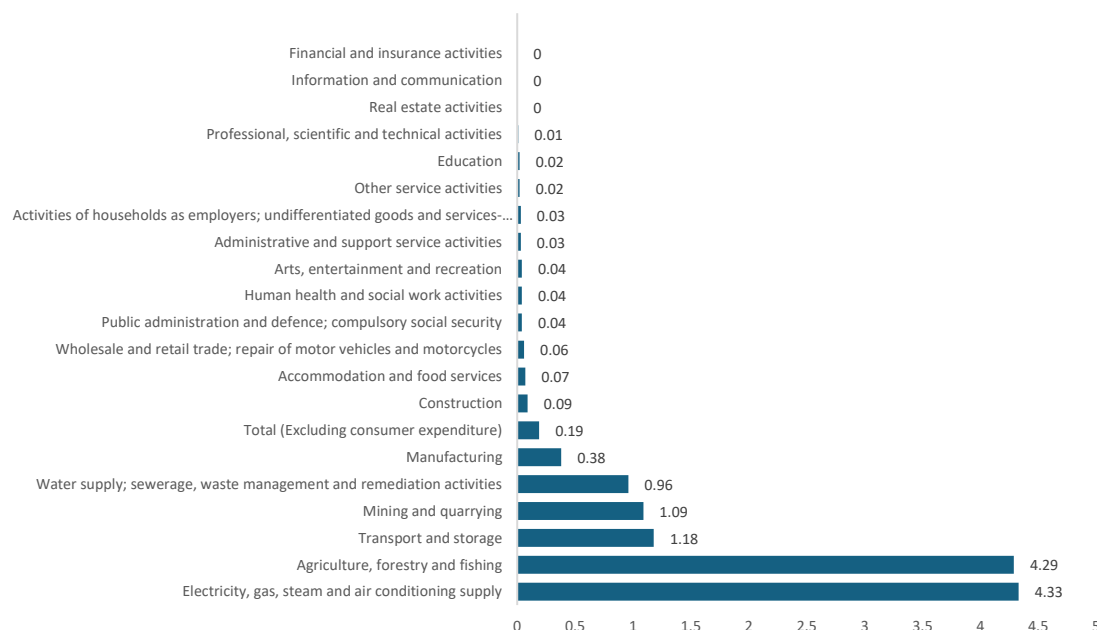
Source: IPCC (2014), p. 47

If we exclude from the analysis the role of population and population growth in the evolution of the environmental impact of economic activity, which, it should be remembered, plays an important role in explaining the deterioration of the environment in the Malthusian and neo-Malthusian perspective,<sup>7</sup> per capita income and the composition of economic activity stand out as the two variables determining the environmental impact of economic activity, and more specifically, global warming. The second variable is relevant because, as mentioned above, the economic activity is the sum of a myriad of very different activities with large differences in their environmental impact,  $t_i$ .

There are therefore two ways to reduce EI. The first is to reduce the environmental impact of different sectors of the economy through technological change and the circular economy, a process known in the literature as decoupling. Using CO<sub>2</sub> emissions as example, CO<sub>2</sub> emissions per unit of output have been reduced by -1.8% from 1995 to 2018, although a rate of -8.7% would be required to achieve net zero emissions by 2050 (Lenaerts et al. 2021). The *Green Growth* strategy adopted by the EU in its *European Green Deal* can be seen as an attempt to square the circle of making the environment compatible with economic growth. The second is to change the sectoral distribution of the economy in favour of those sectors with a lower environmental footprint, i.e. lower  $t$ . To get an idea of the different EI of different economic activities Figure 5 shows, as an example, the 2022 GHG and CO<sub>2</sub> emissions intensity (the level of emissions per unit of economic output), by industry in the UK.

<sup>7</sup> And continues to play an important role in current scientific analysis of policies to combat climate change (i.e., for example, the World Scientist's Warning of a Climate Energy -Ripple et al. 2022)

Figure 5: GHG and CO<sub>2</sub> emissions intensity (the level of emissions per unit of economic output), by industry in the UK in 2022.



Source: Office for National Statistics, Greenhouse gas and carbon dioxide emissions intensity

The third option, whether by choice or as a lesser evil, is to reduce  $Y_{pc}$  (income per capita). This is the option advocated by supporters of *Degrowth*, or, now in a more politically palatable term, *Post-Growth* (Jackson, 2021, 2018; EPRS, 2023) theory.

How might the digital transition affect the variables mentioned above? The literature focuses on three possible effects: (a) the scale effect, (b) the composition effect, and the (c) technological effect. Starting from the last one, new digital technologies can contribute to a reduction of the environmental impact of the existing production processes. For example, domotics can improve the control of temperature; automated production lines can optimize the use of raw materials, reducing waste generation; etc. The second type of impact (composition effect) is less clear. Digital technologies could change the structure of the economy as new digital products or services replace old analogue ones. In this case, the final impact on EI (or GHG emissions) would depend on the environmental impact of the growing sectors of the economy spurred by the digital revolution relative to the old traditional sectors. For example, the shift from LP-cassettes-CD-MP3 to music in streaming might at first sight appear to be a movement towards dematerialisation and a reduction of the EI of music. But a closer look suggests a different conclusion. As early as 2015, Devine (2015) argued:

“What sometimes seems like a story of progressive dematerialisation and eco friendliness - an evolution from sticky resins and fuming factories to pristine data streams and unworldly cloud networks - might in fact be just the opposite. In terms of political ecology, the move to a data-based musical materiality could represent a step in the wrong direction: from the use of raw materials that are relatively renewable (shellac) and commodities which are readily recycled in secondary economies (LPs) to delivery infrastructures that weigh heavily on the environment (server farms) and musical commodities with short life expectancies (accessory electronics) and ambiguous afterlives (MP3's)” (p. 384)

Indeed, according to research conducted by Brennan and Archivald (2019), the apparent dematerialisation of music, confirmed by a reduction in total plastic use from 58 million kilograms in 1977, peak year of US sales of LP, to around 8 million in 2016, has been accompanied by an increase in GHG emissions from 157 million kilograms in 2000 to an estimated between 200-350 million kilograms, in the US alone (Brennan, 2019).

Regarding the first of the above-mentioned impacts (scale effects), the digital revolution has generated, by itself, a new sector of activity, increasing GDP. According to the World Bank (2023) the ICT sector exceeded US\$6.1 trillion in 2022, representing around 6 % of global GDP, while the digital economy, according to some estimates, “makes up more than 15 per cent of the global GDP and has grown 2.5 times faster over the previous ten years than the GDP of the physical world” (UN, 2023). This direct effect of digital technologies on GDP, would, in itself, lead to higher EI, unless full decoupling is achieved. However, if digital technologies succeed in improving productivity and reducing the environmental impact of production, the resulting reduction in prices could lead to an increase in demand with negative implications for the green transition (*i.e.* lower GHG emissions per unit of output, *a*, but higher total emissions). This phenomenon, known in ecological economics as the *rebound effect*, has been known to economists at least since the work of the marginalist economist William Stanley Jeavons (1835-1882), who argued in a book published in 1865, *The Coal Question*, that increases in technological efficiency actually increased the overall consumption of coal, iron, and other resources, rather than reducing them (Alcott, 2005). From a long-term perspective, the study of Fouquet and Pearson (2006) of the price and use of light in Britain from 1300 to 2000 is instructive in this respect. According to the authors, “by the year 2000, while United Kingdom GDP per capita was 15 times its 1800 value, lighting services cost less than one three thousandths of their 1800 value, per capita use was 6,500 times greater and total lighting consumption was 25,000 times higher than in 1800” (p. 139).

Following Berkhout *et al.* (2000), we can distinguish two different rebound mechanisms:

- **Direct rebound effects:** energy and other resource saving measures lead to lower prices, which induce higher consumption. In the case of energy, for example, it is estimated that in the Netherlands about 30% of projected energy efficiency gains could be absorbed by higher energy demand (Berkhout *et al.*, 2000). In the computer sector, the increase in efficiency and performance of computers increases the obsolescence of old equipment and increases the rates of refurbishment and the associated consumption of resources and e-waste. Similarly, in the field of TICs, the average physical mass of a mobile phone decreased by a factor of 4.4 between 1990 and 2005, while the number of mobile phones in Switzerland increased by a factor of 8 (Gossart, 2015). The reduction in editorial costs made possible by electronic editing and publishing (among other reasons) has led to an increase in the number of academic journals published, from 24,000 in 2001 to almost 47,000 in 2020, more than doubling the number of scientific papers published in scientific and technical journals (Curcic 2023). Finally, the increase in fuel efficiency of vehicles could lead to an increase in demand for larger and heavier vehicles, such as SUVs, and encourage consumers to drive more often and further. Table 2 summarises the estimates of rebound effects for consumer energy services, reproducing the estimates of long-run direct rebound effect for consumer energy services in the OECD.

Table 2: estimates of long-run direct rebound effect for consumer energy services in the OECD.

End use	Range of values	Best guess	No. of studies	Degree of confidence
Personal automotive transport	3-87%	10-30%	17	High
Space heating	0.6-60%	10-30%	9	Medium
Space cooling	1-26%	1-26%	2	Low
Other consumer energy services	0-39%	<20%	3	Low

Source : Sorrel and Dimitropoulos (2007), p. vii.

- **Indirect rebound effects:** The price reduction induced by energy or other resources saving measures increases real income and the demand for other goods and services produced in sectors different other than the one in which the innovation was introduced. For example, the

reduction in the cost of accessing and exchanging information triggers a growing demand for information and causes people to waste time filling in useless reports. An interesting example of this type of rebound effect is teleworking. As we will have the opportunity to explore in detail in the next section, teleworking, which allows people to work from home, is one of the paradigmatic examples of the contributions of the digital revolution to the green revolution. However, the transport time and money saved by teleworking is often spent on transport for other reasons, such as shopping or “taxing” family members. Estimates of the rebounds effect of telework reach 73% in Denmark, 43% in the Netherlands and 19% in Germany (Gossart, 2015).

The economy-wide rebound effect is the result of adding the direct and indirect rebound effects. The Greening et al. (2000) summary of the empirical evidence on rebound effects of fuel efficiency on a specific energy service concludes that available measures of the rebound for residential end-uses suggest a range of responses from 0% to 50% for a 100% increase in energy efficiency (*e.g.*, 10-30% for the case of space heating, 10-40% for water heating, 5-12% for residential lighting and 10-30% for motorised transport). According to Sorrell (2009), general-purpose technologies such as ICT are more likely to generate economy-wide rebounds effects.

Against this background, the following section will examine in more detail the positive impact of the digital transition on the green transition, which operates through the contribution of the newly introduced digital technologies to reducing the environmental impact of production in different sectors of the economy. Section 4 then examines the potential negative impacts of the new digital activities, stemming from their often-intensive energy consumption.

## **4. Potential positive effects of the digital transition on the green transition.**

The literature dealing with the twin transition from the “synergy” perspective, *i.e.* considering the digital transition as an important tool for achieving the green transition, consists mostly of a collection of actual or potential cases in which the introduction of digital processes and technologies has facilitated, or could facilitate, or even enable, progress in the green transition. Reading these case studies or assessments of digital technologies in terms of their contribution to the green transition, it can be observed that in most cases the contribution of digital technologies to the green transition relates to two specific areas: (a) improvements in coordination and production efficiency through the collection and processing of large amounts of information, which can now be easily and cheaply gathered using digital tools, (b) dematerialisation and reduction of the material intensity of goods. In the following subsections we will present some examples of the actual or potential contribution of digital technologies to the green transition, first in terms of improved efficiency or *optimisation* and later in terms of dematerialisation or *virtualisation*.

### **4.1 Improvements in coordination efficiency.**

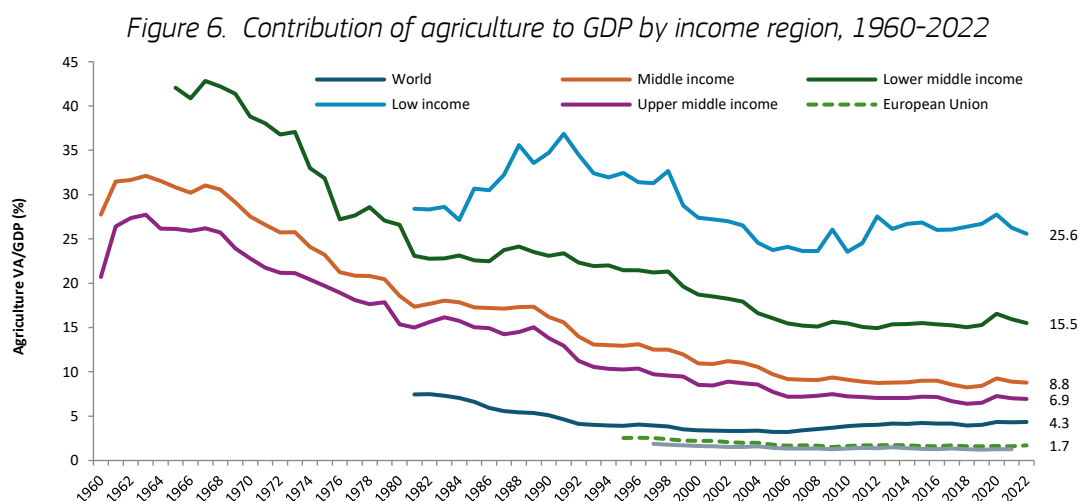
Information and coordination are two key elements in the efficient production and consumption of goods and services and in achieving allocation efficiency in markets and within firms. The ability of digital technologies to generate and process information on production and allocation processes at low cost can improve our knowledge of these processes, enhance the productive and allocation efficiency, and contribute to a better coordination between economic actors. In what follows, agriculture and energy, two sectors of activity crucial to human well-being will serve as examples of the role played by digitalisation in the green transition.

#### **4.1.1. The Twin Transition in agriculture.**

At the outset of this section, it is necessary to note, albeit briefly, the apparent redundancy of talking about a green transition in agriculture, since rural life, agriculture and farms are the epitome of green. Unfortunately, the limits of physics and the biological and productive processes that generate GHG emissions also apply to agriculture. In fact, agriculture is the dominant source of anthropogenic methane

emissions (about 60% of total methane emissions)<sup>8</sup>, one of the most important GHG, and potentially much more powerful than CO<sub>2</sub> in warming the atmosphere. Methane emissions from agriculture, both from livestock (manure and gastroenteric releases) and paddy rice cultivation,<sup>9</sup> contribute to 40% of anthropogenic methane emissions (32% and 8% respectively)<sup>10</sup> (UNEP and CCAC, 2021). In the decade going from 2007 to 2016 agriculture was responsible for 12% of global anthropogenic GHG emissions plus 9% from land use change (conversion of forest to cropland and grassland). Moreover, the progress in reducing GHG emission from the sector has been weak (OECD, 2019a).

From the perspective of this paper, agriculture is important for two main reasons. The first is that, unlike many other goods and services, the goods produced by the agricultural system are essential to human life. Hard as it may be for Generation Z to believe, food is more essential than TikTok. In this respect, the combined effect of population growth and economic growth will lead to increased demand for agricultural commodities in the future, as people switch to less sustainable (more energy-demanding) diets, making the sector more important, even if agriculture's contribution to total output is reduced as economy grows (by Engel's Law). The impact of the war in Ukraine on world food prices and the role of the sector in the rise in inflation in 2023 are two elements that illustrate the important role of agriculture, even in a context of its declining contribution to total output due to economic growth (Figure 6). In this context, according to FAO (2021) projections, the feeding a population of more than 9 billion people in 2050 will require a 50% increase in total food production (plus livestock fodder and biofuels) compared to 2012 production.



Source: Author's elaboration of World development Indicators Data

The second reason is the already mentioned role played by agriculture in greenhouse gas emissions.<sup>11</sup> In 2021, US agriculture contributed about 10% of total GHG emissions (including on-site fossil energy use), of which about half is explained by crop production. In 2022 the EU agriculture contributed 12.9% of total GHG emissions. According to the FAO, the global contribution of agriculture to total GHG emissions

<sup>8</sup> The natural (non-anthropogenic) methane come mostly from freshwaters and wetlands (contributing to over 80% of total natural methane emissions estimates), termites, oceans, geological, wild animals and permafrost soils (UNEP and CCAC, 2021, p. 27)

<sup>9</sup> The flooding of fields to growth rice by preventing oxygen from penetrating the soil create the ideal conditions for the growth of methane emitting bacteria (Methanogens)

<sup>10</sup> The other two major sources are fossil fuels, 35% of human-caused emissions, and waste - landfills and wastewater- 20%.

<sup>11</sup> GHG emissions from agriculture - methane, nitrous oxide and carbon dioxide - are more difficult to measure than those from burning fossil fuels because they are the result of a complex process. Methane is mainly produced by livestock digestion and manure management and is the largest contributor to GHG emissions from agriculture. Nitrous oxide emissions, N<sub>2</sub>O, result mainly from the use of fertilisers and manure management. Finally, carbon dioxide emissions, CO<sub>2</sub>, result from the decomposition of plant matter in soils and the conversion of wild land to agricultural use. This effect is partly offset by CO<sub>2</sub> emissions stored in the soils of cultivated land (Joiner and Toman, 2023).

is 17% (FAO, 2021b). Moreover, in the EU, progress in reducing emissions from agriculture was rather slow in the period 2005–2022 (–5%), compared to energy (–38%) or buildings (–28%) (European Scientific Advisory Board on Climate Change, 2024). Comparing the contribution of agriculture to GDP and to GHG emissions, whether globally or by region, we see that agriculture is an intensive source of GHG emissions, with an index of agriculture's share of GDP to agriculture's share of GHG emissions ranging from 4 at the global level to 7.6 in the EU and 10 in the US.<sup>12</sup>

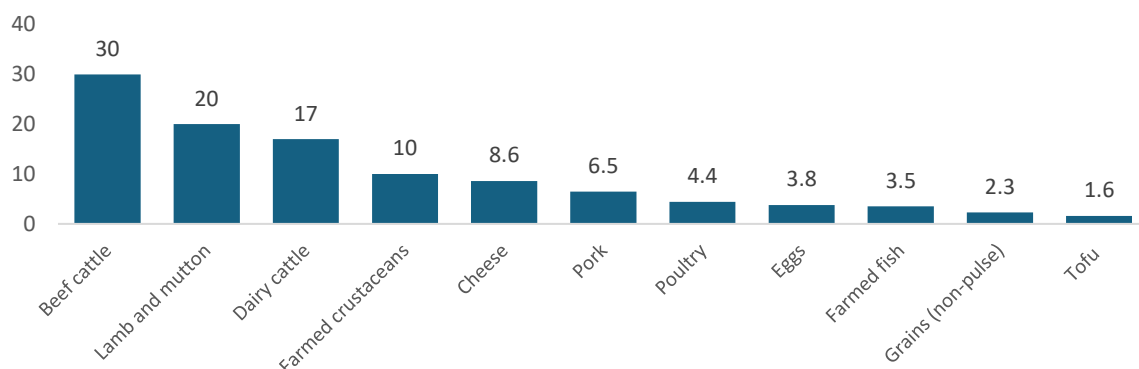
The shift in diets towards meat as a result of the growth in GDP per capita is another cause for concern, since, as shown in Figure 7, GHG emissions from meat production are much higher, at 30 kg CO<sub>2</sub> equivalent per 100 grams of protein, compared to 2.3 for cereals (non-pulses). Fortunately, the expected increase in GHG emissions from this change in diet will be limited (projected at around 5% by 2030) due to shifts towards poultry production, national low carbon initiatives, and higher meat production from a given animal stock (OECD-FAO, 2021, p. 170).

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<sup>12</sup> In absolute terms, though, taking EU as example, the economic activities with the highest GHG emissions were manufacturing and the supply of electricity, gas, steam and air conditioning, in both cases with 745 million tonnes of CO<sub>2</sub>-eq, representing each 21% of total GHG emitted, compared to 467 million tonnes of agriculture (Eurostat).

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Figure 7. Greenhouse Gas Emissions from protein production (kg of CO<sub>2</sub> equivalent per 100 grams of protein).



Source: Crimmins et al.(2023), chapter 11, p. 13

It is also important to highlight that, according to the estimates of the Global Methane Assessments, reducing GHG emissions would contribute to meeting the future demands for increased food production, as methane plays an important role in reducing crop yields, especially in low latitude regions (in South Asia, the Middle East and Africa), through various mechanisms such as increased ozone depletion and temperature changes.

Access to more and more timely information could also improve the efficiency of agricultural policies. To give just one example, according to Weiss and Duveiller (2020), remote sensing, by remotely monitoring vegetation in space and time, can facilitate the identification of new varieties that are better suited to difficult contexts (e.g. phenotyping), monitor agricultural land use, and contribute to forecasting seasonal crop production and the provision of ecosystem services related to soil or water resources, as well as animal or plant biodiversity.

In this context, the literature suggests that digital technologies could contribute to the process of greening agriculture through various mechanisms. As we can see in Table 3, the range of possibilities offered by digital technologies is quite wide. Most of them are related to improving information collection and processing, which would allow a better use of inputs and reduce market transaction costs, rather than directly reducing GHG emissions.

In this context, information is crucial for the efficient functioning of markets. Digital technologies, by improving the collection and analysis of information, could help reduce transaction costs and information asymmetries. To give an example, as mentioned in Schroeder et al. (2021), remote sensing data together with increased computing capacity can improve yield estimates and reduce the cost of monitoring insurance contracts.

In addition, the increase in information at farm level on production and input requirements could increase productivity and output per hectare, thereby reducing costs, as the information collected is used to apply inputs only if, when and at the required intensity (so-called precision agriculture). According to one widely quoted source, 190,000 data points were produced per farm per day in 2014. Experts predict that by 2050, each farm will produce around 4.1 million data points per day. This information, processed by new digital technologies, could be the source of major productivity gains. In addition, easier access to information for farmers could lead to the adoption of better technology.

