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Environmental Sustainability and the Digital Revolution: A Systematic Review of the ICT and its Environmental Impact

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Economics for the Common Good

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Abstract

This report provides an overview and discussion of the current knowledge of the information and communications technology (ICT) sector's effect on global warming, and policies to address this effect. A systematic literature review is conducted that shows that much focus in the literature has been on data centers, the amount of data processed, and the resulting green house gas emissions. The review also shows recent research on data services and traffic (e.g. video streaming), but limited research into how economic policies can mitigate the environmental impacts from data usage.

Keywords: Data centers, Global warming, Green house gas emissions, Information and communications technology, Streaming, Telecommunication networks

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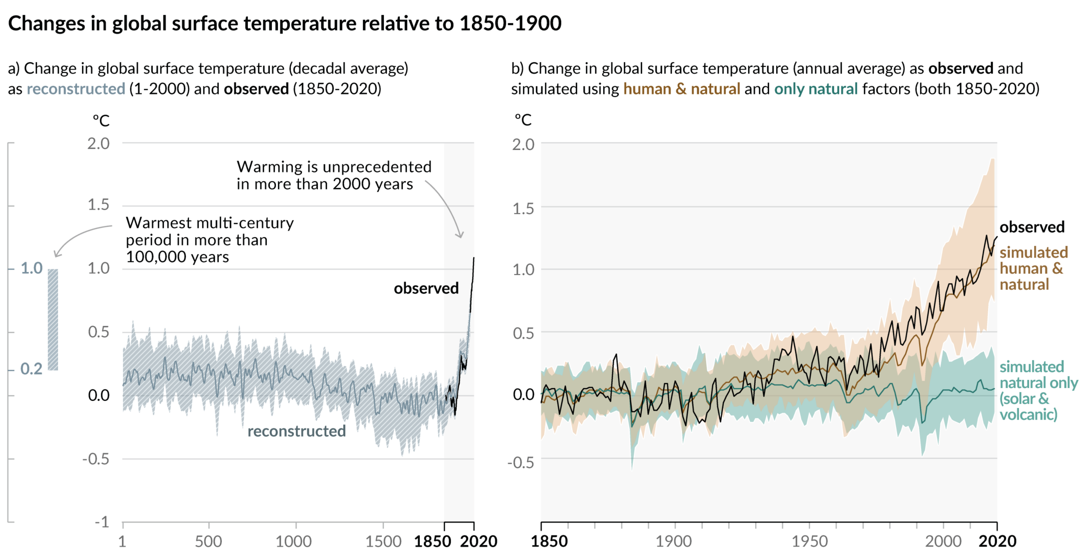
1 Introduction

Society faces several environmental challenges. For instance, the effect of air pollution or contaminated water on human health, the allocation of limited natural resources, or waste management have for a long time been given considerable attention, both from a research and policy perspective. One environmental challenge which, despite being known among scientists for decades, has gained attention more recently is the increase in the average global temperature, often referred to as global warming. Earth experiences natural temperature variations, but there is an overall consensus that the recent rise in temperature is a trend largely driven by human activity. The natural variation and the estimated human impact on the global temperature are illustrated in Figure 1. Emissions of green house gases (GHG), such as CO_2, is the main driving factor of the human impact on global warming.

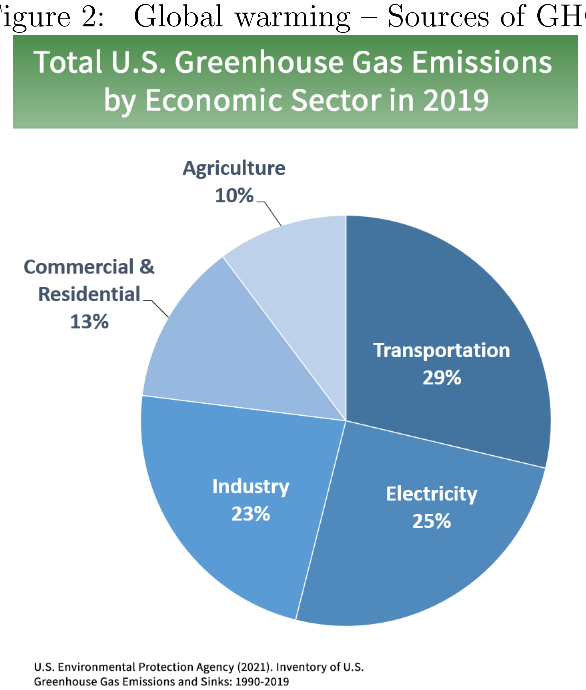
Figure 1: Global warming



Source: IPCC Sixth Assessment Report (2021)

There is a broad understanding that a failure to address global warming can have huge social costs, and may even have catastrophic consequences locally or globally (Tol 2018). According to the International Panel on Climate Change (IPCC), the main sectors contributing to GHG emissions are electricity and heat production (25%), agriculture, forestry and other land use (24%), industry (21%), followed by transportation (14%) (IPCC 2014). Figure 2 shows the contributions from different sectors in the US (US EPA's estimates), with values close to those from the IPCC. Hence, to address global warming, policy makers to a large extent have focused on the reduction of society's dependence on fossil fuels for energy production by promoting energy produced by wind, hydro, or solar power. Other measures have aimed at reducing the impact of transportation on global warming. One example is the push occurring in many countries for the adoption of electric vehicles (Andersson et al. 2023). The attempt to curb airline transportation is another example that has received a lot of attention, driven by both public and private initiatives (Economist 2019). These initiatives have been motivated by the high carbon footprint generated by travel by air compared to other modes such as rail (Ritchie 2020). However, it is worth stressing that the main contributor to global warming in the transportation sector is road traffic (see, e.g., Andersson et al. 2023).