Table 4, based on Schroeder et al. (2021), presents the different expected positive sources of impact of digital technologies on agriculture in three different ways: (a) those related to the direct impact of new technologies that improve information on the situation and needs of crops and allow the adoption of precision agriculture; (b) those related to the new possibilities opened by digital technologies to better monitor agricultural systems and food safety; and (c) those related to the potential behavioural effects of the increase in information on the impact of agriculture and food production on the environment.

As the reader has probably noticed, Table 3 does not include two innovations that are common to the current technological revolution: electric vehicles and robots. With regard to the former, tractors are the

most fuel-intensive mobile agricultural equipment, but due to their specific use (high and transient power demand for the tractor and its accessories) and working conditions (off-road use, higher levels of shock and vibration, etc.), the technologies used in electric road vehicles are not (at least not yet) directly transferable to tractors (or other heavy-duty vehicles) (Noor, 2022). According to Scolaro et al.'s (2021) review of the electrification of agricultural machinery, compared to on-road vehicles, the electrification of agricultural machinery is more challenging, and results to date show that the full electric conversion of high-performance agricultural tractors is still generally considered "unsuitable". However, in the future, as argued by Lajonen et al. (2018), "automation will be major driving force and it will support the utilization of hybrid and electric powertrains because electric components and systems are more accurate in terms of control and measuring than hydraulic or mechanical systems". Driverless tractors can also operate 24/7, with potential benefits in terms of their reduced size. The authors estimate that by 2035, half of all new machines will have some degree of electric powertrain (Lajonen et al, 2018, p. 15).



Table 3. Digital technologies for agricultural and food production.

Technology purpose	Category	Sub-category
Data collection technologies	Remote sensing	Satellite-mounted data acquisition / monitoring systems
		UAV / drone-mounted data acquisition / monitoring systems
		Manned aircraft data acquisition / monitoring systems
	In situ sensing	Water quantity meters
		Water quality sensors & air quality sensors
		In situ meteorological sensors
		In situ soil monitors
		In situ biodiversity, invasive species or pest monitors
		Crop & Livestock monitors
		Data from precision agricultural machinery
	Crowdsourcing data analysis	'Serious games' for gathering agri-environmental data
		Citizen science technologies that facilitate "public engagement in (...) innovation"
Data analysis technologies	Online surveys / censuses	Data collection portals (e.g. online census)
	Financial / market data collection	Retail scanner data
		Business software for recording financial or market information (e.g. database entry systems)
	GIS-based and sensor-based analytical tools	Digital Elevation Modelling
		Land Use-Land Cover mapping
		Watershed modelling
		Soil mapping Landscape modelling
		Software (programs, apps) for translating sensor and other farm data into actionable information. Software for automating agricultural machinery which uses sensor or other farm data as input. Software for measuring and grading agricultural outputs (e.g. carcass grading software)
	Crowdsourcing data analysis Deep learning / AI	Crowdsourcing applications for data sorting / labelling
		Data cleaning algorithms
		Big data analysis algorithms
Data storage technologies	Secure and Accessible Data Storage	Machine learning
		Predictive analysis
		Cloud storage
	Data management technologies	Confidential Computing
		Virtual data centres
Data management technologies Data transfer and sharing: Digital communications, trading, payment and service delivery platforms	Digital communication technologies	Distributed ledger technologies (e.g. Blockchain)
		Interoperability programs and apps
	Online platforms - property rights, payments, services and markets	Digital data visualization technologies
		Social media
		Web-based video conferencing
		Machine-assisted communication (e.g. chatbots, natural language generation algorithms)
		Online property rights and permits registries
		Online trading platforms
		Platform-based crowdfunding for agriculture and agri-ecosystem services
		Online payment platforms (for public programs)
		Service delivery platforms

Source: OECD (2019b), p. 22-23

Table 4. Positive potential impact of digital technologies in agriculture

Description	Example
Direct effects	Changes of production and distribution processes. Precision agriculture allowed by the collection and processing of information through new digital technologies
Enabling effects	Improved environmental monitoring of agricultural production systems
Behavioural effects	Environmentally friendly change of consumer and producer behaviour regarding food
	<p>Precision technologies apply water, fertilizers, herbicides, and pesticides only when and where they are needed, limiting the harm to soil and water resources caused by excessive or inadequate applications</p> <p>Better traceability of food using blockchain technology that could reduce food waste and increase food security</p> <p>Improve information on ways to reduce food waste. According to estimates of the UNEP Food Waste Index Report 2021, 17% of total global food production and 8-10% of GHG emissions are associated with food that is not consumed</p>

Source: Schroeder et al. (2021), p. 4

#### 4.1.2 The role of digitalisation in the energy transition

The transition to green renewable energy is key to decarbonising the economy and combating climate change. In 2022, energy (electricity, gas, steam and air conditioning supply) accounted for 32% of total emissions of CO<sub>2</sub> in the EU, with transport and storage contributing a further 18.5% of total GHG emissions. A successful fight against global warming, therefore, depends crucially on our ability to replace traditional carbon-emitting energy sources, such as oil or coal, with clean renewable energy sources such as wind or solar power. This substitution process faces two challenges. The first one is the deployment of sufficient capacity to offset the phase-out of the traditional carbon-based sources of electricity and the generation of new capacity to meet the growing demand associated with the use of electric vehicles, EVs, instead of internal combustion vehicles<sup>13</sup>. Based on current policy settings, sales of light-duty EVs, which represent the majority of EV sales, would reach 40% of total sales of this type of vehicle in 2030, and 55% in 2035. The IEA (2024, p. 148) estimates that electric vehicles could increase the electricity demand from 0.5% today to 6-8% of total electricity demand by 2035.

The second is to efficiently manage the growing demand for electricity from renewable sources. In less than five years, the IEA (2024b) estimates that under current policy and market conditions, renewables will account for 42% of global electricity generation, with wind and solar PV accounting for 25%. This means that renewables will account for almost all new capacity additions. In the Net Zero Scenario, NZS, the increase would be even higher by 2050, with existing renewable capacity tripling by 2030 compared to 2022 (compared to the 2.5-fold growth considered above) (IEA, 2024b). This poses new challenges for the management of electricity distribution.

Traditional electricity systems manage a variable but relatively inflexible and predictable demand for electricity. This means that small variations in the expected level of demand can be easily accommodated by activating standby capacity (usually fossil fuel or hydro power stations). In other words, variable demand is met with supply-side flexibility by switching plants on and off the grid. This situation could change in a future where a large proportion of energy is renewable and dependent on weather conditions, increasing the variability of supply and posing increasing operational challenges. At least until battery technology and storage capacity improve to allow the transition from variable power generation to a stable power supply.<sup>14</sup> In the meantime, to cope with this new source of variability, as

<sup>13</sup> The projected global EV fleet is estimated to displace 6 million barrels per day (mb/d) of diesel and gasoline in 2030, a sixfold increase on displacement in 2023, and from 11 to 12 md/d, depending of the scenario, by 2035 (IEA, 2024, p. 151-2)

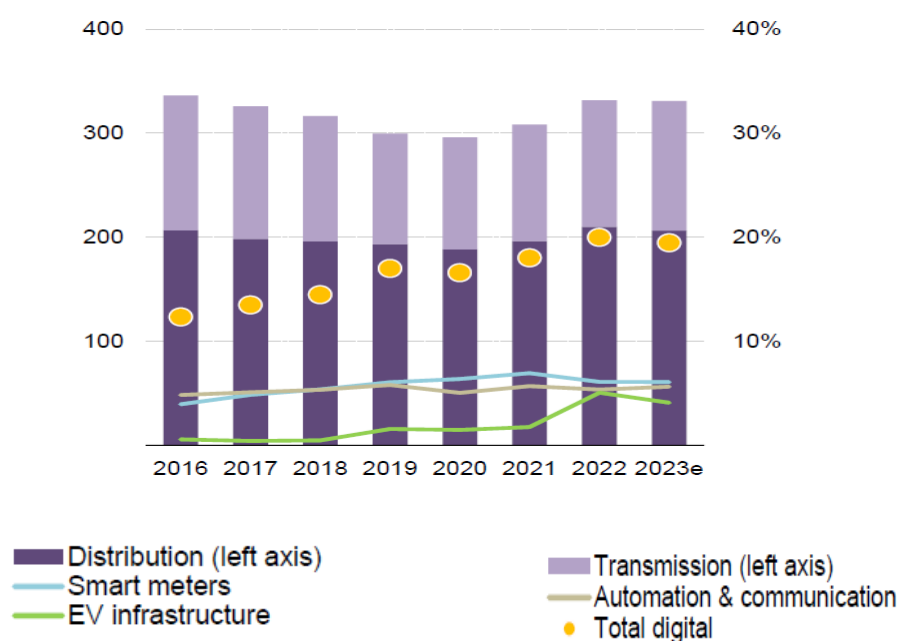
<sup>14</sup> In fact, we have already seen significant improvements in battery technology over the last few decades. According to estimates by Ziegler and Trancik (2021), the real price of lithium-ion cells has fallen by around 97% in terms of capacity since their commercial introduction in 1991. The authors suggest that battery technologies developed for stationary

IRERA (2022) argues, it will be necessary to resort to new sources of flexibility on the demand side. And this is where digitalisation can contribute to the green transition by allowing demand to adapt to changes in supply in real time using smart digital devices. For example, with the support of new digital technologies, the charging of electric vehicles (EVs) can be adjusted to follow fluctuations in the system. According to IRENA (2019), smart charging devices can reduce the investment required in the distribution network for EV deployment by between 40% and 90%. In this context, digital technologies are considered by IRENA (2020) as the third pillar of the energy transition, acting as a key link between the growth of renewable energy generation and widespread electrification:

“The third pillar of the transition is crucial, as it will be the key link between the expansion of renewable generation and widespread electrification. It is the deployment of “smart” digital devices, information and communications technology (ICT), and related operational practices, which offer the prospect of even greater efficiency gains through much more flexibility and optimisation of demand, delivery and use of renewable electricity” (IRENA, 2022, p. 17).

Similarly, according to the European Commission, “in the longer-term, digitalisation will be a prerequisite for the integration of decentralised forms of renewable energy in the grid” (EC, 2022). Indeed, grid-related investments in digital technologies have increased by more than 50% since 2015 and are expected to reach 19% of total grid investments in 2023 (Figure 8).

Figure 8: Digital investment in power grid infrastructure, 2016-2023e



Note: e = estimated

Source: World Energy Investment 2023, p. 49

By 2023, the number of smart electricity meters is expected to increase by 1 billion, while the global stock of digitally enabled automated devices (sensors and other IoT, smart meters, lighting, audio devices and others) is expected to reach 13 billion, up from less than 1 billion a decade ago (IEA, 2023). These devices enable more efficient use of energy and add flexibility to the electricity system. By turning

applications (as would be the case for large-scale energy storage), with fewer volume and mass constraints, could achieve faster cost reductions in the future. In 2022, the US Energy Information Administration estimated that US battery storage capacity would grow from less than 5 GW in 2021 to 30 GW in 2025. (<https://www.eia.gov/todayinenergy/detail.php?id=54939>)

off at peak times or turning on when renewable energy output is high, they facilitate the integration of renewables, relieve grid congestion and reduce peak demand, which is often met by costly, CO<sub>2</sub>-emitting power plants (Roize et al., 2023).

Together with these devices, according to the review by Antonopoulus et al. (2020),<sup>15</sup> AI and machine learning approaches are promising technologies to enable demand side response, DSR, by selecting the optimal set of consumers to respond, learning their attributes and preferences, dynamic pricing, scheduling and control of devices, learning how to incentivise participants in the demand response schemes and how to reward them in a fair and economically efficient way.

Clearly, to realise the full efficiency potential of these smart devices, all the data generated by these devices must be accessible and generated by compatible systems with sharing protocols. This is not the case, as the current use of data from small meters is well below its maximum, with only an estimated 2-4% of the data produced currently being used to improve the efficiency of grid operations (Roize et al., 2023). While the proliferation of data on energy generation and use allows for better management of the system and reduces the need for investment in grid upgrades, it also presents new cybersecurity risks as the attack surface increases.<sup>16</sup>

#### *4.1.3 Two of many. Potential impact of digitalisation on energy savings in other sectors of activity.*

If we consider digitalisation (computers, internet, IoT, AI, etc.) as a general-purpose technology, GPT,<sup>17</sup> then its ubiquitous application in all or most economic activities (albeit with varying intensity) would mean that the sectors considered above would be only two among many sectors where digitalisation could contribute to the green transition. To conclude this section, in the following pages we will briefly touch upon the contribution of digitalisation to the green transition in other sectors of the economy.

Passenger transport.

According to Noussan and Tagliapietra (2020), digital technologies can be a game changer in the process of decarbonising passenger transport, “fostering the deployment of innovative mobility solutions and technologies” (p.1). Autonomous driving and the use of algorithms to optimise energy efficiency, based on the reduction of travel time, smoother driving that minimises braking and acceleration phases, the reduction of congestion (by adapting the route in real time to the level of congestion of different alternatives) and the reduction of the time needed to find a parking space (using IoT communication between vehicles) can lead to significant energy savings. Another potential source of energy savings is the use of platooning or carpooling, facilitated by digital devices and apps; according to analysis by Greenwald and Kornhauser (2019), carpooling could reduce vehicle miles travelled by around 30%. On the other hand, the reduction in transport costs could increase the demand for mobility, leading to higher energy consumption. The use of automated algorithms in public transport could also make this type of mobility more flexible and attractive (i.e. facilitate multimodal journeys).

Noussan and Tagliapietra (2020) present a very interesting estimate of the impact of these innovations on energy consumption and CO<sub>2</sub> emissions under two different scenarios. The first one, named Responsible Digitalisation, RD, is characterised, among other things, by a shift towards public transport in cities and the optimisation of public transport thanks to AI-driven mobility platforms, the development of carpooling, car and bike sharing, and a reduction in urban demand due to agile working and e-commerce. In contrast, the Selfish Digitalisation, SD, scenario is characterised by, among other things, by a shift from public transport to single-person taxi rides, a substitution of public transport for car-sharing in cities, and no significant changes in agile working and e-commerce. The results show the importance of

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<sup>15</sup> In the paper, the authors review over 160 papers, published between 2009 and 2019, 40 companies and commercial initiatives, and 21 large projects to identify the trends for AI and Machine Learning approaches in the energy Demand Respond sector.

<sup>16</sup> In fact, energy is the first sector considered in the list of “Sectors of High Criticality” included in the NIS2 Directive on cybersecurity (Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union, amending Regulation (EU) No 910/2014 and Directive (EU) 2018/1972, and repealing Directive (EU) 2016/1148 (NIS 2 Directive)).

<sup>17</sup> For a debate about computers as a GPT see, for example, Thompson and Spanuth (2018)

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the strategy chosen, as the same technological developments can lead to very different results in terms of energy consumption and CO<sub>2</sub> emissions: from a value of around 828 Mt of GHG emissions in Europe in 2015, the estimated emissions in the SD scenario in 2050 are 766 Mt, compared to 472 Mt in the RD scenario (38% lower).

In this regard, a recent report by the *European Environmental Agency* (EEA, 2022) on the role of digitalisation in mobility systems, explains that while “digitalisation has the potential to support the sustainable transition of the mobility system, promoting positive behavioural shifts, fair business models and system(s)-wide optimisation possibilities”, it can also “considerably worsen the pressures exerted on the environment, increasing demand for transport because of improved efficiency and reduced costs and increasing the attractiveness of less sustainable personal mobility modes such as private cars” (p. 5).

#### *E-commerce.*

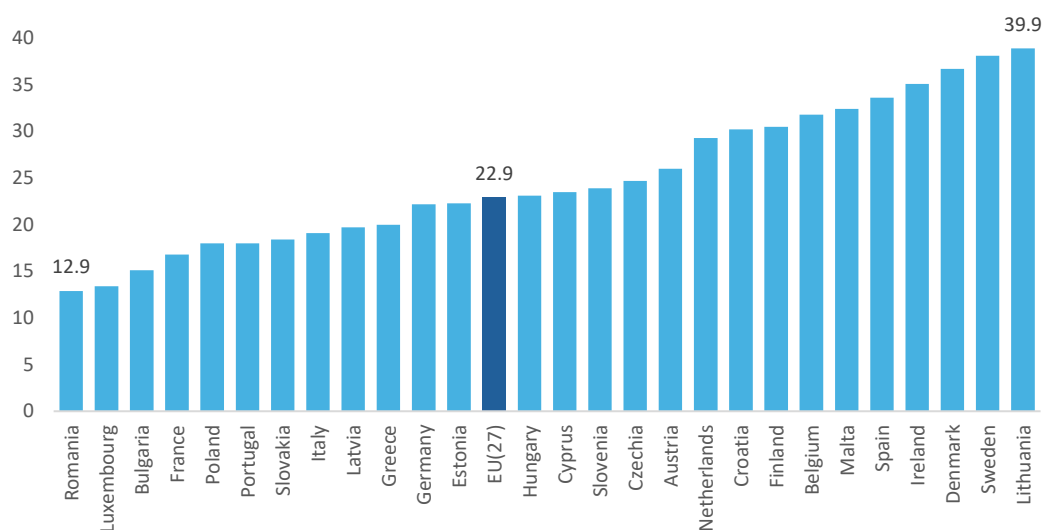
Another sector of interest in our review of the impact of the digital transition on the green transition is retail. Since the generalisation of internet access, e-commerce has replaced a significant part of what was traditional bricks-and-mortar retail before the internet. As we can see in Figure 9, in 2023, 23% of EU enterprises with 10 or more employees had e-commerce sales, with significant differences between Member States: Romania at one end (12.9%) and Lithuania at the other (39%). From the point of view of purchasers, according to Eurostat, 58% of EU residents had made a purchase over the internet in the previous 3 months.<sup>18</sup>

As with many other activities, the environmental and greenhouse gas emissions of e-commerce compared to traditional commerce are complex to estimate. On the one hand, e-commerce eliminates the need for personal transport of customers to and from the store (although the energy footprint of this depends on the type of transport used: private car vs. public transport), as well as the energy consumption of the physical store. It has also been suggested that e-commerce can extend the life of products through second-hand and resale applications (e.g. ebay). On the other hand, e-commerce involves a much higher intensity of packaging and more frequent returns, as well as the electrical footprint of data transfer associated with online shopping. In terms of returns, according to a comparative analysis by Hischier (2018, p. 9), the number of ordered items returned to the retailer can multiply the global warming potential of online shopping by three. Aggregate return rates suggest that in the US, 20% of online purchases are returned to the retailer (Ludmir, 2023). In the UK, according to returns logistics company ZigZag, in 2022 almost half of customers ordered multiple items to make a choice and returned some, up from a third in 2021 (Butler, 2023). In Germany, in a bricks and mortar and online women's clothing store, return rates for products sold online ranged from 13% to 96%, with an average of 53%, compared to just 3% for items purchased on site (Dzyabura et al., 2023). In Europe (EEA, 2024b), the average return rate for clothing purchased online is estimated to be 20%. The EEA estimates that 22-43% (i.e. on average a third of all returned clothing bought online) ends up being destroyed.

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<sup>18</sup> Eurostat, Internet purchases by individuals, Online data code: isoc\_ec\_ib20

Figure 9. Enterprises with 10 or more persons employed with E-commerce sales (%), 2023



Source: Eurostat, E-commerce sales of enterprises by size class of enterprise

In addition, the origin of the purchased product may be different, implying a longer total transport distance. It may also be the case, as argued in the literature, that e-commerce often adds to, rather than simply substitutes for, local purchases (i.e. it is not a one-for-one item), especially in the case of digital devices and travel (Wyman, 2021). Various studies reviewed by Buldeo Rai (2021) suggest that online shopping complements, rather than replaces, traditional shopping. All this makes it difficult to estimate the net impact of e-commerce. In fact, according to Collini et al. (2022) in a review of the approaches used to calculate the environmental footprint of e-commerce, most of the assessments lack scientific rigour, partly because they do not consider the life cycle of the goods or services purchased. In any case, as argued by Buldeo Rai (2021), “there is no particular type of shopping that has an absolute environmental advantage and it is in no way possible to shop ourselves out of the environmental crisis” (p.8).

## 4.2 Dematerialisation.

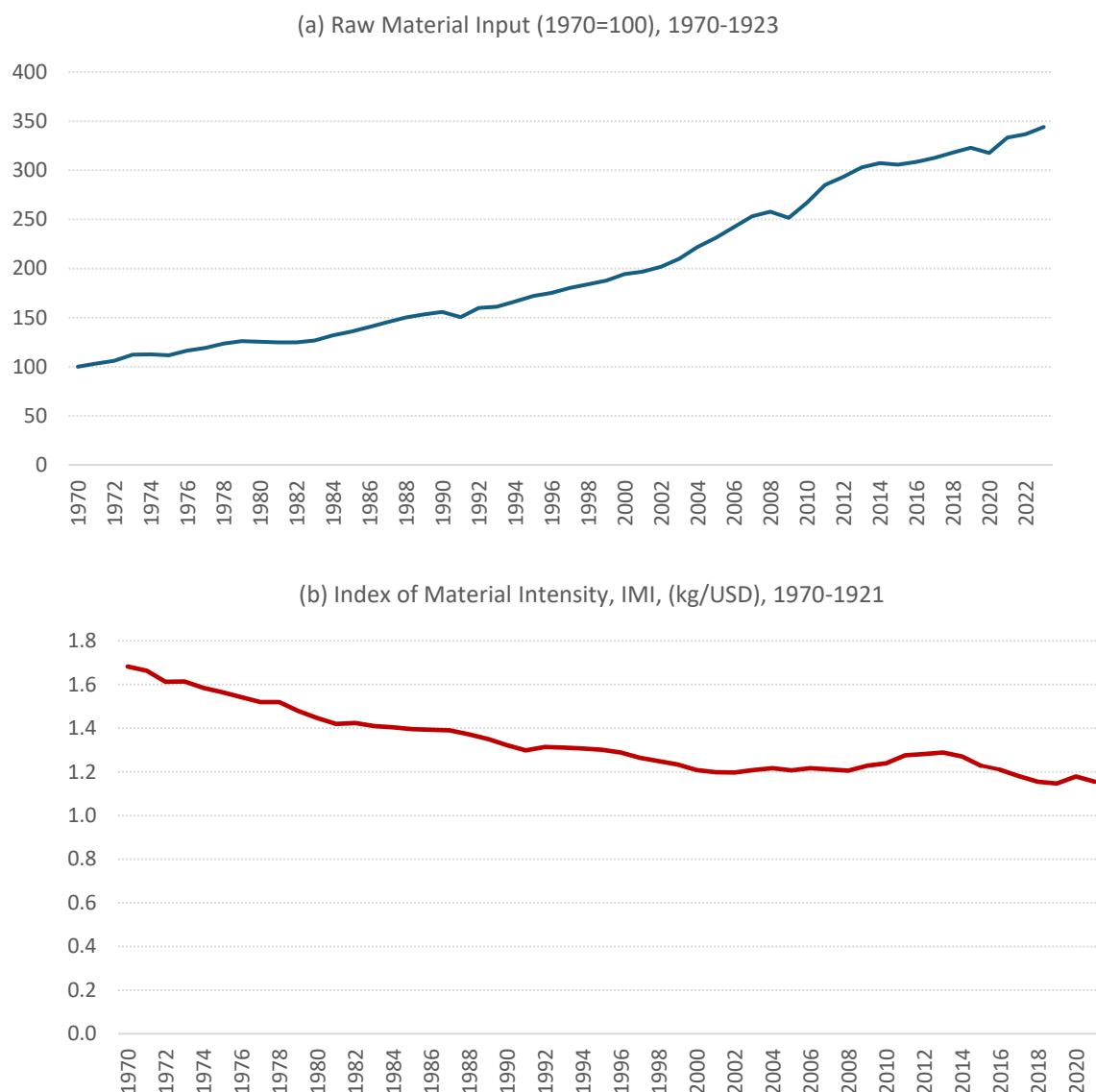
As mentioned above, the second axis of the digital transition's contribution to the green transition is that it enables the dematerialisation or virtualisation of goods and services, reducing the material production requirements per unit of output. According to Rankin (2014), dematerialisation is the absolute (*strong dematerialisation*) or relative (*weak dematerialisation*) reduction over time in the amount of materials used,  $X_i$ , or in the amount of waste generated,  $W_i$ , or both, per unit of output,  $Y_i$ . An often-used inverse measure of dematerialisation is the Index of Material Intensity,  $IMI_i = X_i/Y_i$ .

From a global perspective, according to the estimates provided in the United Nations Environment Programme and the International Resource Panel Global Material Flows Database, since 1970 there has been an increase in the use of raw material (biomass, fossil fuels, metals and non-metallic) in the production of goods and services, which use has multiplied by 3.5, as a result of GDP growth. However, from 1970 to 2021 this increase in the total use of raw materials has been accompanied by a 31.1% decrease in the Index of Material Intensity of GDP, IMI, (kg/USD). This means that there has been a process of relative or weak dematerialisation during the last half-century, but this process has not been strong enough to compensate for the growth in GDP (which has almost quadrupled over the period observed), leading to an increase in the total use of raw materials in production.

It is worth noting that the largest fall in the IMI occurred during the 1970's, probably as a result of the first oil crisis, -14%, followed by falls of 8.5% and 8.7% respectively in the following two decades. At the turn of the century, in the first decade of the 21st century, the IMI rose by 2.6%, only to fall by 6.8% in the following decade.

In this section we will present and discuss some areas in where the digital revolution has contributed, or could contribute, to the process of dematerialisation. These areas are teleworking, the substitution of physical products by digital products (i.e., the paperless office), and digital twins. Before doing so, however, we will briefly review the scarce literature available on the relationship between digitalisation and energy use from an aggregate macro perspective, since the reduction in the intensity of energy use is an important source of dematerialisation.

*Figure 10: Global Index of Total Raw Material Input (1970=100) and Global Index of Material Intensity, IMI (kg/GDP).*



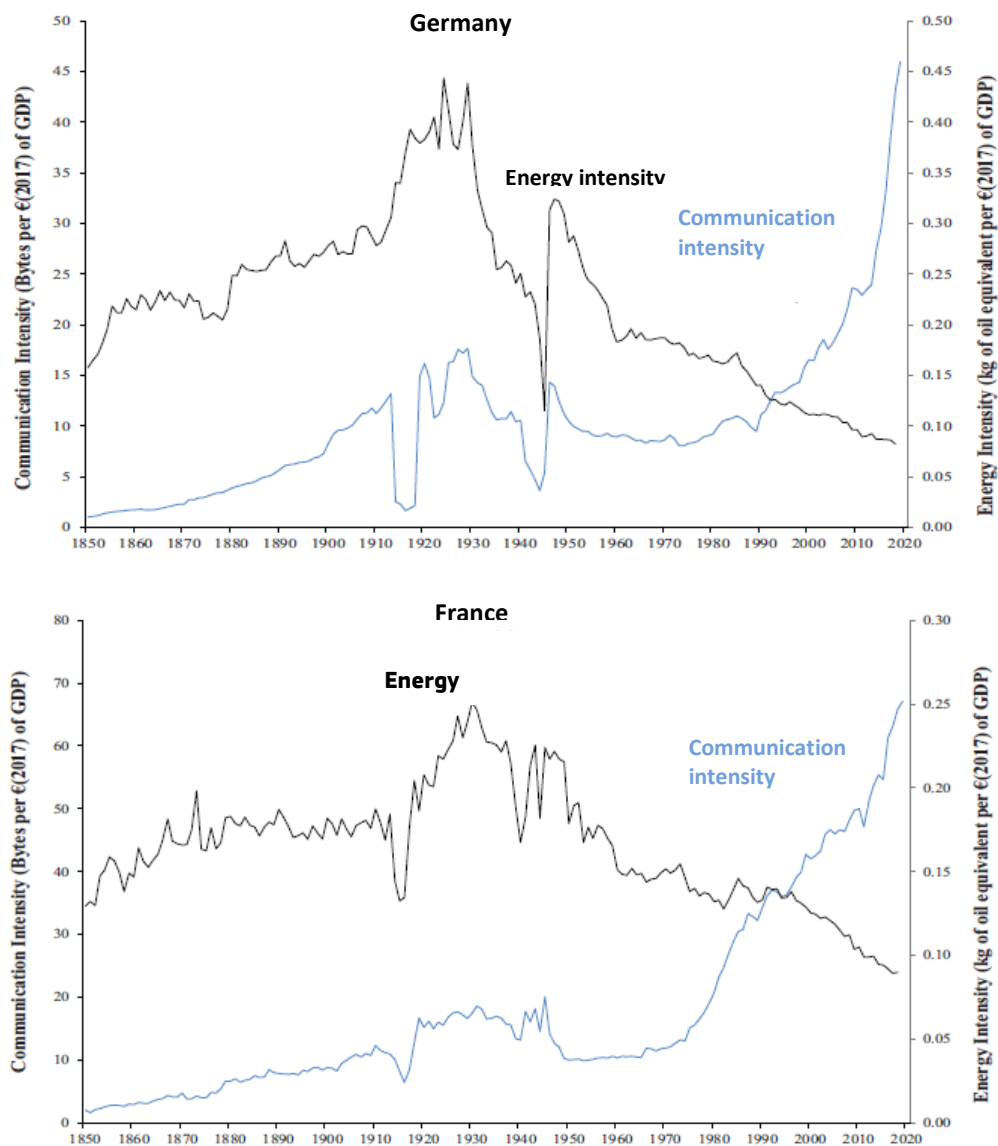
Source: Author's analysis from UNEP IRP Global Material Flows Database

#### *4.2.1. A brief note on the empirics of digitalisation and energy use.*

The research by Fouquet and Hippe (2022) on the structural changes associated with the “twin transitions” of decarbonisation and digitalisation in five European economies (Germany, France, Italy, Spain and the UK), from a long-term perspective since 1850, is an excellent way to start approaching this question. According to their analysis, in a first phase of economic development -from about 1850 to the 1960's approximately- energy and communication intensities co-evolve and follow a similar path.

This first phase was followed by a second phase in which the paths of energy and communication intensities diverged, with countries showing increasing communication intensities and decreasing energy intensities (as well as convergence between them). Figure 11 illustrates the cases of France and Germany. In any case, as the authors remark, a crucial question is whether such trends “are casually connected (...) or cofounded by another factor (...) that influences both intensities (...) or is just spurious correlation” (p. 14).

*Figure 11: Communication (bytes/€) and energy intensity (Kg of oil equivalent/€) in Germany and France, 1850-2019.*



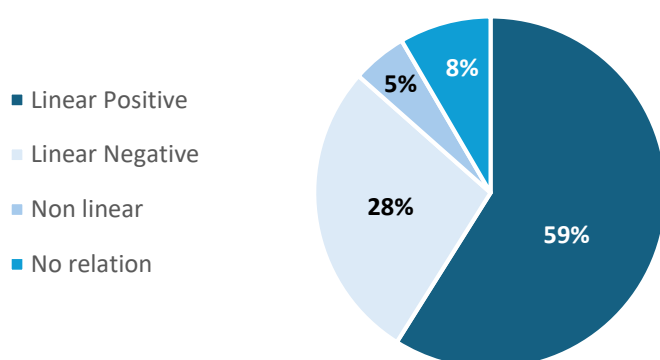
Source: Fouquet and Hippe (2022), p. 14

Although the above conclusion (the inverse relationship between communication and energy intensity) is good news, it cannot, as the authors point out, be interpreted in terms of the existence of a “twin transition” through which digitalisation (or communication, in the term used by the authors) contributes to the energy transition. This question is difficult to answer empirically, as it would mean isolating digitalisation from the myriad of other variables that influence the energy transition, both positively and negatively. Nevertheless, several authors have tried to shed some light on the issue, using different empirical strategies.



To give an idea of the results obtained by aggregate analyses, using different econometric strategies, most commonly Generalised Method of Moments (GMM), Autoregressive Distributed Lag (ARDL), and Fixed Effects (FE) models, the review of 166 empirical papers (including almost 300 relationships) on the ICT sector, digitisation and environmental sustainability made by Charfeddine and Umlai (2023) concluded (see Figure 10) that in most of the cases, 58%, digital technologies had a positive impact on climate change and air pollution (*i.e.* reduced environmental impact of production), although in 28% of the cases the impact on climate change and air pollution was negative. In a small number of cases, 5%, the results showed a non-linear relationship between the dependent variable, digitalisation, and the independent variable, environmental quality: a U-shaped relationship in 3 cases, a Kuznets type inverted U-shaped relationship in 10 cases, and an inverted N-shape relationship in 2 cases. Finally, in 8% of the models analysed, no relationship was found between the variables.

*Figure 12. Summary of the survey of Charfeddine and Umlai (2023) on the impact of the ICT sector and digitization on environmental sustainability*



Source: author's analysis of Charfeddine and Umlai (2023), pp: 14, 16.

To give an example of the type of papers reviewed, one of them, the study by Zheng and Wang (2021), uses panel data from seven countries (USA, Canada, UK, Germany, Italy, Netherlands and Poland) to examine the extent to which mobile ICTs have a positive impact on renewable energy production. According to their analysis, a one per cent increase in ICTs would lead to a 0.2/1.1 per cent increase in renewables in the long-run/short-run. The underlying logic of such a relationship taps into very different sources, from the increase in revenues from wireless spectrum auctions in the first stages of ICTs that can be used to promote renewable energy, to the role of mobile networks in generating the information and control mechanisms needed for the development of renewable energy. In any case, this result, interesting though it may be, does not answer the question of the overall relationship/contribution of the digital transition to the twin transitions, as it focuses on only one (probably minor) aspect of them.

More in line with the aims of this section, but still from an aggregate perspective, Rieger (2021) examines whether there is any relationship between the adoption of information and communication technologies which should, theoretically, facilitate the dematerialisation of goods and services, and the reduction of material consumption, as measured by the Eurostat Material Flow Accounts dataset (specifically, domestic extraction and imports, which includes most solids, gases, and liquids, except for water and air) in twenty-five European nations from 2005 to 2017. According to the results of this econometric analysis, there is not a statistically significant relationship between ICT use and material consumption in European countries.

To conclude this sub-section, the paper by Bianchini, Damioli and Ghisetti (2023) is a good example of the variety of approaches taken in the research on digitalisation and the environment. In this case the authors study whether those European regions with higher levels of environmental and digital innovation, as measured by environmental and digital patent applications, also show better results in

terms of GHG emissions<sup>19</sup>. Their results, using Tobit models and instrumental variables for 1051 EU metropolitan regions and the period 2017-16, suggest that: (1) the regional endowment with environmental technologies helps to reduce emissions (negative coefficient of green technologies on GHG emissions); (2) in contrast, regions with higher endowments of digital technologies show worse environmental performance; (3) the joint presence of higher endowments of digital and environmental technologies contributes to a reduction in GHG emissions; this result is interpreted by the authors as the confirmation that green and digital technologies are mutually reinforcing; (4) not all the elements of the “digital ecosystem” have the same environmental impact: as expected, those more energy intensive have a greater negative environmental impact. To summarise in their own words: “While the local development of green technologies reduces GHG emissions, the local development of digital technologies has a negative effect on the environment, which is only partially mitigated in regions that are sufficiently endowed with green technological knowledge” (p. 902).

All in all, the growing empirical literature on the contribution of the digital transition to the green transition, while highlighting some of the links between different aspects of both spheres (digital and environmental), has not yet been able to show, and probably never will be able to show, to what extent the digital transition facilitates a net reduction of GHG emissions and contributes to the green transition. This is not surprising since, as shown in section 3, the introduction of digital technologies leads to changes in many aspects of the economy: (1) GDP, as ITC is another economic sector and as such part of GDP, (2) the structure of the economy and production processes within the different economic sectors, and (3) possible rebound effects. In addition, we lack knowledge of the counterfactual of what a world would look like without digital technologies, against which the current situation could be measured.

#### ***4.2.2 Dematerialisation across sectors: teleworking***

Our first example of the contribution of the digital revolution to the dematerialisation of production is teleworking. In fact, we can think of teleworking as a way of dematerialising one input of production: the input used by workers (transport) to get to and from work. Table 5 shows the estimated commuting time of workers in the US, EU (27) and the five largest European countries (Germany, the UK, France, Italy and Spain).

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<sup>19</sup> The analysis is limited to First, the industrial emissions of highly energy-intensive and highly polluting plants subject to the European Trading Scheme (around 45% of total GHG emissions).

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Table 5: Commuting time to work in the EU, USA, Germany, the UK, France, Italy and Spain. (Excluding those working from home).

Minutes	US	EU (27)	UK	Spain	France	Germany	Italy
Less than 10	14,4	13,2	12,3	15,8	13,9	14,5	21,2
10 to 14	15,5	13,6	13,8	17,5	13,6	14,7	20,1
15 to 19	14,7	15,7	11,8	14,6	14,2	14,0	14,6
20 to 29	19,5	21,6	19,0	17,9	20,7	19,8	15,6
30 to 44	21,2	20,6	21,2	19,5	20,6	21,3	16,6
45 to 59	6,2	7,6	7,8	4,7	8,0	6,9	3,7
60 or more	8,5	7,7	14,1	10,0	9,0	8,9	8,1

Note: EU 2019, USA, 2022

Source: Author's analysis from Eurostat, Persons in employment by commuting time 2019, United States Census Bureau, American Community Survey, 2022.

Comparing commuting time in the EU and the US, we can see that, surprisingly given the difference between the two areas, the distribution is very similar between them, with just over 1/3 of employees (excluding those working from home) spending more than half an hour commuting each day. Only in the case of the USA does the source provide the average commuting time, which is 25.6 minutes in 2022. Regarding the average means of transport used, in the US, excluding teleworkers, 92% of employees use their own car (including car-pooling) to get to work, with only 3% using public transport. In the EU, although there are no equivalent figures, the available data for 13 Member States show that in terms of distance travelled per person per day, the car (including as a passenger) is the dominant mode of transport, with a simple average of 67% of the distance travelled using this mode, while the use of public transport (bus, urban rail, train and taxi) accounts for only 20.2% of the distance travelled (European Community, Passenger Mobility Statistics).<sup>20</sup>

In this context of a high share of workers commuting to work and using the car the main mode of transportation, teleworking seems like a good alternative to reduce the material intensity of products (by reducing the material input related to commuting) and GHG emissions. However, as highlighted by Akgüç et al. (2023) in their review of remote work and the green transition, the relationship between telework and a greener economy "is extremely complex (...) and it is mediated by a number of variables and contextual factors" (p.45). But before presenting some of the nuances of the environmental impact of telework, it is convenient to delimit its potentiality, that is the limitations of this way of managing work in order to see the potential of this way of production dematerialisation. According to the estimates of Sostero et al. (2020) using occupational task descriptions, 37% of dependent employment in the EU is considered to be teleworkable, with the highest share in Luxembourg, the Netherlands or Sweden (over 40%), and less than 30% in Romania and the Slovak republic, depending on the sectoral structure of their economy. However, as shown in Figure 11, in 2019 only 5,7 % of EU (27) employed people usually worked from home, with another 9% teleworking occasionally (at least sometimes). A total of 14,7%, compared to 9.7% in 2002. The share among self-employed was much higher, almost 36% (considering those who work from home usually and occasionally) versus 11% among employees. With the COVID-19 pandemic, the lockdowns and the recommendation of social distancing, telework increased dramatically, reaching 24.2 in 2021. Much of this increase stayed after the pandemic and the return to the new normality, with 22,4% of workers working from home in 2023. In the US, between 2019 and 2021, according to the American Community Survey, the number of people primarily working from home tripled from 5.7% (roughly 9 million people) to 17.9% (27.6 million people). In 2024, 22,3% of workers

<sup>20</sup> Although the Eurobarometer (2020) on Mobility and Transport doesn't ask specific questions about commuting to work, one of the questions, that enquires about the main mode of transport on a typical day, shows that for 62% of people the car is the main mode, with values that go from a maximum of 94% in Cyprus to a minimum of 45%-46% in Bulgaria and Romania. In fact, when analysed by socio-professional category, the percentage of people using the car as the main mode of transport increases to 66% among employees and 81% among self-employed, compared to 32% among students.

teleworked or worked at home for pay (11,5% some hours, 10.8% all hours) (CPS, June 2024). In both cases these numbers show an important increase from pre-covid numbers, while being still far from the potential share of telework. In the case of the US, according to the Pew Research Center (Parker, 2023), 35% of workers with jobs that can be done remotely are working from home all the time (down from 55% in October 2020, but up from just 7% before the pandemic).

In any case, it must be recognised that the fact that a job can potentially be done at home does not mean that the net effect of working at home compared to working at the employer's premises is positive for the employer, the employee or both. This potential benchmark must therefore be seen as a maximum (given today's sectoral and occupational structure). Anyway, this means that whatever the impact of teleworking on the green transition, it would be limited to a maximum of -not insignificant- around one third of the workforce.

And what is contribution of telework to the green transition? As mentioned above, in order to estimate the impact of telework on the green transition we have to go beyond the "simple" arithmetic of the energy saved by reducing the number of journeys to work. Figure 11 summarises the different first and second order effects of telework that need to be considered in order to estimate the potential contribution of telework to the green transition mostly in terms of energy savings and reduction of GHG emissions.

*Table 6. First a second order effects of teleworking on the green transition.*

Effects		Contingent on	
		Distance and type of transport	
1	Reduction in travel	Reduction in energy input and GHG emissions	2 <sup>nd</sup> rounds effects Use of car by other person/family member Increase in non-work commuting Choice for distant residence
2	Reduction in energy consumption at the office	Reduction in energy input and GHG emissions Increase in energy consumption at home x number of teleworkers	The net effect will depend on the energy efficiency of workers' homes compared to the firm premises and the feasibility of partially reducing climatization in the firms' buildings
3	Potential increase in productivity and GDP	Increase in energy input and GHG emissions	Increase in productivity

Source: Author's elaboration.

The first and most important item is the direct reduction in energy consumption and GHG emissions resulting from the reduction of the number of commuting trips to work. This first order impact will depend on the distance between home and the working premises and the type of transportation used, and will be most relevant when the distance is large and internal combustion private cars are used as means of transportation (without car-pooling) and the car is use by only one person (76% of cases in the US in 2019, Vigderman, 2022). When public transport or other non- polluting mean of transportation such as bicycle or waking are used, or the distance covered is short, the saving will be modest or non-

existing. In this regard, according to the analysis of the IEA (2020), for people who commute by car, telework is likely to reduce CO<sub>2</sub> footprint if they commute for more than 6 kilometres. Otherwise working from home could increase CO<sub>2</sub> emissions due to extra residential energy consumption, as a day of working from home could increase household energy consumption by between 7% and 23% vis a vis a day working at the office (see further down). According to a detailed study by Tenaillon et al. (2021), based on an analysis of a medium-sized French city, Besançon, teleworking leads to a reduction in emissions of -0.42% for every 1% increase in the teleworking rate. Similar results are obtained by Stefaniec (2024) for Ireland in the case of moderate working from home practices. Moreover, as telework (hybrid work) is usually related with higher working time flexibility, it can contribute to a reduction in traffic congestion, and the corresponding reduction in CO<sub>2</sub> emissions (Hostettler Macias et al., 2022, Shabanpour et al., 2018, Asgari and Yin, 2018, Ellder, 2020, Wöhner, 2022).

This positive impact (i.e., reduction) of teleworking on commuting and GHG emission related to transport, could be partially compensated by the different behaviour of teleworkers in relation to non-work mobility. In this regard, according to different studies (Zhu, 2012, and Zhu and Mason, 2014 for the US; Kim 2016, for South Korea; Caldarola, and Sorrell, 2022, for the UK, etc.) teleworkers do more additional non-work-related travel than commuters, among other things because many of such additional travels (e.g., taking the kids to school or buying groceries) were done before during their daily commute to work. For example, according to the study of Budnitz et al. (2020) for the UK, while telecommuters record fewer commute trips, they record “more trips for other purposes, and the marginal utility of additional non-work trips to telecommuters is greater than for many other socio-economic characteristics”. In Switzerland too hybrid work is associated with larger distances of nonwork-related travel (Wöhner, 2022). Telecommuters in California that have at least a trip during their workdays travel 1.37 more Vehicle Miles Traveled, VMT, and 0.53 more trips than their counterpart commuters although they drive alone less and tend to have more complex schedules visiting more locations (Goulías, Su and McBride, 2020). From a household perspective, according to Kim et al., (2015), the increase in additional travel time could be related with ‘freeing’ of the household car for use by other household members, transforming the patterns of activities and travel within the household (Pigalle, 2024).

The literature has also found a direct relation between telework and places of residence of workers farther away from work, although the causality is not always clear, as it could go from living farther away from work affecting the probability of teleworking or vice versa (having the possibility to telework reducing the advantages of living closer to work). For example, in the UK telework is often related to “longer average distances for work trips, which are often associated with more remote residential locations” (Cerqueira et al., 2020). This result is confirmed by the study of Caldarola and Sorrell (2024) of the impact of teleworking on English travel patterns over the period 2005 to 2019, who present evidence that suggest that teleworking leads to longer commute distances, being telework the cause of people living farther from their workplaces and not vice versa. A similar pattern is observed in the Netherlands, where according to the estimates of De Vos et al. (2018) “working from home allows people to accept 5% longer commuting times on average, and every additional 8 h of working from home are associated with 3.5% longer commuting times” (p. 375). The same effect is found in Switzerland, where according to Ravalet and Rérat (2019) teleworkers live farther away from the workplace than their colleagues (24.6 km vs. 16.1 km).

The second item to consider when analysing the environmental implications of teleworking is its implications in terms of household energy consumption. As teleworkers spend more time at home higher energy expenditure in electricity and heating or cooling needs is to be expected. The net result would be contingent in whether there is an equivalent reduction in energy consumption at the firm’s premises and on the energy efficiency of the workplace and the home of teleworkers. As only a small percentage of companies are fully remote<sup>21</sup>, given that telework is usually combined with traditional onsite work. This implies that there is not a perfect substitution between energy expenditure on site and at the teleworkers’ home, increasing overall energy expenditure. This increase will depend on the energy efficiency of home offices, the type of energy used (renewable versus non-renewable), the feasibility of

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<sup>21</sup> According to the Owl Labs Global State of Remote Work 2018 16% of companies are fully remote with no headquarters or office option available. All employees work from workspaces, their homes, or wherever they choose (<https://resources.owllabs.com/state-of-remote-work/2018>).

reducing energy expenditure at the firm premises with the increase in workers teleworking (e.g. reducing the office size and using a system of hot desks). The role played by these variables explain that there is no consensus in the literature (Shi et al., 2023; O'Brien et al, 2020) on the net impact of teleworking on these variables on energy consumption excluding transport. For example, based on data from the UK Energy Performance Certificate (EPC) database for the period 2008 to 2022, Shi et al. (2023) estimate that teleworking increases total emissions unless teleworkers meet the following conditions related to the intensity of teleworking and the characteristics of their home heating systems: (a) they telework 3–5 times per week, (b) they heat their home office on teleworking days rather than their entire home, (c) they heat this office to a temperature of no more than 21C for no more than 3 hours, (d) they use air source heat pumps rather than other heating systems such as gas boilers.

In any case, there is consensus on the need to consider the increase in energy expenditure at home related to telework and its role in reducing the overall contribution of telework to the energy transition. For example, for the US, Larson and Zhao (2017), using a numerical simulation of the standard urban model, conclude that if 1/5 of workers teleworked one day a week, commuting energy consumption would decrease by 23%, but home energy consumption would increase by 5.3%, increasing household overall energy consumption by 0.4%, although CO<sub>2</sub> emissions would change by -0.1% due to the carbon intensity of the energy mix (the shift of energy consumption from gasoline to electricity). Although less important, telework also leads to a duplication of digital infrastructure at home, also with environmental implications.

The last point to be considered in this sub-section is of a different nature and is related to the rebound effect discussed above, as well as to the potential positive contribution of telework to increasing productivity and GDP growth, with the corresponding negative impact on the green transition (in the absence of full decoupling) as argued, for example, by Lachapelle *et al.* (2018). In this respect, Criscuolo *et al.* (2021), after analysing the results of a survey of managers and employees in 25 countries on their experience of teleworking during the pandemic, concluded that both had an overall positive assessment of teleworking in terms of business performance. For the French case, Bergeaud et al. (2023) analyse a dataset of about 1700 French manufacturing firms and conclude that firms that teleworked benefited from significantly higher total factor productivity than those that did not. According to the analysis of Bloom et al. (2015) of a call centre in China, those workers who were randomly assigned to remote work were more productive than in-person workers. The highly recommended review of studies on telework and productivity by the GAO (2023) also found that telework generally had a positive impact on worker productivity and firm performance in certain sectors.

However, other studies reach different conclusions. For example, Akin, Schoar and Shinde (2023) argue that differences in the productivity of teleworkers and in-office workers may arise because of differences in the skills of workers sorting into these options. To avoid this problem, they conduct a natural experiment by exogenously assigning workers in the data entry sector in Chennai, India, to telework or work in the office and find that the productivity of workers randomly assigned to telework is 18% lower than that of those working in the office. In addition, workers who prefer to telework are significantly less productive at home than in the office. The growing number of large companies that have stopped teleworking altogether since the end of the pandemic is another example of doubts about the impact of teleworking on productivity (O'Sullivan, 2024).<sup>22</sup> In summary, as noted in GAO (2023), methodological issues complicate efforts to estimate the long-term productivity effects of telework.

There is another strand of literature that is not directly aimed at investigating the environmental impact of telework, but which is nevertheless worth mentioning in order to conclude this subsection. One of the arguments used in the debate on reducing working hours (Spiegelaere and Piasna, 2017), and in particular in the discussion on the benefits of a four-day working week is its potential positive effects in terms of reducing greenhouse gas emissions and improving environmental sustainability. This positive impact is based on two different effects. The first, the so-called substitution effect, argues that labour-intensive (i.e. long working hours) households tend to consume products with a higher environmental

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<sup>22</sup> The analysis of Dijcke *et al.* (2024) of the return to office policy of the largest US tech companies Microsoft, SpaceX, and Apple, points to the existence of potential negative impact of these policies for productivity, as they “can lead to an outflow of senior employees, posing a potential threat to the productivity, innovation, and competitiveness of the wider firm”.

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footprint (Devetter and Rousseau, 2011). The second, the scale effect, argues that productivity gains used to 'finance' reductions in working time have a lower environmental impact than productivity gains translated into higher wages (and consumption) growth. For example, Nassen and Larsson, (2015) conclude that every 1% reduction in working time in Swedish households is associated with a 0.7-0.8% reduction in energy consumption and greenhouse gas emissions. According to the model developed by Knight et al. (2013) for 29 high-income countries with data from 1970 to 2007, reductions in working hours are associated with reductions in the Ecological Footprint, carbon footprint and CO<sub>2</sub> emissions, with larger scale effects than compositional effects: A 10% reduction in working hours reduces the Ecological Footprint by 12.1% through the former effect and by 4.9% through the composition effect. A more recent paper (Mompelat, 2021), commissioned by the Four Day Week campaign as part of the debate on the benefits of a shorter working week, and which included a review of the relevant literature on the subject, concluded that a shift to a four-day week (at constant pay) could reduce the UK's carbon footprint by 21%. For the U.S Mallinson and Cheng (2022) find a positive and statistically significant relationship between average hours worked and CO<sub>2</sub> emissions at the state-level, with each roughly 1% lower emissions for every 1% reduction in weekly hours.

To conclude this sub-section, teleworking, a child of the digital transition, is clearly a powerful tool in the green transition. However, the extent of its contribution depends, among other things, on whether telework leads to an increase in non-work car mobility, contributes to a process of living further away from the workplace, and increases energy consumption. As in other areas, we fear that teleworking, while a useful tool, is not a silver bullet in the green transition because of the above elements.

#### *4.2.3 Substitution of physical products by digital products.*

The digital revolution has triggered a process of substitution of material goods (and services) by digital goods (and services) which, it is argued, should contribute to a lower use of material inputs in the production process. This process of dematerialisation is another area, and another often-used example, of the contribution of the digital transition to the green transition. In what follows, we will briefly consider as example of this process of dematerialisation the substitution of paper by electronic-virtual documents and e-books, and the substitution of CDs by stream music.

##### *Substitution of paper by e-paper*

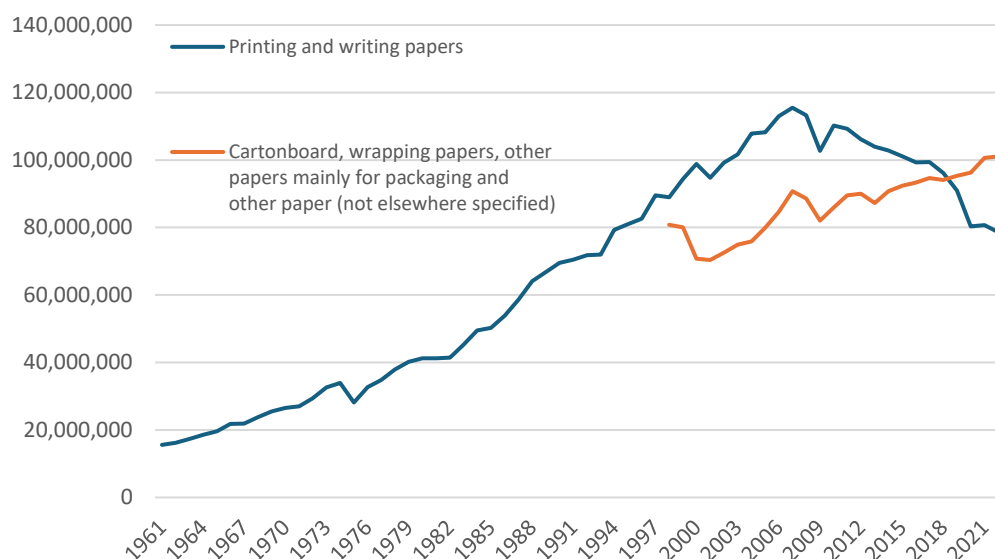
Figure 13 shows the evolution of the world production of printing and writing paper and paper and paperboard, wrapping paper, and other paper mainly for packaging (and other paper not elsewhere specified) since 1961 in the first case and 1987 in the second. The data on the production of writing paper are clear, as it increased sevenfold up to 2007 and then decreased as a result of the process of substitution of paper by virtual documents. At the same time, however, the production of the remaining types of paper (cardboard, wrapping paper, other paper mainly for packaging and other paper not elsewhere specified) is increasing. This trend can be explained by the growth of carton board as a result of the growth of e-commerce. This is a first conclusion we can draw about the process of digitisation: the same technologies can have very different effects on material use, dematerialisation in the case of e-documents and e-books, and re-materialisation in the case of e-commerce. The link between these processes and the green transition is direct, as the pulp and paper industry accounts for 13-15% of total wood consumption and uses between 33-40% of all industrial wood traded globally, according to the WWF.

Since the first eBooks readers were launched and the first ISBN to an eBook was issued in 1998, and especially since Amazon launched his first Kindle in 2007,<sup>23</sup> eBooks have increased their share of total global books sales, with a share of global books sales in 2023 around 16% (Curtic, 2023) up from 12% ten years earlier (Cout and Sorrell, 2020).

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<sup>23</sup> Amazon accounts for over 80% of all e-books sold in the US (Curtic, 2023)

Figure 13. Evolution of global production (tonnes) of printing and writing papers (1964-2022) and carton paper and other (1998-2022)



Source. Author's analysis from FAOSTAT data (Forestry Production and Trade)

Several studies that have estimated the environmental impact of a physical book compared to an e-reader. As we know, the production of paper requires huge amounts of water, wood and energy, as well as pollution from the chemicals used in the pulping and bleaching process. On the other hand, the production of e-readers is based on non-renewable materials. In addition, their use requires electricity and access to internet and data centres, which are also energy hungry. Although the estimates differ, the number of books read is the key element in deciding whether paper books or e-readers are preferable. As the environmental cost of an e-reader is largely a fixed cost related to its production<sup>24</sup>, the higher the number of books read in the reader, the lower the average environmental cost of each book and the better the comparison between e-books and paper books in favour of the former. The comparison also depends on the number of persons reading the physical books. From a Life Cycle Assessment, LCA, according to some estimates, e-readers produce 168 kilograms of CO<sub>2</sub> compared to 7.5 for a paper book (LaMonica, 2009). This result is like the estimate made by Hedgehog Company (2021) according to which buying and reading 120 paper books (2 books per month for 5 years) results in GHG emissions of 153 kg, compared to 52.3 kg in the case of eBooks on a e-reader. The breaking point in favour of e-readers is 25 books in 5 years, under this number paper books have lower environmental impact, while over 25, e-readers do. The analysis of Moberg et al (2011) also emphasises the role of the number of books read (and the number of people reading each book). According to their calculus eBooks require 71% less energy use per book, suggesting an energy break-even point of 20 books during the e-reader's lifetime, or 40 if paper books are read by two persons.<sup>25</sup> Other LCA concluded later in time, such as the one by Amasawa et al (2018) concluded a much lower threshold of advantage of e-reader vis a vis paper books (4.7 books per year and a use of less than 10 hours per day; 9 books and 1,6 hours/day for tablets) largely because it assumes advances in the production of e-books that allow now lower GHG emissions. All in all, the available estimates tend to favour the use of e-readers from an environmental perspective, with potential energy saving around 70%-80%, although this result is largely sensitive to

<sup>24</sup> According to Moberg et al. 2011 as much as 95 % of the environmental impact of E-readers is explained by the production of the device. This is especially true if renewable energy is (mostly) used when charging the device.

<sup>25</sup> For a review of the environmental impact of e-readers versus paper books see, for example, Jeswani and Azapagic, 2015, or Court and Sorrell (2020)



assumptions regarding the type of book (paperback vs hardcover), the number of books read per year, the number of person reading the same paper book, the efficiency of the electronic reading divide (e-reader vs tablet, or E-Paper displays vs traditional screens), the life span of the electronic device (more than 3 years) or even the number of trips to the bookstore and the mean of transport used (Court and Sorrell, 2020).

Although a completely different market, physical newspapers have also been affected by the digital revolution and internet. Taking US as example, the total estimated circulation of US daily newspapers (print and digital combined) reached a maximum of 63 million in the 1970's and 1980's, starting since the early 1990's a slow reduction until an estimated circulation of 21 million in 2020 (Pew Research Center, 2023). There are no data to gauge the share of digital audience, but the top 50 U.S. daily newspapers had the fourth quarter of 2022 an average of 8.8 million monthly unique visitors (with an average visit of 1,5 minutes, down from 2,6 in 2014) and 21% of consumers pay for online news content in 2022 (compared to 39% in Norway, 13% in Spain or 9% in the UK)<sup>26</sup>. Digital newspaper revenue coming from digital advertising was in 2022 48% of total. In contrast with books, all these data shows that there has been a radical move toward digital news and digital papers, as the disappearance of news stand in our cities show.

There are several papers that estimate the environmental impact of traditional newspapers compared to digital newspapers, unfortunately none of them recent. The problem with most of these estimates is that they were published, at least, more than a decade ago, and their results depend largely in the type of device used for reading the digital press, with a lower energy efficiency that the devices used today<sup>27</sup>. In this regard, in an interesting paper taking the UK paper *The Guardian* as a case study, Wood et al. (2014) highlight that the GHG emissions associated with Guardian website amounted to nearly one third of the total footprint of the parent company, and that 3/4 of the online footprint derived from the electricity consumed by consumer devices. In any case, in the review of these probably outdated papers, Court and Sorrell (2020) conclude that the literature suggests that e-news has the potential to reduce energy use and emissions (up to 70% in some cases), largely because it displaces energy-intensive paper production and printing. However, this literature is based on the assumption of substitution of paper by digital press, whereas there is evidence that what is happening is an increase in the consumption of digital news from very different sources, from the tradition digital newspaper to new forms of communication such as tik-tok.<sup>28</sup> In fact, as we can see in Figure 14, in addition to the movement from the written (printed) press to the online press, there has been a movement from the press as a source of information to social media and video platforms. This movement is particularly strong among young people, making social media platform the preferred source of news for the 15-24 age cohort. Overall, according to the Global Web Index, the daily time spent on social networking by internet users worldwide increased from 90 minutes in 2012 to 143 minutes in 2024.<sup>29</sup>

Thus, the relevant question is probably not so much whether digital news are more energy and resource efficient than traditional paper news, but rather the environmental impact of the new digital information channels, which, according to the available data, are used much more intensively, especially by younger cohorts.

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<sup>26</sup> Redline (2024) US Newspaper Industry Statistics, <https://redline.digital/us-newspapers-statistics/>

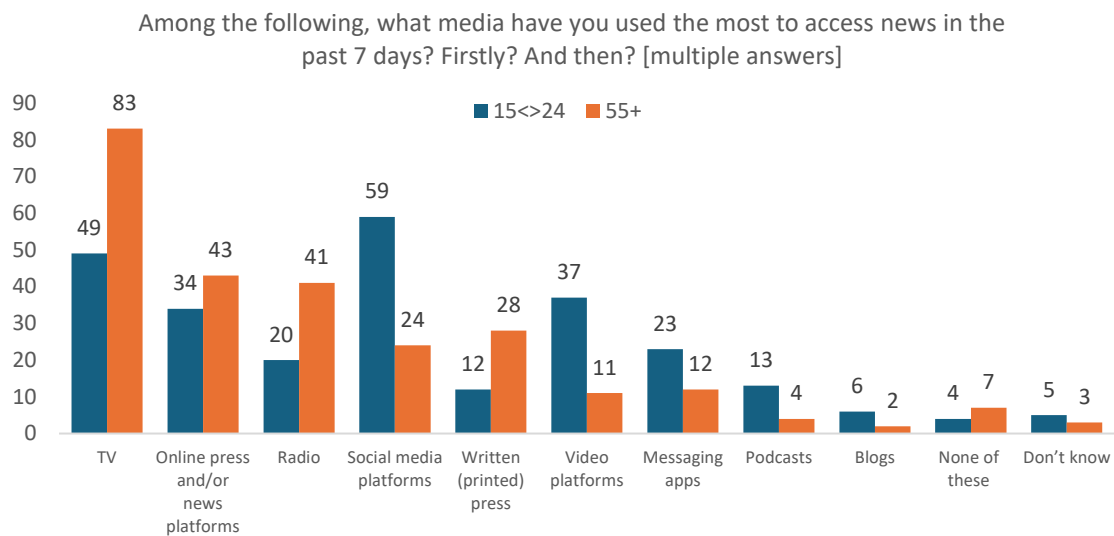
<sup>27</sup> The 2000 Pentium 4 drew approximately 63 watts during idle and nearly 100 watts under maximum load, the 2017 Intel Core i9 10900K draw 33 watts during idle and around 500 watts under maximum load. In the new 2024 Intel Core 15 (Arrow Lake-S) the last figure is reduced to 333 watts.

<sup>28</sup> Average users spend 58 minutes on the TikTok (compared to 27 in 2019), and 22% of US teenagers spend 2-3 hours a day on TikTok, Duarte (2024). According to the analysis of Ammar (2023), Tiktok is the social app with highest GHG emission per minute (0,96gEqCO<sub>2</sub>/min).

<sup>29</sup> An updated global perspective on the role played by digital news can be found in the Reuters Institute Digital News Report 2024 (Newman et al., 2024)

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Figure 14. Use by age of media to access news in the EU, 2023.

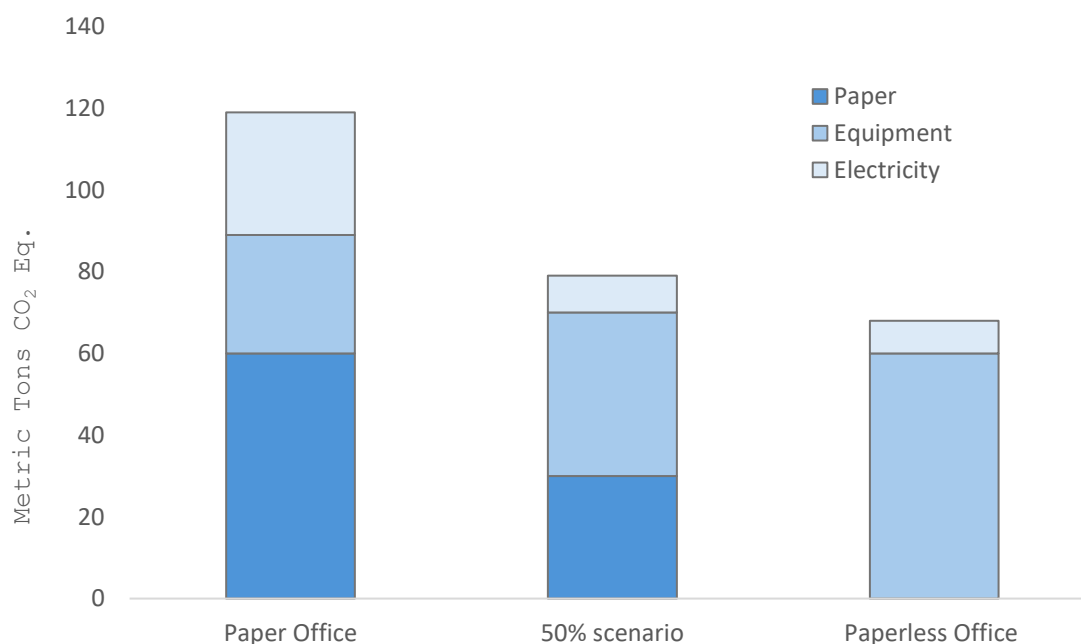


Source: Author's analysis from Flash Eurobarometer FL012EP, Q2ab

We cannot conclude this subsection without at least mentioning another area where paper has been (at least partially) replaced by electronic documents: the office. There are two main drivers for the so-called "paperless" office. The first, common to the changes explored above, is to reduce the use of a resource-intensive good such as paper, a source of pollution in its production and disposal (paper and cardboard account for 17% of global waste, 25% in high-income countries, Kaza, 2019). Second, the space required to archive paper and the complexity of managing large numbers of documents, including their destruction). As explained by Bock (2022), the paperless office started with the development of word processors, spreadsheets and PCs in the early 1980s and evolved with the internet, client-server networks and the development of cloud computing. The goal was to replace paper documents with electronic ones. Several decades later, there are trillions of digital documents, but that doesn't mean the use of paper has diminished. According to Officer Dasher (2023), global paper consumption has increased by 400% in the last 40 years. The average American office worker prints about 31 pages a day, 45% of which is thrown away at the end of the day. In 2002 the Bank of America had 90,000 printers, with desktop printing costs ranging from \$70 million to \$90 million \$ per year. In 2010 the Standard Chartered Bank in China estimated the cost of paper consumption (including printing) to be in \$3 million per year, Shah et al. (2021). Interestingly, printers are energy-intensive devices. In fact, the opposite of a paperless office is an office with computers and printers, not a 1950's office with lots of paper and typewriters.

The paperless office seems like an elusive goal, a moving target. This doesn't mean that achieving a paperless office, or perhaps more realistically a low paper use office, would save resources, especially considering that many of the digital resources needed to achieve such a goal will still be used for other purposes. Figure 15 reproduces the simulations of Kim et al. (2021) with LCA methodology of the impact of paper use on global warming in 3 different scenarios: paper office, 50% paper use and paperless office. As we can see, both alternative scenarios to the paper office are associated with lower global warming potential. The counter-intuitive higher electricity consumption in the paper office scenario is explained by the more intensive use of printers in this case.

Figure 15. Global Warming Potential of 3 Scenarios of Office Paper Use.



Source: Kim et al. (2021).

The concluding words of Court and Sorrell (2020) of their survey on e-business, the term they use for what we have called in these pages the paperless office suits perfectly the current understanding of the potentiality of the substitution of paper by digital communications: “these studies suggest the potential for large energy savings from e-business, but only if it substitutes for rather than complements the paper alternative”(p.20) which, as we have seen, often is not the case for different reasons such as the ease provided by digital systems to print on demand, and the advantage of paper when it comes to taking side notes or studying<sup>30</sup>.

#### *Substitution of CD's and other devices of listening to music streaming.*

In 1982 the first CD, jointly developed jointly by Philips and Sony, was produced in Germany, and this new type of music medium quickly replaced the rest of the other systems in use (mainly cassettes and vinyl). According to the Recording Industry Association of America's US Music Revenue Database, in 2023, CD album sales in the United States accounted for 3.1% of total revenues (down from 95% in 2002-3), even behind the revenues of LPs, 7,9%, which have made a comeback. In contrast, paid subscription (59,3%) and other forms of on-demand streaming accounted for 84% of recorded music revenues. We can therefore say that in this sector, which is the paradigmatic example of the dematerialisation of goods, there has been a perfect substitution of physical goods by digital goods.

But even though streaming music is the quintessential virtual good, that doesn't mean it doesn't use resources. The music is stored on power-hungry, active cooling servers, and every time music is streamed online, the track has to be retrieved and sent over the network to a router to be delivered to the device used to listen to it. And this has to happen every time we listen to a particular song. So the environmental impact of streaming music is multiplied by the number of times we listen to a track. In contrast, the environmental impact of a CD or LP (or downloaded music stored on our computer) is independent of the number of times we listen to it (if we exclude the energy used by the audio device).

<sup>30</sup> According to the meta-analysis of Altamura (2022) leisure digital reading does not seem to pay off in terms of reading comprehension, at least, as much as traditional print reading does. In the context of undergraduate learning, Senthuran et al. (2023) conclude that studying with e-books compared to print books is related with lower exam performance and retention.

In fact, according to estimates by George and McKay (2019), "streaming an album over the internet more than 27 times is likely to use more energy than it takes to produce and manufacture the same CD". Moreover, as emphasised by Court and Sorrell (2020), streaming is cheaper than previous formats or music 'containers' and makes it possible to reach a much wider range of music, so it could stimulate music consumption and therefore energy consumption, offsetting the reduction in environmental impact per track.

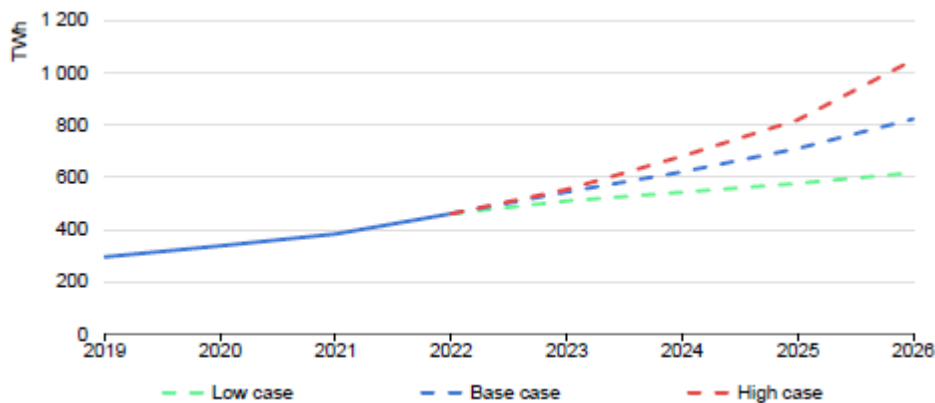
## **5. A look at the energy and resource demands of the digital transition.**

At various points in the previous section, the narrative has referred to the high energy demands of areas of the digital revolution that should also act as a lever for the energy transition. If this were the case, the digital transformation would both contribute to foster and hinder the energy transition. In this section we will present the existing evidence on the energy needs of some of the core elements of the digital revolution, such as cloud computing or AI. In addition to energy needs, the chapter also examines the important issue of the disposal and recycling of the digital waste.

### *5.1. Energy and water demand of digital technologies.*

As mentioned by the IEA (2017), digital technologies have contributed to the improvement of energy systems for decades. In fact, power utilities were digital pioneers, using IT to facilitate management and operation of the grid. But digital technologies are also important factors on the energy demand side. According to the IEA (2024c), in 2022 data centres, cryptocurrencies, and artificial intelligence (AI) consumed an estimated 460 terawatt-hours (TWh), around 2% of total energy demand. As we can see in figure 16, in just two years' time, according to IEA forecast, global electricity consumption of data centres, cryptocurrencies and artificial intelligence could range between 620 (low case) and 1 050 TWh (high case), with the base case reaching over 800 TWh, i.e., an increase of 74% in just four years. To put these numbers in context, the forecast energy consumption in high case scenario is equivalent to the yearly energy consumption of Germany plus France and Sweden in 2023. However, considering the fast increase of development of generative AI, and its intensive use of energy, it is probable that this forecast would result overoptimistic.

*Figure 16: Global electricity demand from data centres, AI, and cryptocurrencies, 2019-2026*



Source: IEA (2024c), p. 31

This subsection reviews the available information on the energy and water demand of cryptocurrencies, cloud computing and storage, and AI. Before proceeding, it's important to stress that the existence of ICT sectors, such as those mentioned above, with high and increasing energy consumption does not per se imply that the digital economy is a net contributor to global warming and has a negative impact on the green transition. These negative impacts need to be weighed against its (actual or potential) positive contributions, some of which were explored in section 4. The problem we face in attempting such an

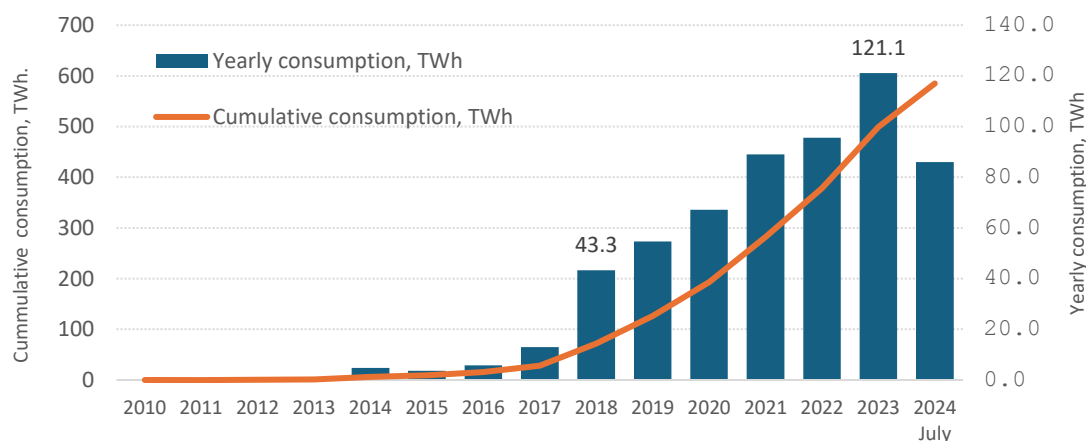
exercise, in calculating the net effect, is that while the downside is reasonably visible and measurable, the upside is much more dispersed, fractional and fuzzy. We will begin our review with an analysis of the environmental impact of cryptocurrencies.

### 5.1.1. Environmental impact of cryptocurrencies.

In 2008, Satoshi Nakamoto, a still unknown person or group of people, published a white paper entitled "Bitcoin: A Peer-to-Peer Electronic Cash System", arguing the need for a pure peer-to-peer version of electronic cash that would "allow online payments to be sent directly from one party to another without going through a financial institution (...) an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party". The following year, version 0.1 of the Bitcoin software was released and Bitcoin, the first and most important cryptocurrency to date, began its journey. Other cryptocurrencies were created in the wake of bitcoin, hundreds of them, although two of them, Bitcoin and Ethereum, dominate the market. Explaining the complexities of cryptocurrencies is beyond the scope of this paper. For the purposes of this section, it is enough to know that the technology behind digital currencies, especially in the case of the jewel in the crown, Bitcoin, is based on the principle that all transactions are verified by a double-layer system that makes it impossible to counterfeit or double-spend cryptocurrencies. As a decentralised system, it often involves thousands of computers competing against each other to verify transactions on a decentralised blockchain ledger.<sup>31</sup> In addition, most cryptocurrencies (and Bitcoin is one of them) use a proof of work method to create new cryptocurrencies. This activity is known in the jargon as mining. Crypto miners add blocks of transactions to a blockchain by solving complex cryptographic puzzles that require significant computing power (EIA, 2024).<sup>32</sup>

This process, based on using enormous quantities of computing power, is associated with growing needs of energy. As can be seen in Figure 17, that shows the estimates made by the Cambridge Centre for Alternative Finance for the Cambridge Bitcoin Electricity Consumption Index 2010-2024 (July),<sup>33</sup> since the start of the project there has been a huge increase in energy consumption.

Figure 17. Cambridge Bitcoin Electricity Consumption Index 2010-2024



Source: Authors analysis of Cambridge Centre for Alternative Finance data

<sup>31</sup> In January 2024, there were 900 Bitcoins mined daily, resulting in 6.25 Bitcoins paid to a miner every 10 minutes, worth upwards of \$250,000 at current market rates for each block validated. (just Energy, 2024)

<sup>32</sup> Ethereum uses a different mining technology, known as *proof of stake*, that requires less computational power, and so, less energy. In this case, to validate transactions and add new blocks to the blockchain, participants stake a portion of the blockchain's native tokens as collateral. These validators are rewarded if the transaction is completed successfully or penalized if attempting to perform illegitimate activity (eia, 2024). In September 2022 Ethereum modified the underlying structure of its mining software reducing dramatically its energy requirements (De Vries, 2022)

<sup>33</sup> For the methodology used see <https://ccaf.io/cbnsi/cbeci/methodology>

All in all, the authors of the index estimate the use of energy of bitcoins in 0.6% of world energy consumption. To better gauge the intensity of the energy consumed in the process, Table 7 gathers several examples of the equivalent of the total annualized Bitcoin carbon footprint, electrical and freshwater consumption and electronic waste and the footprint of a single Bitcoin transaction taken from Digieconomist, a blog and website created by Alex de Vries with the aim of exposing the unintended consequences of digital trends. As we can see, to mention only some of the example, the carbon footprint of a single Bitcoin transaction is equivalent to nearly 1 million of VISA transactions, while the electronic waste generated in a year by Bitcoin is estimated to be equivalent to the small IT equipment of the Netherlands. The same source also compares Bitcoins with gold mining, as often cryptocurrencies have been compared to gold: “Bitcoin is the new gold” (Allen, 2022), among other things because there is a finite amount of coins available to be mined (21 million bitcoins). The results are telling as the carbon intensity of mining Bitcoins is higher than the carbon intensity of gold mining: the carbon footprint of one Bitcoin’ worth of gold mined is less than 4% of the carbon footprint of one Bitcoin (including fees)<sup>34</sup>.

*Table 7. Comparison of environmental impact of Bitcoin with other economic activities.*

Annualized Total Bitcoin Footprints	
Carbon Footprint	96.08 Mt CO <sub>2</sub> : Comparable to the carbon footprint of Uzbekistan
Electrical Energy	172.26 TWh: Comparable to the power consumption of Poland
Electronic Waste	Comparable to the small IT equipment waste of the Netherlands
Fresh Water Consumption	2,715 GL: Comparable to the total water use of Switzerland
Single Bitcoin Transaction Footprints	
Carbon footprint	432.25 kgCO <sub>2</sub> : Equivalent to the carbon footprint of 958,022 VISA transactions
Electronic Waste	47.30 grams: Equivalent to the weight of 0.29 iPhones 12 or 0.10 iPads.
Fresh Water Consumption	12,214 litres: equivalent to the amount of water consumed per capita in Spain in 3 months. **
Electrical Energy	774.98 kWh: Equivalent to the power consumption of an average Spanish household over 2,8 months. *

\* Red Eléctrica Española (REE), \*\* Spanish National Statistical Institute, INE.

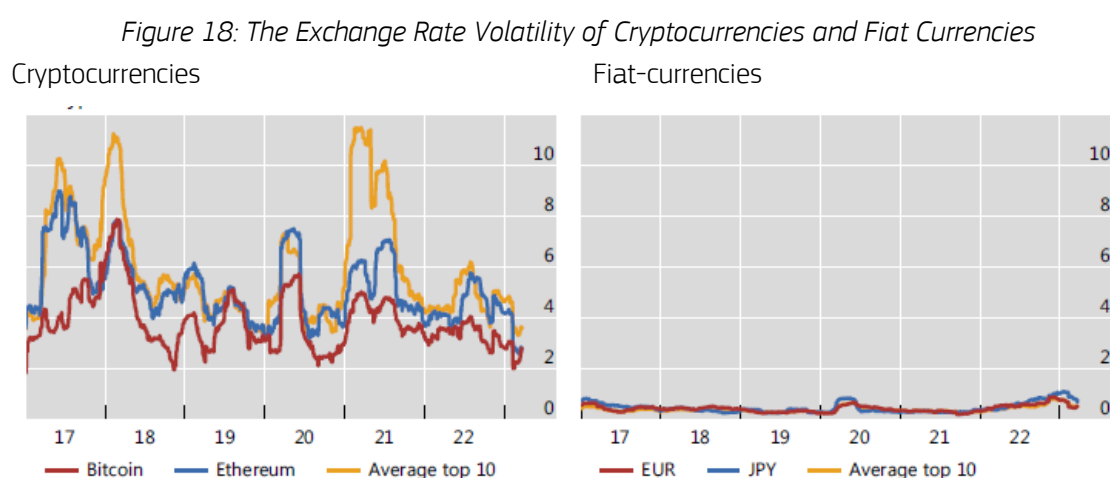
Source: Author’s elaboration from Digieconomist’s Bitcoin Energy Consumption Index. <https://digieconomist.net/bitcoin-energy-consumption>

However, as mentioned in the introduction to this section, the higher or lower energy consumption of a given production process, good or service, based on digital technologies must be considered together with the usefulness of what is produced by such technology. It is from this perspective that we can have a better view of the overall environmental impact. In this regard, if according to its developer, the purpose of Bitcoin was to create an online payment system without going through a financial institution, the results are not very encouraging. In 2022 cryptocurrencies and stable coins are used in less than 0.2 per percent of global e-commerce transactions (in value terms). In the same line, according to a survey of central banks conducted by Statista in December 2022, cryptocurrencies and stable coins (a cryptocurrency designed to have a stable price) are hardly used in regular payment transactions (De

<sup>34</sup> See <https://digieconomist.net/bitcoin-energy-consumption>

Best, 2024). The results of the Reserve Bank of Australia's triennial survey of payment methods point in the same direction, with cryptocurrencies used by no more than 2% of the adult population (although more than 60% had heard of them). Similar results were found by the US Federal Reserve (2%) and even lower by the Swedish Riksbank (1%) (Hawkins, 2023). This conclusion also applies to a country, El Salvador, whose president, Bukele, made bitcoin legal tender in 2021. Two years later, according to a survey conducted by the Public Opinion Institute of the University of Central America, 88% of Salvadorans did not use it, only 1% of remittances were sent in bitcoin (25% of Salvadorans live abroad) (Kinosian and Renteria, 2024), and only 1/5 of businesses accepted bitcoins. Furthermore, among this relatively small group of firms, only 11% had positive sales in bitcoins and only 5% of sales were paid in bitcoins. This meagre result was obtained even after offering a \$30 incentive to people who downloaded the Chivo wallet, a digital wallet that allows users to convert bitcoin into dollars and vice versa without a fee (Alvarez et al., 2023).

The high volatility of cryptocurrencies compared to traditional fiat money (see Figure 18) explains the low use of cryptocurrencies compared to other payment methods.



Note: (a) Top 10 cryptocurrencies by market capitalization for which the share of inactive coins was available on coinmetrics.io as of end-2016: BTC, ETH, LTC, XRP, ETC, DASH, MAID, ETC, REP and DOGE.

(b) Top 10 fiat-currencies by FX turnover based on BIS Triennial Survey 2016: EUR, JPY, GBP, CNY, AUD, CAD, CHF, HKD, SGD and SEK.

Source: Garrat and van Oordt (2023), p. 2

In fact, according to a report about people holding cryptoassets in the UK (multiple answers allowed), 52% of people said that the reason for holding cryptoassets was *fun investment*, which probably can be understood in terms of gambling (Hawkins, 2023), and for another 8% the reason was straightforward gambling. For the rest, 32% said it was out of *interest in the underlying technology*, 19% as an *investment*, and 18% to *buy goods and services* (Fearn and Saunders, 2022). In this context, the question is whether the environmental costs of cryptocurrencies are justified by simply having another speculative financial instrument and another way to gamble. Moreover, a gambling instrument without the stigma of gambling and with the allure of technological hype. Probably not. Moreover, according to Europol, cryptocurrencies are increasingly being used as part of criminal activities and to launder criminal proceeds. A study by Foley et al. (2019), based in the analysis of a blockchain dataset containing almost 220 million Bitcoin transactions between 2009 and 2017, concluded that around \$76 billion of illegal activity per year involve Bitcoin (46% of bitcoin transactions).

But there are more environmental impacts of crypto mining, as the high energy consumption of cryptocurrencies requires large amounts of water, both directly and indirectly. Directly, for cooling and humidification of the bitcoin servers, some of which is not available for reuse due to evaporation. Indirectly, as a result of the water consumption of the energy systems used to generate the electricity used by the mining companies. According to De Vriers (2023), the total water consumption of US Bitcoin miners in 2023 is in the range of 93-120 gigalitres (most of it from indirect use), equivalent to the annual water



consumption of a city like Washington D.C. Globally, the water footprint of bitcoin in 2023 "could be 2237 GL" (De Vries, 2023, p. 1), an increase of 278% in three years.

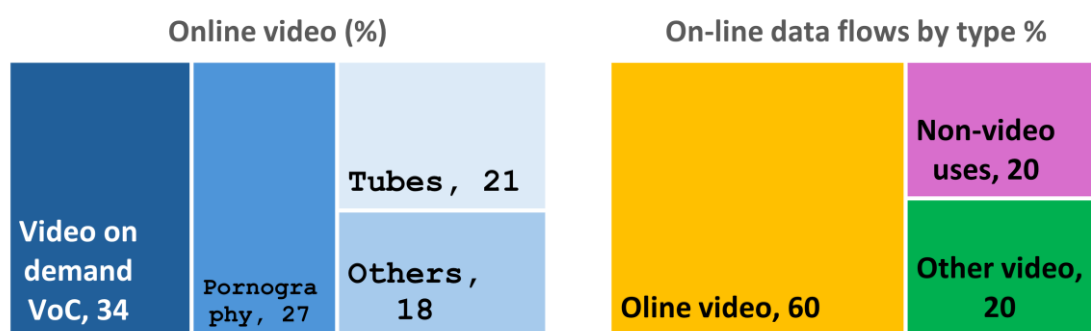
— 5.1.2. Environmental impact of data cloud computing and data storage.

Nothing could be more misleading than to call the myriad of things that make remote computing and data storage possible (the coils of coaxial cable, fibre optic cables, mobile phone networks, air conditioners, power distribution units, transformers, water pipes, computer servers, etc.) the "cloud". Borrowing the title of a working paper by MIT anthropologist Steven Gonzalez Monserrate (2022), "the cloud is material".

And this materiality is growing rapidly as a result of the rapidly increasing rate of data creation associated with new consumption and production patterns. To take just one example, Rise Above Research expects the number of photos taken worldwide to reach around 1.8 trillion by 2023, an increase of 10%. They expect this trend to continue at a linear rate until 2028, with smartphones accounting for the majority of these photos (Lee, 2024). Photos that will largely be stored (often automatically) in the cloud. 25 years ago, in the early days of digital photography, analogue photos were not cheap, and people rationed the number of rolls they took on holiday; now, at virtually no cost, the number of photos taken has probably multiplied by the hundreds.

Photo storage on the cloud and its weight in terms of data flows comes handy as an example, but photos can't match the role played by videos in global data traffic. According to the Shift Project (Efoui-Hess, 2019), videos suppose 80% of global data flows (Figure 19), with the remaining 20% accounted by web sites, emails, instant messaging, the previously mentioned storage of photos and data, company networks, etc. Within the category of videos the author distinguishes between Online Video, 60% of total traffic, composed by video on demand, with the largest share, 34% of the category and 20% of total data traffic, pornography videos, 27% of the category and 16% of total flow of data, Tubes (videos hosted on streaming platform of various types of contents for all audiences, dominated by YouTube) and other, composed by videos hosted in social networks such as Facebook, Tik Tok, etc. The general category of other video, 20% of total traffic, include television streaming, live video, video monitoring, etc. According to the estimates of the author, GHG emissions of online videos generated more than 300 MtCO<sub>2</sub>eq, similar to the total carbon print of Spain at the time.

Figure 19. Distribution of global data traffic by type, 2018.



Source: Author's elaboration from Efoui-Hess (2019), p. 11

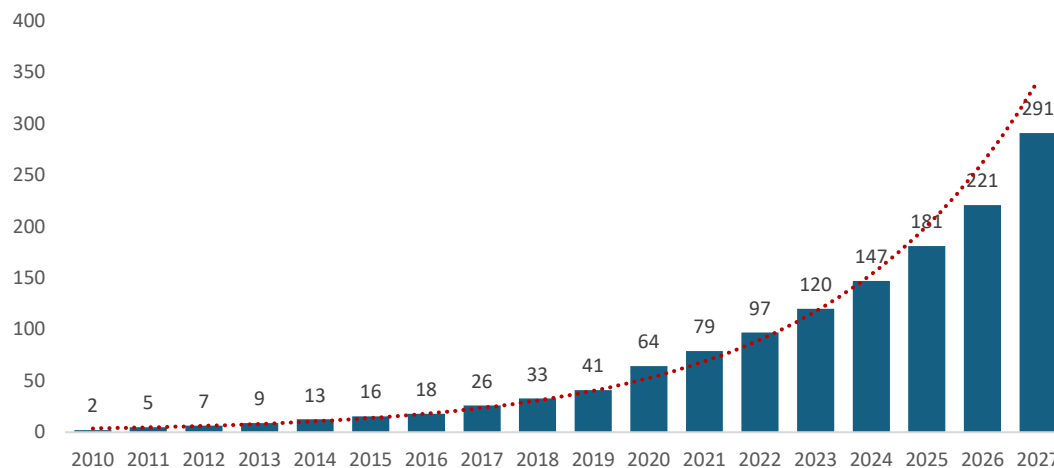
Looking now at the global picture, Figure 20 shows the estimated zettabytes, ZB, (one ZB is a trillion gigabytes) of data produced per year from 2010 to 2023 and the estimates from 2025 to 2027. As we can see, the amount of data produced has followed an almost exponential trend. And it is estimated that around 60% of corporate data is stored in the cloud (Taylor, 2024).

This explosion in data generation and the policy of companies to outsource data storage has led to the emergence and growth of cloud services in the areas of infrastructure (Infrastructure as a Service, IaaS), software (Software as a Service, SaaS) and platform (Platform as a Service). This business is highly



concentrated, with just three companies controlling 65% of the market: AWS, Azure and Google Cloud (owned by Amazon, Microsoft and Google respectively). The index of concentration of the seven largest companies of cloud services, IC7, was 79% in 2023. Overall, the global cloud computing market is estimated to be worth around \$652 billion in 2024 (and more than double that by 2029).<sup>35</sup>

*Figure 20: Zettabytes of data produced yearly, 2010-27.*



Source: Author's analysis from Statista (2010-24), IDC DataAge 2025; IDC Worldwide Global DataSphere Forecast, 2023–2027.

As the majority of global Internet Protocol, IP, traffic<sup>36</sup> travels through data centres (IEA, 2017), the increase in Internet traffic will lead to an increase in the number and size of data centres as for every bit of data that travels over the network from the data centre to the end user, another 5 bits of data are transmitted within and between data centres (Cisco, 2016). Figure 21 shows the growth in global data centre IP traffic from 2012 to 2021 by data centre type. During the period the share of traffic going through the cloud increased from 11% to 95%.

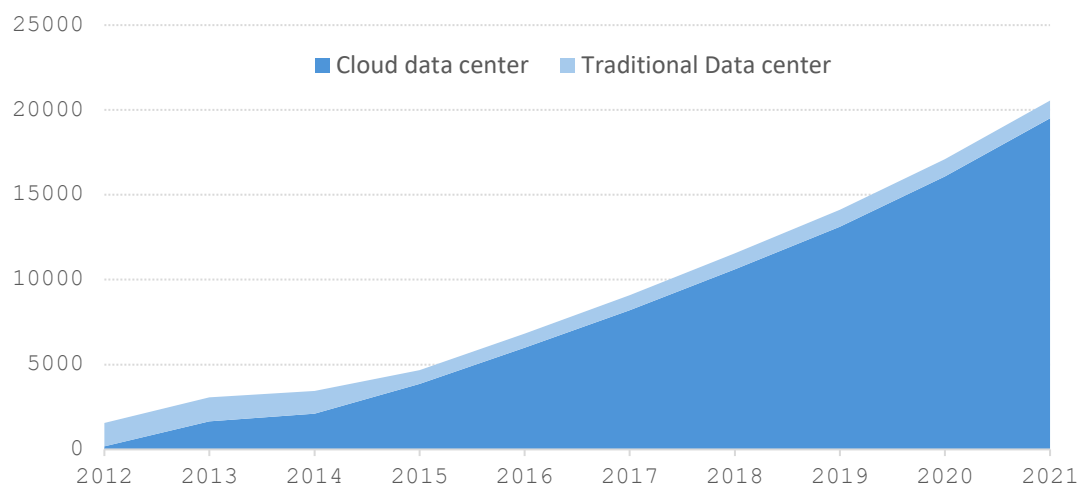
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<sup>35</sup> Precedence Research, *Cloud Computing Market Size, Share, and Trends 2024 to 2034*.

<sup>36</sup> IP traffic is IP traffic is the flow of data across the internet and includes fixed and mobile internet traffic, corporate IP wide area network, WAN, traffic, and IP transport of TV and video on demand, VoD. Cisco (2020) estimated the number of networked devices connected to IP networks in 2023 in around 29 billion,

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Figure 21. Global data centre IP traffic from 2012 to 2021, by data centre type (in exabytes per year).



Source: Statista

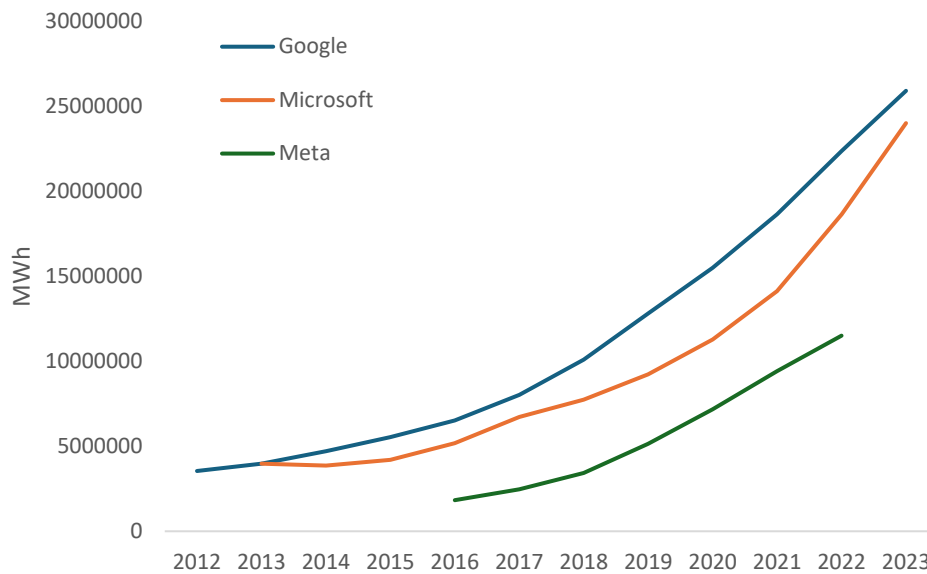
There are more than eight thousand data centres worldwide. In the US, that hosts around 1/3 of these, the use of electricity by data centres is forecasted to increase from around 4% of total electricity demand nowadays to 6% in 2026. In Europe, with around 1400 data centres (Data Center Map), the energy used by these infrastructures is also almost 4% of total energy consumed, with a consumption estimated by the IEA (2024) to grow by 50% in 2026, increasing in more than one percentage point its share of total energy demand.<sup>37</sup> In countries such as Ireland, with 71 data centres and 9 cloud service providers, a large number for a small country, the IEA (2024) estimate a doubling of energy consumption from the sector, reaching 32% of total energy demand in 2026.

Although all major cloud service providers publish environmental reports, it is not always possible to extract data on their separate business areas. In fact, for the dominant firm of the sector, AWS, there is no data on energy consumption. Interestingly, as we will see further down, there are studies available comparing the energy efficiency of AWS vis a vis on site data centres. Nevertheless, even if aggregate, the information available on the evolution of energy consumption of two major cloud providers is telling. In figure 22 we can see the evolution of total energy consumption of Google, Microsoft, and Meta<sup>38</sup> during last decade. In the three cases the magnitude of the trend is very similar, with 5-fold increases for the whole decade. In the case of Google, the amount of energy consumed is the equivalent of consumption of energy of Ireland (including the above-mentioned data centres). Combined electricity use<sup>3</sup> by Amazon, Microsoft, Google, and Meta more than doubled between 2017 and 2021, rising to around 72 TWh in 2021 (IEA,2023c)

<sup>37</sup> Palo Alto-based research organisation EPRI estimates that in its higher growth scenario, US data centre energy demand could grow from an estimated 4% of US electricity generation today to as much as 9.1% annually by 2030 (EPRI, 2024).

<sup>38</sup> Meta Environmental Sustainability Report presents desegregate information of total energy consumption and energy consumption of its data centres. For homogeneity with the other two companies, we have reproduced the data on total energy consumption, although, in this case, data centres suppose 97% of total energy consumption.

Figure 22. Total energy consumption of Google and Microsoft and Meta, 2012-2023



Source: Author's analysis from Microsoft Data Factsheet: Environmental Indicators and Google environmental report and Meta Sustainability Report. Different years

Having established the important role that data centres and cloud data services play in the growth of energy demand, there are two questions that are relevant to our analysis. The first, which is important to ask but cannot be answered in these pages, is to what extent all the data generated, managed and archived in the growing infrastructure of data centres (and the archived data it supports) is really necessary from the perspective of a world of scarce resources, and whether it contributes to our well-being. We asked the same question about cryptocurrencies, but the answer was probably simpler in that case. For those who work within the confines of neoclassical economics, this question would probably seem at the very least strange, and probably out of place and self-answering. From this perspective, *de gustibus non est disputandum*, and if something is produced in a given market and survives competition, it is because it is worth doing. But beyond the confines of neoclassical economics, and even within those confines, when there are externalities and not all costs (especially environmental costs) of production and consumption are taken into account, it is not only reasonable but necessary to ask such questions.

The second, and more specific question, relates to the role of cloud service providers compared to traditional on-premise data centres. There are two major variables that explain the high energy intensity of data centres. The first one is the energy needed to cool the servers and computing processes and other ancillary activities. The sector uses an indicator known by its acronym, PUE or Power Usage Effectiveness, defined as:

$$PUE = \frac{\text{Total energy consumption}}{\text{IT equipment energy consumption}} = 1 + \frac{\text{Non IT energy consumption}}{\text{IT equipment energy consumption}}$$

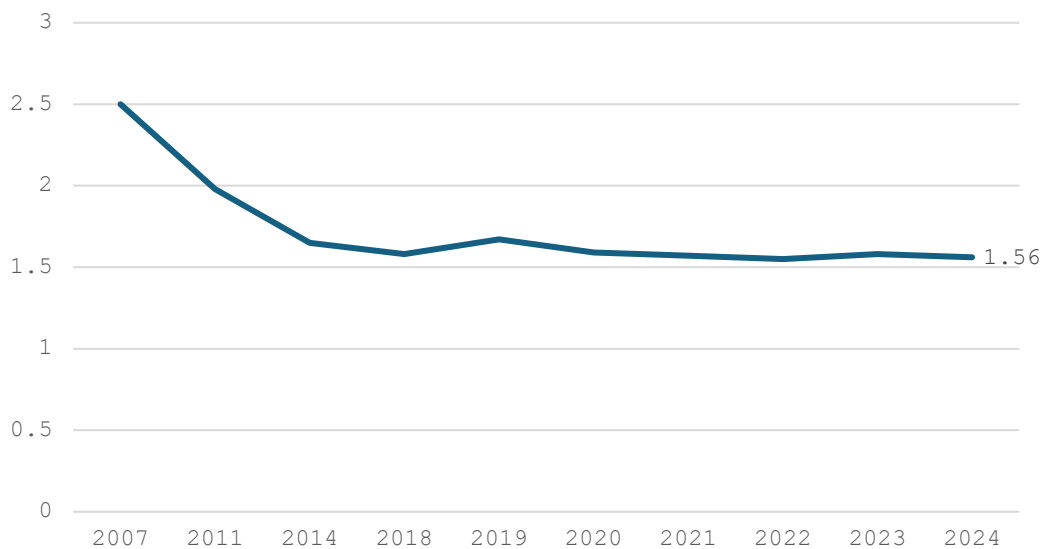
This indicator has a straight interpretation, as an indicator of 1,6 would mean that the facility spends in cooling and other non-core activities 60% of the energy consumed by the IT equipment.<sup>39</sup> As we can see in Figure 23, from 2007 to 2018 the average PUE of data centres dropped from 2.5 to around 1.5, staying around this value since then. This means that an average data centre spends 50% more energy in in cooling and other ancillary activities than in IT equipment consumption (Uptime Institute, 2023). By age of the establishment, as expected, younger establishment (6 years or less) have a lower PUE, 1.45,

<sup>39</sup> However, as argued by the program director of the US Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E), as a pure technological metric the PUE has different drawbacks, such as including the energy used by the fans of the servers in the denominator as part of the IT energy load (Schuchart, 2024)

compared to, 16.3-16.5 of establishments with 11 years or more (Bizo, 2023). According to Google, their global large scale data centres have an average PUE of 1.1. (down from 1.2 in 2008).<sup>40</sup> Meta discloses a PUE of 1.08 in 2022, down from 1.11 in 2018.<sup>41</sup> The same conclusion is reached by Upjohn (2022), that finds that larger facilities tend to have the lowest PUEs, which means they will likely be running increasingly dense, more efficient infrastructures. According to IDC (2024) public cloud data centres had an average PUE of 1.22 against 1.83 of enterprise data centres, a difference explained by their better control of location of data centres in areas that facilitate natural cooling economies of scale.

The second variable affecting energy consumption is the average utilisation rate, as data centre operators often have low levels of capacity utilisation to have room of manoeuvre in case of an increase in demand, to be able to stand the peaks of demand and possible failures if one system fails. According to IDC (2024), public cloud data centres enjoy larger capacity utilization rates compared to enterprise centres: 56% vs 47%. This implies that, for a given level of operation, large plants need fewer servers, thus less construction, cooling and less energy consumption as idle servers still consume up to 60% of their peak power draw (Meisner et al., 2009).

*Figure 23. Global Average Power Usage Effectiveness, PUE, of data centres, 2012-23: What is the average annual PUE for your largest data center?*



Source: 12th annual Uptime Institute Global Data Center Survey 2024.

We have been able to identify only a few comparative analyses of the environmental impacts of enterprise data centres and public cloud data centres. The first and oldest is the study by Masanet et al. (2013) of the prestigious Berkeley Lab, the Lawrence Berkeley National Laboratory and Northwestern University, with support from Google. The study focuses on three common applications: email, productivity software, and customer relationship management software, which at the time were used by 87, 59, and 8 million workers respectively. Their findings suggest that the potential for energy savings is significant: "If all US business users shifted their email, productivity and CRM software to the cloud, the primary energy footprint of these software applications might be reduced by as much as 87%" (p.1). The main driver of the savings is the reduction in energy consumption from the many inefficient local data centres to the more efficient cloud data centres.

The second paper, the study made by IDS (2024), also focuses on a comparative analysis of public cloud data centres compared to enterprise data centres. This time the analysis was sponsored by AWS, the main player in the cloud data centres sector. According to their findings, in 2023 public cloud data

<sup>40</sup> <https://www.google.com/about/datacenters/efficiency/>

<sup>41</sup> Meta Sustainability Report 2023, p.52

centres were 4.7 times more carbon efficient (and 3.8 times more energy efficient) than enterprise data centres. The study also predicts that this gap will widen, increasing to 7 times by 2027. This result can be explained by four different factors: (1) the different energy source of cloud data centres compared to enterprise data centres, due to the increasing reliance of the former on carbon-free energy sources (including nuclear); for example, since 2020 Meta data centres use 100% renewable energy (2023 Meta Sustainability Report) (2) more efficient (and often more modern) hardware and equipment, (3) better utilisation rates, (4) the use of more energy-efficient silicon chips. Table 8 shows the role of these differences between the two types of data centre in explaining the overall result in favour of public cloud services. It could be argued that there is a big difference between the last three areas, which represent real productivity gains of cloud platforms, and the first one, which represents the choice of platforms in favour of a specific type of energy source. Although in some cases this is closely linked to the choice of location (close to a nuclear or hydroelectric plant), in others it simply reflects the choice of provider. Something that could be perfectly replicated by corporate data centres.

*Table 8. Comparative performance of Public Cloud Data Centres and Enterprise Data Centres, 2023.*

	Enterprise Centre	Data Public Centre	Cloud Data	Difference (%)
Carbon free energy sources (%)	61	74		21,3
PUE	1,84	1,22		-33,7
Utilisation rate (%)	47	56		19,1
Carbon Usage effectiveness, CUE*	0,77	0,16		79,2

(\*) CUE = carbon emissions (kilograms of CO<sub>2</sub>) divided by IT equipment energy consumption (kilowatt hours).

Source: Author's analysis from IDC (2024) data.

A third paper, which to our knowledge was not sponsored by a cloud data provider, is the study by Park, Han and Lee (2023) on US economy-wide data from 57 industries over the period 1997-2017. Their results suggest that cloud-based IT services improve the energy efficiency of users. However, the improvement depends on the cloud service models, energy types and internal IT hardware intensity: Software-as-a-Service, SaaS, is associated with both electrical and non-electrical energy efficiency improvements across all industries, while Infrastructure-as-a-Service, IaaS, is positively associated with electrical energy efficiency only for industries with high IT hardware intensity.

Although not a comparative study, the papers by Shehabi et al. (2018) and Masanet et al. (2020), which compare the estimated evolution of global data centre energy use in the US with actual energy use over the past decade, provide some insight into whether the sector's improvements in energy efficiency have been driven by the shift of operations to the cloud, which, as noted, now accounts for 95% of total data centre workload. According to Masanet et al. (2020), the combined effect of improved server efficiency and greater server virtualisation has enabled a sixfold increase in compute instances with only a 25% increase in global server energy consumption. This improvement has been accompanied by improvements in storage drive efficiency, allowing a 25-fold increase in capacity with only a 3-fold increase in energy consumption. This trend has been made possible, according to the authors, by the shift "from smaller traditional data centres (...) to larger and more efficient cloud (including hyperscale)<sup>42</sup>

<sup>42</sup> Although there is no official definition of a hyperscale data centre, a working definition used is a facility that is 10,000 square feet or larger and hosts at least 500 servers. According to Synergy Research Group (2024), there will be over one thousand hyperscale data centres in world by 2020 (with an estimated 440 more in the pipeline). A 2016 report of the Lawrence Berkeley National Laboratory estimates that if 80% of servers in small US data centres were moved over to hyperscale facilities, in 2020 a reduction of 25% reduction in total energy demand could be achieved in 2020 compared to the Current Trends scenario (10% from server energy savings due to consolidation and 15% from infrastructure energy

data centres (...) which have much lower reported PUE values due to state-of-the-art cooling system and power supply efficiencies" (p. 985). However, while "the trend in data centre electricity use since 2000 is an energy efficiency success story", Masanet is cautious about its replicability in the future "at a rate commensurate with the ever-growing demand for digital services from these buildings" (Shehabi et al., 2018, p. 9). A feeling shared by Dale Sartor, of the Center of Expertise for Energy Efficiency in Data Centers at the US Department of Energy's Lawrence Berkeley National Laboratory in Berkeley, California who believes that the "trend is good right now, but it's questionable what it's going to look like in 5–10 years" (Jones, 2018).

Aware of the high consumption intensity of their business, all major technology companies (Google, Microsoft, AWS, etc.) have adopted renewable energy policies and, according to their own environmental sustainability reports, have managed to source their energy towards renewables. The problem is that much of this renewable energy is not supplied directly by local or nearby renewable energy producers, as the target is met through Renewable Energy Credits (RECs), which may not lead to an increase in total renewable energy (see Box 1).

So far, this sub-section has focused on the energy consumption of data centres, and on the comparative energy performance of traditional data centres vis a vis cloud service providers. The focus on energy is understandable, as GHG emissions result from the use of non-renewable energy. But data centres are also heavy users of water, which is also a scarce resource.<sup>43</sup>

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savings due to reduced server energy combined with moving servers to data centres with lower PUE values (Shehabi et al, 2016, pp. 36-7). The combination of increased use of hyperscale data centres with improved management or best practices could lead to even higher savings of 38% and 40% respectively.

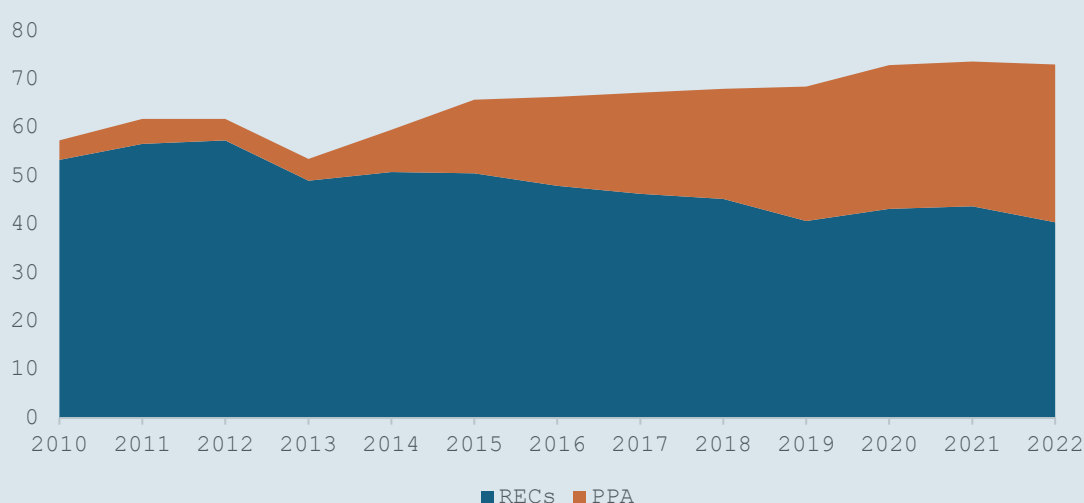
<sup>43</sup> According to UN-Water (2021) 2.3 billion people live in water-stressed countries (territories that withdraws 25% or more of its renewable freshwater resources), of which 733 million live in high and critically water-stressed countries.

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### Box 1. Renewable energy certificates and the energy transition

Renewable energy certificates, RECs, or Guarantees of origin, GOs, as they are known in Europe<sup>44</sup>, are electronic documents that certify 1MWh of electricity from renewable sources. These certificates are produced and sold by green energy producers on a REC market and are purchased by companies to offset their indirect (scope 2) greenhouse gas emissions resulting from the purchase of electricity, steam, heating and cooling for their own use. The key element of this instrument is that RECs do not guarantee that companies are buying electricity from renewable sources. What they do certify is that a utility somewhere is producing electricity from renewable sources. Only if the trading of RECs leads to increased investment in renewable energy sources will the RECs result in increased overall green energy production. On the other hand, with a price of around \$1 per MWh in 2024, RECs are a relatively cheap way for companies to meet their emissions commitments. As we can see in Figure B.1.1, although less popular than in the past, RECs are the main mechanism used by US companies to meet their emissions commitments.

Figure B.1.1 U.S. Voluntary Green Power Market: Share of RECs and PPA, 2010-2022



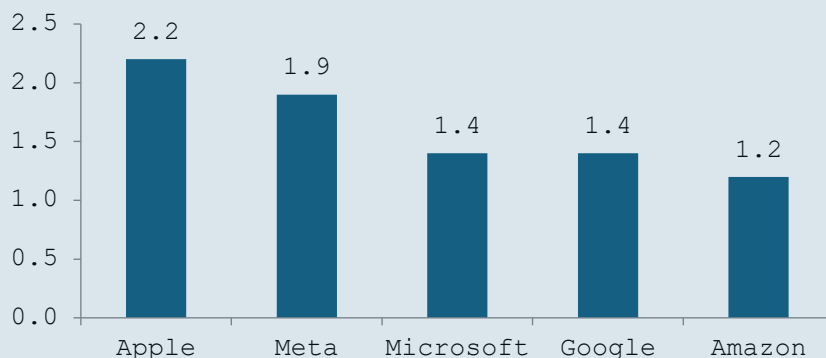
Source: author's elaboration of O'Shaughnessy (2022) data

The second most common mechanism, the Power Purchase Agreement (PPA), which is different in nature, is a long-term contract (between 5 and 20 years) between an electricity producer and a customer to purchase renewable energy at a pre-negotiated price. This mechanism is more likely to incentivise new renewable capacity than RECs.

The problem with RECs is that they can give the false impression that companies are using renewable energy in line with their own targets, when this is not necessarily the case. Figure B.1.2 shows the site-based actual emissions of five major digital companies compared with their official emissions, taking into account the RECs they have subscribed to. As we can see, RECs increase emissions by more than 100% in the case of Apple at one extreme, and by 20% in the case of Amazon at the other.

<sup>44</sup> Article 19 of the European Directive 2018/2001/EC on the promotion of the use of energy from renewable sources

Figure B.1.2 Location base actual emission/Official emissions (taking into account RECs), 2023.



Source: author's elaboration of O'Brien (2024) data.

In fact, according to the analysis of Langer et al. (2023), the impact of RECs on renewable energy production depends on the purchase terms of the RECs, as annual volumetric and annual emissions matching do not lead to significant emission reductions compared to a counterfactual without a REC market. In contrast, hourly matching (with PPAs involving local and new RES generators) leads to significant emission reductions.

A similar conclusion is reached by Bjørn et al. (2022) after examining the climate change disclosures of 115 companies, participating in the Science Based Targets initiative, which aims to align voluntary company-level emission reduction targets with the global temperature goal of the Paris Agreement (1.5 °C global mitigation). These companies reported a combined reduction in market base Scope 2 emissions of almost 31% between 2015 and 2019, most of which was obtained through the purchase of RECs. The authors estimate that without RECs, the reduction would have been only 10%. The authors conclude that: "the common voluntary corporate practice of using RECs that are unlikely to drive additional renewable energy production casts serious doubt on the veracity of reported corporate emission trajectories and their apparent alignment with the most ambitious Paris Agreement temperature goal" (p. 545)

Data centres use water at two different stages of production: indirectly in the process of generating the non-renewable (and hydroelectric) electricity used by data centres, and the electricity used, and water losses associated with the treatment of wastewater, and directly in the process of cooling the heat produced by the IT equipment. Data centres' rooms are designed to operate at 20-22°C, with higher temperatures increasing the risk of failure at a non-linear rate. The most common mechanism for cooling data centres is to reduce the air temperature using chilled water (7-11°C) as a heat transfer mechanism.<sup>45</sup> In the process water is lost through evaporation. Cooling water is the main source of energy consumption (Mytton, 2021). The intensity of water use depends on the location of the data centre (*e.g.*, AWS uses no water to cool its data centres in Ireland and Sweden for 95% of the year) and the cooling technology used.

One way to measure the intensity of water used by data centres is by the Water Usage Effectiveness, WUE, an indicator, similar to the above-mentioned PUE, that measures the water used by data centres in relation to the energy used by ICT equipment. The WUE is defined as the annual water consumption at the site divided by the energy consumption of the ICT equipment (litres/kWh). Unfortunately, of the major cloud data providers, only Meta has published this index since 2017. In 2022, Meta's WUE was 0.2, compared to 0.26-0.27 in previous years. In 2022, AWS reported a WUE of 0.25 (Miller, 2022). These indices are much lower than the average industry WUE of 1.8 reported in a study by the US Department

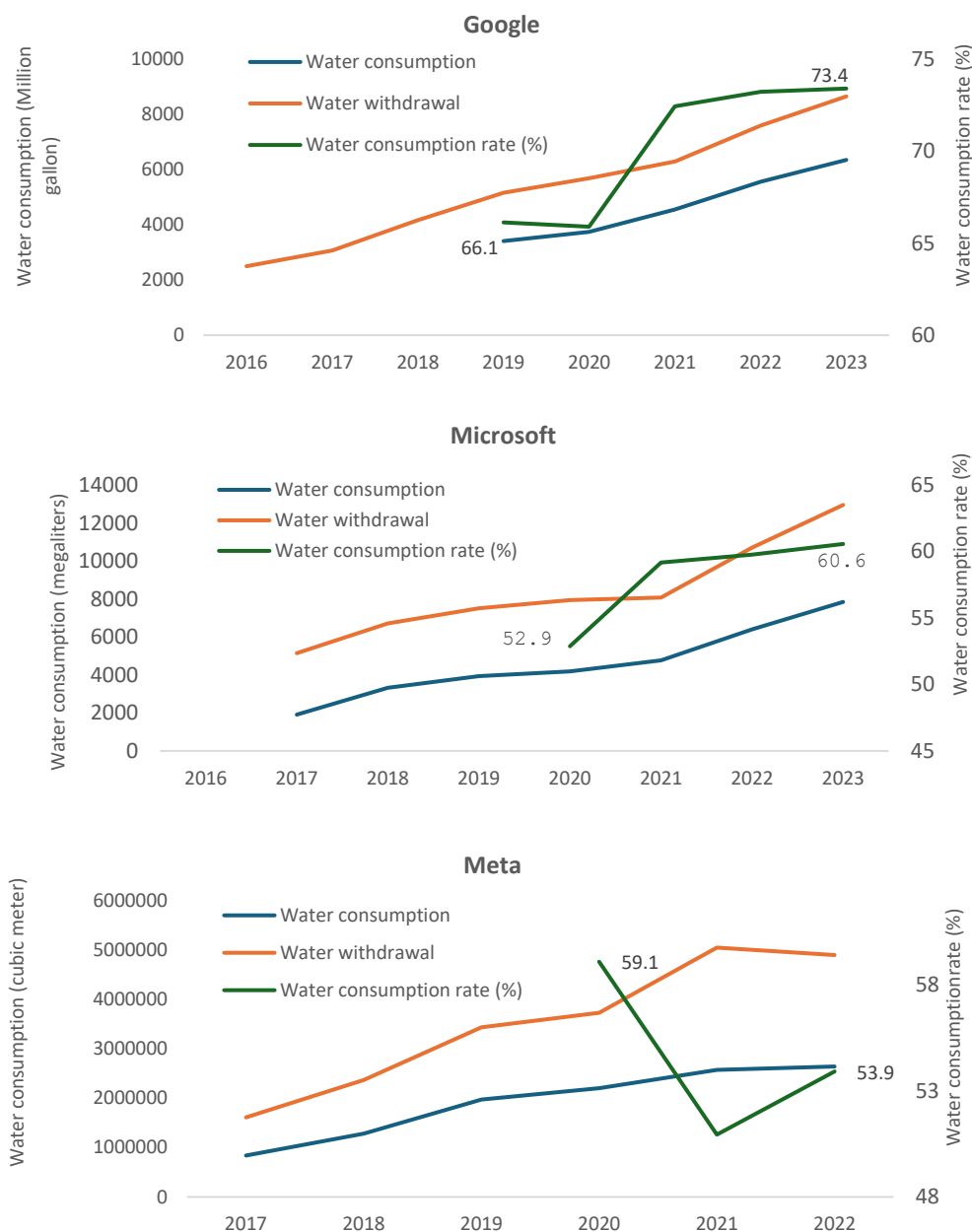
<sup>45</sup> For an introduction on the working of these cooling systems see Heslin (2016)



of Energy's Lawrence Berkeley National Laboratory (Shehabi, 2016) and around 1.55 liters per kWh for medium-to-large data centers, according to advisory firm Bluefield Research (Holger, 2022). It is important to keep in mind that this is only the direct water footprint, without considering the water used in the generation of the energy used by data centres<sup>46</sup> (not in the case of Meta that uses 100% renewable energy) and down the stream.

As shown in Figure 24, Google's, Microsoft's and Meta's water use has been increasing steadily since data has been available, as has their water use ratio, defined as water use as a percentage of total water withdrawals.

Figure 24. Water consumption data of Google, Microsoft and Meta, 2016-23



Source: Author's analysis from Microsoft Data Factsheet: Environmental Indicators and Google environmental report and Meta Sustainability Report. Different years.

<sup>46</sup> The Berkeley report also points out how the indirect water impact of data centres is much higher than its direct impact, as in the US, on average, it takes around 7.6 liters to generate 1kWh of electricity.

Of the three companies, only Meta provides disaggregated data for its data centres, which account for almost three-quarters of total water consumption. Again, around 17% of Meta's water consumption comes from water stressed areas. The overall global consumption of data centres is estimated by Bluefield Research in more than 292 million gallons per day, up from 194 million in 2015, and could jump to 450 million gallons per day by 2027 (including on-site cooling and off-site power generation) (J.P. Morgan, 2024).

In fact, concerns about the massive use of water and electricity by data centres have led the European Commission to adopt a delegated regulation on 14 March 2024 on the first phase of establishing an EU-wide scheme to assess the sustainability of EU data centres. This new regulation requires data centres with an installed IT power demand of at least 500 kW to report annually to the European database from September 2025 on key performance indicators such as total water consumption, total drinking water consumption, average waste heat temperature, how much of their energy comes from renewable sources, cooling degree days, WUE, etc. (see Annexes I-IV of the regulation). This information will be publicly available at Member State and Union level.<sup>47</sup>

### *5.1.3. Environmental impact of AI.*

AI requires huge amounts of data in the training phase, and that means huge amounts of energy and, depending on the energy mix, huge amounts of greenhouse gas emissions. The energy used in the inference (use) phase is relatively small by comparison, but the overall demand can be even greater as the number of queries increases. Unfortunately, as noted in the Artificial Intelligence Report 2024, major AI developers such as OpenAI, Google, Anthropic and Mistral don't report GHG emissions in training. In contrast, Meta does.

The race to develop AI applications, the increase in the number of parameters used in their training, and the corresponding increase in the number of computing operations used to create each of the largest AI models (currently doubling every 10 months) has led the US Senate to propose a bill, the "Artificial Intelligence Environmental Impacts Act of 2024", which would require the Administrator of the Environmental Protection Agency to conduct a study on the environmental impact of artificial intelligence.<sup>48</sup>

The energy requirements of AI models depend on the so-called parameters of the model (the numerical values learned during model training that determine how the model interprets the input data and makes predictions), the training compute (i.e. the computational resources required to train the model) and the PUE. The environmental impact in terms of GHG emissions will in turn depend on the energy mix used to power the data centres.

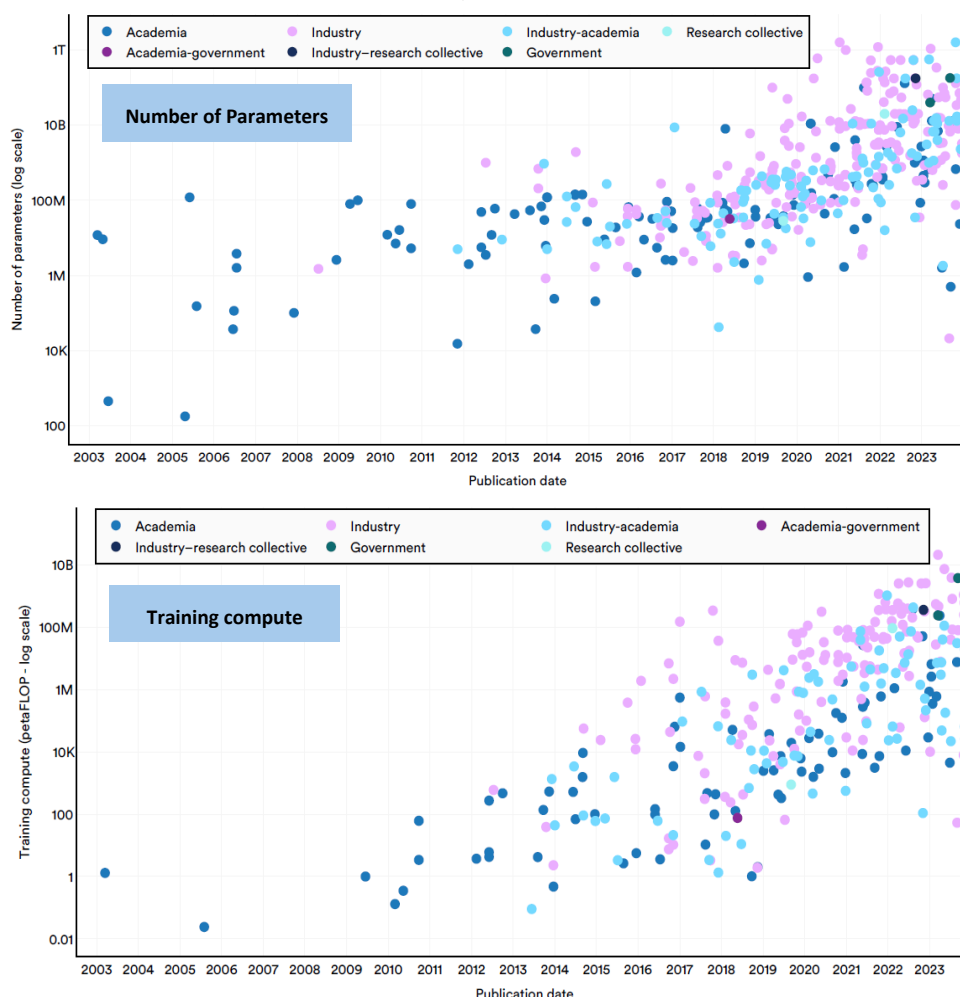
Figure 25 shows how the number of parameters and training compute of major machine learning models have increased rapidly across the sector over the last decade. In contrast, as we know from Figure 18, Power Usage Effectiveness, or PUE, has remained roughly constant.

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<sup>47</sup> The delegated regulation on the first phase of the establishment of a common Union rating scheme for data centres - C(2024) 1639 final- stems from the politically agreed text of the recast Energy Efficiency Directive (Directive 2012/27/EU), which introduces a requirement to report on the energy performance and sustainability of data centres.

<sup>48</sup> "Not later than 2 years after the date of enactment of this Act, the Administrator of the Environmental Protection Agency, in collaboration with the Secretary of Energy, the Director of the National Institute of Standards and Technology, and the Director of the Office of Science and Technology Policy, shall carry out, and submit to Congress and make publicly available a report describing the results of, a comprehensive study on the environmental impacts of artificial intelligence".

Figure 25: Number of Parameters and training compute of notable machine learning models by sector, 2003-23



Note: FLOP stands for “floating-point operation”, a single arithmetic operation involving floating-point numbers (e.g. addition, subtraction, multiplication, or division) used as indicator of computational power. Source: Stanford HAI Research (2024), p. 50.

As the US Senate initiative mentioned above illustrates, little is known about the energy requirements of AI models, although the available estimates show that there are large differences between models. For example, Meta’s Llama-2 70B model released approximately 291.2 tonnes of carbon during its training, compared to 1900 for Llama-3 70B, while OpenAI’s GPT-3 released 502 tonnes.<sup>49</sup> As mentioned above, the actual release of GHG emissions will depend on the energy mix used and the policies and existence of GHG offsetting programs by companies. In addition to the different energy requirements of the different AI models, we also know that the energy requirements of the inference phase vary depending on the tasks performed by the AI model. Table 9, which shows the energy requirements of different queries by task, is clear in this respect, with tasks related to text and image classification requiring much less energy per thousand queries than image generation, at the top.

<sup>49</sup> AI Index, 2024, p. 154, and <https://huggingface.co/meta-llama/Meta-Llama-3-70B> for Llama-3.

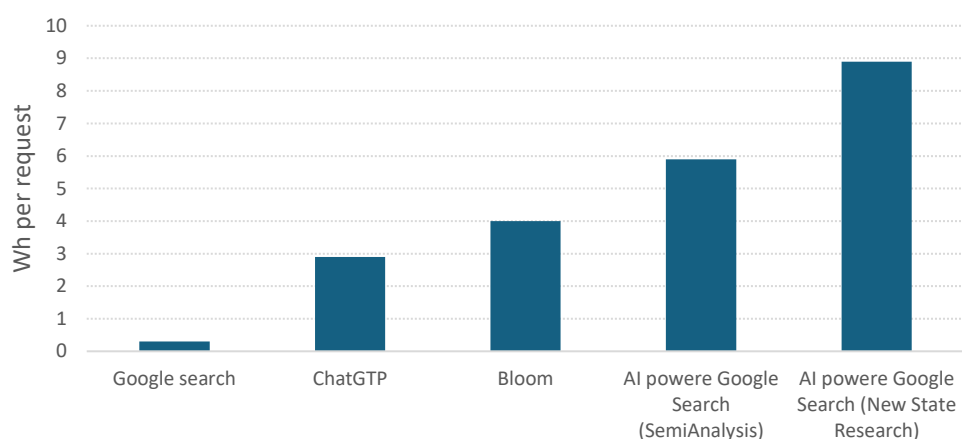
Table 9: Mean and standard deviation of energy per 1,000 queries by task

Task	Mean	Std	Task	Mean	Std
Text classification	0,002	0,001	Object detection	0,038	0,02
Extractive QA	0,003	0,001	Text generation	0,047	0,03
Masked language modelling	0,003	0,001	Summarization	0,049	0,01
Token classification	0,004	0,002	Image captioning	0,063	0,02
Image classification	0,007	0,001	Image generation	2,907	3,31

Source: Luccioni et al. (2024), p. 4.

In summary, as the authors point out, the most energy-intensive and, caeteris paribus, more environmentally damaging tasks in terms of GHG emissions are those related to generating new content, text generation, summarisation, image captioning and image generation, especially those involving images. Another interesting finding of the paper is that, for a given task, multipurpose models are more energy intensive than task-specific models. For example, according to the authors, the average emissions of a BERT-based model fine-tuned for extractive query answering a task similar to an extractive web search is 0.70g per 1,000 queries, which is less than three times that of the multipurpose models. This conclusion is very interesting as there seems to be a move away from specific AI models towards general AI models such as GPT-4. The large potential impact of using AI LLM for Internet search is also highlighted by de Vries' (2024) estimates, shown in Figure 26, of the energy consumed by a standard old-fashioned Internet search compared to a search using an application with an integrated AI LLM. Taking all this into account, it is important, as de Vries (2024) points out, to critically consider which application would benefit more from the use of AI, rather than simply making it available to all.

Figure 26: Estimated energy consumption per request for various AI-powered systems compared to a standard Google search.



Source: de Vries (2023), p. 3

Before concluding this subsection, it is important to mention that major AI developers are aware of the energy needs of this tool, as evidenced by Microsoft's 2023 document on Accelerating a Carbon-Free Future, which presents its policy on nuclear micro-reactors and small modular reactors (SMRs). Citing the IEA (2022), the company argues that advanced nuclear technologies can offer a range of generation volume options (in megawatts), reduce land and transmission requirements, closed-loop systems, and improved security and non-proliferation systems to complement renewables. From a more futuristic perspective, in 2023 Microsoft signed a contract to purchase electricity from 2028 on with a company called Helion Energy, which is developing a nuclear fusion power plant. In addition, one of Bill Gates'

companies, TerraPowers, is experimenting with a sodium nuclear reactor that, if successful, promises to be 25 times cheaper than nuclear fission (Pascual, 2024).<sup>50</sup> Similarly, AWS recently bought a data centre in Salem Township, Luzerne County, PENN, near the US's sixth largest nuclear power plant, the Susquehanna Steam Electric Station (Lewis, 2024).

Finally, it is important to mention that, as with data centres, AI training and inference use huge amount of water. As we saw in the previous subsection water is consumed by the data centers used in training the models, because of the energy used by the same data centres and in the production of the hardware used in training and inference. Leaving this last item out of the analysis, the research of Li et al. (2023) estimates that training a LLM such as GPT-3 can consume millions of litres of fresh water, and running GPT-3 inference for 10-70 queries consumes 500 millilitres of water, depending on when and where the model is hosted (e.g., 10 inferences in Washington, 30 inferences in the US average, and 70 inferences in Ireland). The Global AI water withdrawal for 2027 estimated by the authors range between 4.2 and 6.6 billion cubic meters, equivalent from 4 to 6 times the annual withdrawal of Denmark or half of the UK.

## **5.2 A comment of waste and waste management.**

So far, the analysis of the environmental implications of the digital revolution has focused exclusively on the energy and greenhouse gas impacts of the digital transition. However, there are many other environmental impacts and challenges associated with the widespread use of digital devices. Given the huge increase in the number of electrical and electronic devices used in the manufacturing process and by households,<sup>51</sup> another major environmental concern related to the digital revolution is the impact of electronic and electrical equipment (EEE) on waste, or what is known as e-waste. According to the *UN Global E-waste Monitor 2024*, 64 billion kg of e-waste will be generated worldwide in 2024, equivalent to 7.8 kg of e-waste per capita. Just over 1/5 of this e-waste (22.3%) was documented as formally collected and recycled, leaving the vast majority of e-waste outside the formal recycling loop. In fact, since 2010, the generation of e-waste has exceeded the existing recycling capacity by almost a factor of 5. Figure 27 shows how this e-waste is managed globally. As we can see, the majority of it, 18%, is handled by low and lower middle-income countries with no formal e-waste management infrastructure, mostly by the informal sector. 6% is estimated to be collected and recycled outside the formal system in high and upper middle income countries with a developed formal e-waste management structure. A further 14% is disposed of as residual waste, mostly in landfills. The remaining 13.8% is collected and recycled in an environmentally sound manner through the formal system.

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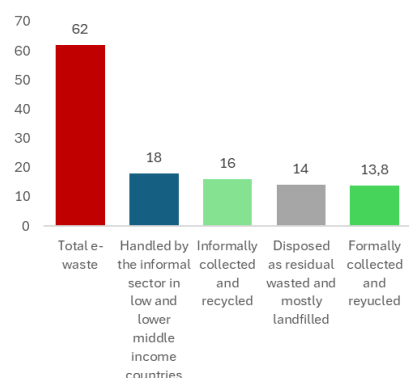
<sup>50</sup> According to TerraPower webpage, the Sodium technology will use the high-temperature heat from the reactor to power a molten salt storage system that can retain tremendous amounts of energy, much greater than the energy stored in typical battery facilities. That energy can be used to power the grid at peak demand when weather and darkness hamper renewable output. The nuclear island is expected to be ready this decade (<https://www.terrapower.com/faq/>).

<sup>51</sup> It is estimated that in high-income countries households, businesses and public sector have an average of 109 EEE items (excluding lamps). In comparison, low-income countries have 4 items (*UN Global E-waste Monitor 2024*, p. 116).

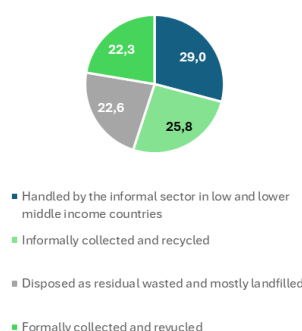
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Figure 27. Allocation of global e-waste, 2022

Billions of e-waste by allocation



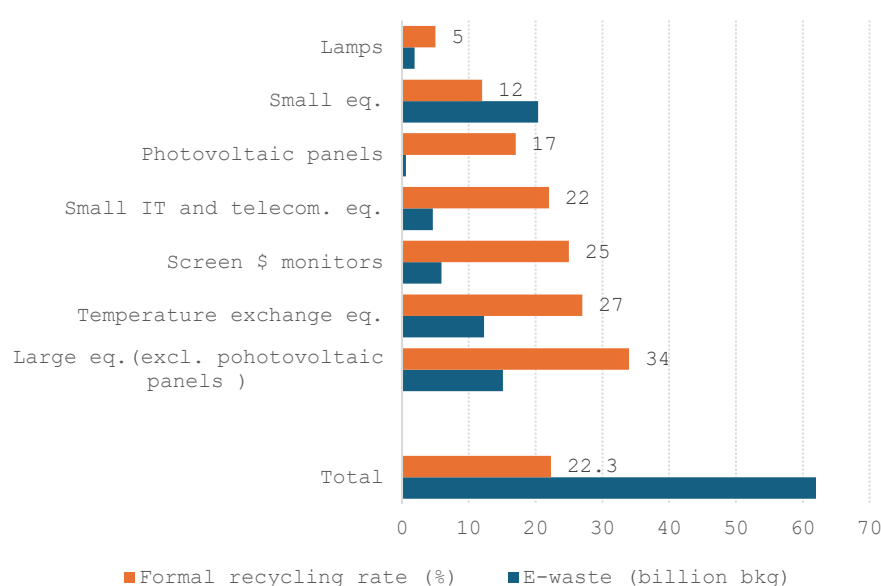
Share of total e-waste by allocation



Source: Author's analysis of UN *Global E-waste Monitor 2024* data, p.11

This e-waste consists of metals (about half of the total e-waste) and plastics (27%), with the remainder made up of other materials. Recycling rates are very low for small items such as toys, microwave ovens or vacuum cleaners, around 12% globally, and still low but higher for small IT equipment such as laptops or mobile phones, around 22%. Typically, recycling rates are higher for bulkier and heavier items such as monitors or temperature exchange equipment (Figure 28). Worth noticing is the relatively small recycling rates of photovoltaic panels of which only 17% is managed through the formal collection and recycling system.

Figure 28. Global e-waste and recycling rates (%) by product type, 2022

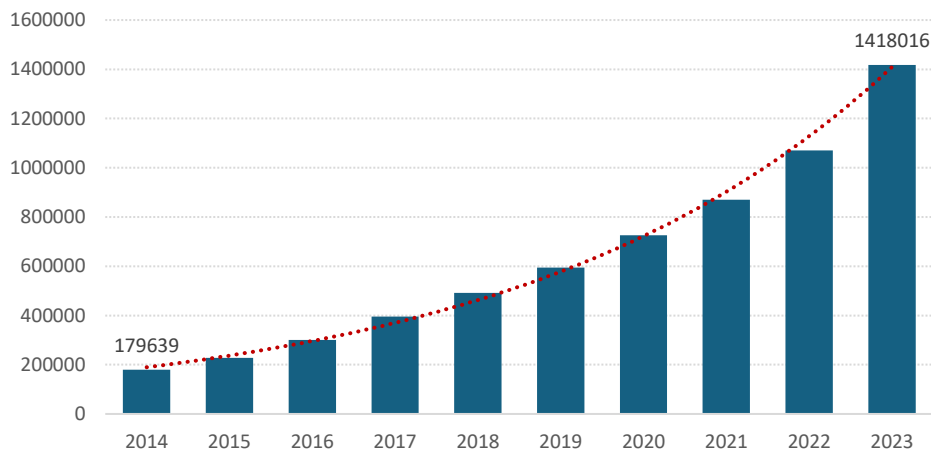


Source: Author's analysis of UN *Global E-waste Monitor 2024* data, p.11.

As expected, recycling rates are higher for high income countries. However, these are far from covering the whole array of e-waste. For example, in Europe, with a population of 742 million (around 9% of total population), that generates around 21% of total e-waste, the formal collection and recycling covers only 43% of it (58% in the case of Western Europe). In North America, with a population of 742 million (around 5% of total population) which generates 13% of total e-waste, recycling covers only 52% of it (*Global E-waste Monitor 2024*).

As we can see in figure 29, the global capacity of installed photovoltaic panels has followed an exponential path in the last decade, multiplying by 8 since 2014. Solar panels last around 25-30 years. That means in the future there will be a growing need for recycling growing quantities of solar panels at the end of their lifetime. According to the EIA (2022) supplies from recycling solar panels could meet over 20% of the solar photovoltaic, PV, industry's demand for aluminium, copper, glass, silicon and almost 70% for silver between 2040 and 2050 in the IEA's Roadmap to Net Zero Emissions by 2050. The question is whether the revenue generated by the process will cover the recycling cost. In this regard, policies to develop recycling are vital, as shown by the EU, where the share of end-of-life, EoL, solar panels being recycled is close to 95% due to the existence of specific EoL policies, such as the Directive 2012/19/EU on waste from electrical and electronic equipment (WEEE), compared to the US where the rate is less than 10%.

Figure 29. Global cumulative installed photovoltaic panels (MW), 2014-2022



Source: Authors analysis from IRENA (2024), p. 40

In 2016 the International Renewable Energy Agency, IRENA, in its report *End-of-life management: solar photovoltaic panels* estimated that by 2050 in the regular-loss scenario (duration of PV panels of 30 years) the cumulative PV waste would reach 60 million tons (and as much as 78 million in the case of early loss due to failures of PV panels before the 30 year life span). In turn, the IEA (2022) estimates that by 2050 decommissioned capacity as % would reach 25% of gross capacity additions. This makes the full deployment of PV recycle capacity a vital pillar of the energy and environmental transition.

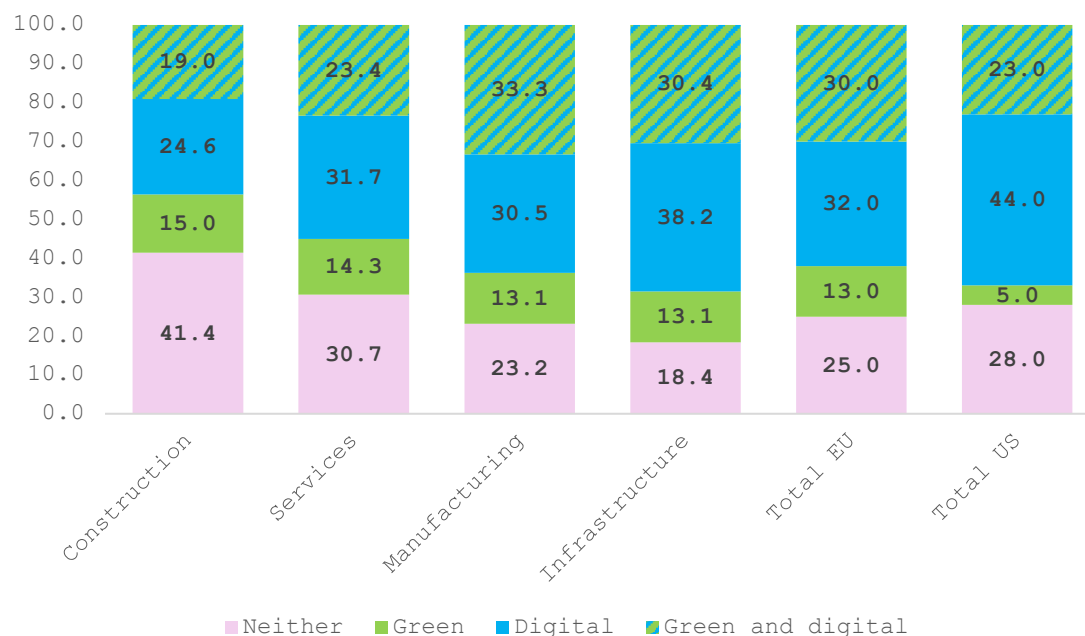
## 6. The twin transition from a business perspective: are companies making the digital and green transitions simultaneously?

To complement the review of the twin transitions, in this section we will take a purely pragmatic approach and examine, regardless of the interrelationships between the green and digital transitions, to what extent companies are approaching both processes simultaneously.

Our starting point with that aim is the European Investment Bank Survey (EIBIS, 2021) on investments on digital and green technologies by EU and US firms. Following Delanote et al. (2022) we can define four different types of firms according to whether they have already invested in addressing climate change risks on one side, and in digital technologies on the other. These two criteria result in a taxonomy of four types of firms: (1) Green firms, defined as those with investments related to climate change but not in digital technologies, (2) Digital firms, defined as those that have implemented at least one advanced digital technology but with no investment to tackle climate change, (3) Green and digital firms, defined as those with investments in both areas, and finally, (4) firms that have not invested in either area, or “Neither” firms. Figure 30 shows the distribution of enterprises according to this taxonomy in EU and the US and in four main economic activities: Construction, Services, Manufacturing and

Infrastructure. According to the EIBS, digital firms are much more common than Green firms in both the US and the EU, although Green firms at 13% of all firms, are more common in the EU than in the US (5%). Some 30% of EU firms can be considered as Green and digital, compared with only 23% in the US.

Figure 30: Green and digital profile of EU (total and by sector of economic activity) and US firms.



Fuente: Delanote et al. (2022), p. 738 and EIBIS (2021).

There are significant differences by sector of activity: 1/3 of EU manufacturing firms can be considered as green and digital compared to 19% in construction or 23% in services. Important differences are also found in terms of firm size, as 41% of large EU firms meet the criteria to be considered green and digital, compared to 10% of micro firms and 15% of small firms (Delanote et al.2022, p. 737).

The EIBIS (2022) explores in more detail the interaction between green and digital investments by EU and US firms, finding that firms using advanced digital technologies are more likely to report having invested in measures to mitigate the physical risk of climate change and to reduce greenhouse gas emissions (EIB, 2023).

From a country perspective, a survey of more than 250 executives from the automotive, IT and healthcare sectors conducted by *future* in Germany found that digitalisation and sustainability go hand in hand that in 30% of firms, while 26% pursue separate strategies. For Ireland. Kren and Lawless (2024), using data of the Annual Business Survey of Economic Impact (ABSEI) covering some 4200 Irish firms in conclude that there is a strong statistically significant association between having a climate and having a digital plan, controlling for a number of other firm characteristics. On average, 17% of Irish companies had both climate and digital plans, compared to 4% with only climate plans. As in the EIBS, the proportion of large firms with both plans is much higher (48%) than for small (16%) or medium-sized firms (22%).

In Italy, Montesor and Vezzani (2022), after analysing the Permanent Census of Firms of the Italian National Statistical Office, a large sample of more than 150,000 firms, conclude that the contribution of digital technologies to the eco-innovation of firms, defined as new environmentally sustainable production processes, is mainly driven by investments in AI (big data and interactive technologies). In their own words, “it is not the digital transition across the board that appears amenable to be exploited for green, but only the specific digital technologies from which the advent of the smart factory is deemed to depend to the greatest extent” (p. 17-18). Finally, according to the authors, the probability of adopting new sustainable production processes increases with the number of digital technology areas in which a company invests.



To conclude this brief review from a country perspective, recently there has been a growing interest in research regarding the existence of the twin transition in Chinese firms. According to the summary presented in Table 10, the analysis conducted by Chinese scholars on the twin transition in Chinese firms concludes that digital transformation has a positive impact on reducing carbon emission intensity, CEI, of Chinese firms, especially when the digital transformation is applied to production processes.

*Table 10: Twin transition in Chinese firms.*

Authors	Sample	Results
Ma and Tao (2023)	Shanghai and Shenzhen A-share listed companies from 2008 to 2015	Digital transformation decreases enterprise carbon emission intensity, CEI, especially in firms located in cities without national carbon trading pilot policies and heavy industrial sectors.
Deng, Cai, and Ma (2023)	Shanghai and Shenzhen A-share listed manufacturing companies from 2013 to 2020	Positive impact of digital transformation on the CEI, of firms. CEI reduction is more significant for the energy-intensive manufacturing industry and firms facing strong environmental regulations and competition.
Tang, Lu and Tian (2023)	China world input-output database (WIOD)	The results depend on the sector as the productive input digitalization can reduce CEI, but the distributional input digitalization may increase CEI.
Wen, Lee and Song (2021)	China Industrial Enterprise Database, Enterprise Pollution Database from the Ministry of Ecology and Environment 2002 to 2012	Industrial digitalization has a significant positive impact on enterprise environmental performance by adopting front-end cleaner production technologies, rather than by increasing pipe-end pollutant treatment facilities

Source: Author's elaboration from the referenced papers

## 7. Summary and conclusions.

Summing up the narrative presented in the previous pages is certainly not an easy task. In a context of multiple and, as we have seen, often contradictory impacts of the digital transition on the green transition, it is impossible to present a simple yes/no conclusion regarding the interaction between the two. But that doesn't mean that the analysis has been in vain. Our journey through the links between the digital and green transitions allows us to present some worthwhile conclusions.

The first is that, as detailed in section 2, the green and digital transitions are processes with their own characteristics, actors, drivers and timing. The digital transition is more mature and has been mainly driven by business and markets, while the green one is still nascent and mainly driven by governments, often with a half-hearted contribution from business, if not outright opposition. The aim of the digital transition is ostensibly to enable another major increase in productivity, leading to another long wave of economic growth. The aim of the green transition is to decarbonise economic activity and reduce its environmental impact, in the hope of limiting global warming to the increasingly elusive target of 1.5 degrees. The main reason why digital technologies can contribute to the green transition is because of their ability to handle information flows. But that is not their main purpose, not in the past and not now. This means that the development of digital technologies is not measured by their role in the fight against global warming and the green transition, but by their role in increasing profits, the standard unit of measure of private economic activity, that, as we have seen, can have serious implications for the health of the planet.

The second conclusion is that, as discussed in section 3, even when environmentally successful technologies, including digital technologies, reduce the use of natural resources or the emission of greenhouse gases, they can, through the so-called rebound effect, lead to an overall increase in the demand for natural resources or energy and an increase in greenhouse gas emissions. This means that

technology alone is not enough, even if the direct impact is positive in terms of reducing the environmental impact of economic activity.

The third conclusion is that, notwithstanding the caveats mentioned above, digital technologies often make a decisive contribution to the decarbonisation of the economy. From the perspective adopted in this working paper, the contribution of digital technologies to the green transition can be seen in two different ways. The first is by improving information and coordination in the production process. The second is by contributing to the dematerialisation of goods (and services). In section 4 of this paper, we examined examples of how specific digital technologies have contributed (or could contribute) to the green transition through these two different paths. These and many other examples are at the heart of the idea of a 'twin transition', through which digital technologies may enable and accelerate the green transition.

But this sweet environmental perspective of digital technologies, their role in enabling the development of green technologies that will facilitate the decarbonisation of the economy, neglects two other effects which go in the opposite direction.

The first is that, as noted in the first conclusion, digital technologies have been and are being developed for many other purposes beyond their role in facilitating the green transition. From this perspective, if digital technologies contribute to an acceleration of economic growth, they will also contribute to a further increase in environmental problems, unless growth is fully decoupled from environmental degradation and natural resource use, something which has not happened yet.

The second is that digital technologies, especially those related to data processing, cloud computing, and now AI, are very energy intensive. At a time when energy conservation, and the use of renewable energy, are necessary to the green transition process, the significantly growing energy needs associated with the development of large language models and generative AI, is a major problem on the road to the green transition. In this context, Goldman Sachs (2024) forecasts a compound annual growth rate of 15% for data centre energy demand in the US between 2023 and 2030, increasing their share of total US energy demand from 3% today to 8%. Additionally, as we discussed in previous pages, these digital technologies also require a very significant and growing use of water, a finite environmental resource which is also in crisis.

These two elements, the energy growth associated with the impact of new digital technologies on overall GDP growth and the specific high energy intensity of some of the new activities associated with these technologies, such as cloud computing or AI, are factors that need to be considered when making an overall assessment of the impact of the digital transition on the green transition.

The million-dollar, or rather trillion-dollar question is how to promote the positive effects of digital technologies on the green transition, i.e. those that facilitate energy savings and the deployment of green technologies, including renewables, while at the same time controlling the development and deployment of those digital technologies that contribute to higher greenhouse gas emissions and the rebound effects associated with all energy and resource-saving technologies. This is a particularly difficult problem to solve in a world where technological development is in the hands of companies (often just a handful of them) with agendas that diverge from public objectives such as the curbing global warming and accelerating the green transition, operating in non-competitive markets where, unfortunately, there is no *invisible hand* (if there was ever one) to balance private and public interests.

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