Figure 2: Global warming – Sources of GHG



While it is well known that the sectors listed above contribute to GHG emissions, there is less awareness of the contribution from information and communications technology (ICT) (telecommunication networks, data centers, mobile phone networks, etc.). One source of GHG from the ICT sector is from the production of equipment, like computers and electronic hardware.[1] However, a major source of GHG from the sector is related to

[1]In addition to GHG emissions, these products also contain toxic materials that may end up polluting nature by, e.g., contaminating water (Uddin & Rahman 2012). For instance, Faucheux & Nicolaï (2011)

the usage of equipment. It is estimated that ICT contributes to about 2% of global GHG emissions (Jones 2018, Shaikh et al. 2020). A recent report for the French regulator shows that most of these emissions come from end users' use of their equipment (computers, cell phones, etc.) and data centers (Lees-Perass et al. 2022). The sector's contribution to GHG puts its footprint on par with the aviation industry, which, as explained, has been given much public attention for its contribution to global warming. Given the rapid increase in data usage in the ICT sector, and the predicted continued increase, it is appropriate to examine the sector's impact on climate change and whether any negative effects can be mitigated, and if so how. When doing this, it is important to keep in mind that, as the recent COVID-19 pandemic showed, the ICT sector also has the potential to decrease GHG emissions and other negative environmental impacts of other sectors of the economy, which will be discussed later.

Society becomes more and more digitalized and interconnected, and there is a nascent awareness of the environmental costs related to the data we consume every day. However, whereas most people know that driving vehicles powered by fossil fuel is highly polluting, still many do not perceive data usage, for instance video streaming, as generating large CO_2 emissions. The Shift Project, a French think tank, published a highly publicized report in 2019 estimating the amount of CO_2 emissions generated by video streaming (Shift Project 2019). While claims from the initial report were shown to be based on flawed assumptions and exaggerated (Kamiya 2020 and Shift Project 2020), new estimates of the sector's contribution to GHG emissions remains high, considering its total energy consumption. The fact that the initial analysis by the Shift Project got so much attention highlights the lack of knowledge about the impact from data usage on climate change.

The aim of this report is to describe the current knowledge on data usage in the ICT sector and its contributions to climate change. It would be good to disentangle the contributions of various elements of ICT, for instance, terminals, data centers, radio equipment, and fixed-line network, but the academic literature is not substantial enough yet.[2] While terminals, transmission and storage matter, a large part of the existing literature has focused on data centers and only recently on computers' electricity use or on intermediaries between users and data centers, like the networks transmitting data.

estimated that in France in 2007 16 kg of electrical and electronic products per capita/year were placed on the market, with only 2.5 kg per capita/year being recycled.

[2]Moreover, as all components are complementary products, an economic perspective on the contributions of various elements may differ from the physical contributions of each component.

The report is structured as follows. In section 2 we describe the systematic literature review that was conducted and its results, and review in some detail the most recent contributions. This is followed by a summary of the findings concerning data demand and its environmental impacts in section 3. Section 4 discusses experiences from COVID-19 and expectations about how demand for data and energy will develop. The role of the sector itself and governments are discussed in section 5, followed by a discussion and some concluding comments in section 6.

2 Systematic literature review

2.1 Search criteria and selection process

A literature review was conducted in August 2022 with the objective to get an overview of the findings in the literature on data usage and GHG emissions. This review was conducted using *Web of Science* and was divided into two separate searches. The searches were restricted to scientific articles published in English from 2012 to 2022. The reason for not including older studies is related to the rapid development of data usage, and hence older studies were considered obsolete. Special care was devoted to defining the most relevant final search terms and how to combine them. For instance, the term "data" turned out to be particularly problematic since it included many studies not related to the topic of this report, like studies using market or other type of data for empirical research. The final search terms and their combinations are shown in Table 2 in the appendix.[3]

The first search focused on data usage, energy use and GHG emissions. After the initial searches results were screened and search terms were revised to make sure that relevant finds were kept, whereas irrelevant finds were excluded. The final search specification resulted in 150 articles. These articles were then screened more closely and after inspection it was found that 21 studies met the selection criteria, i.e. the other articles were not in the area of "data usage, energy use and GHG emissions". The selected articles are included in Table 3 in the appendix, which includes for each paper the title, the type and a brief description.

The second search instead focused on data usage and policies to mitigate negative effects from this usage. The same approach was used as for the first search; initial searches resulted in revisions of search terms based on screenings, narrowing the list

[3]We are grateful to Yahnis Adje for research assistant related to the systematic literature review.

without excluding any relevant articles. This resulted in a list of 40 articles, which then based on closer inspection ended up in a list of 5 articles. Theses articles are also included in Table 3 in the appendix.

The systematic literature search suggests that this is an area where research findings are scarce, especially regarding policies to curb negative effects from data usage. Much of the focus has instead been on examining the impact of data usage on energy use, the effect of energy use on GHG emissions, and on different measures like technological advancements to reduce energy use and emissions. The literature review also suggests that whereas the former was more common in the early literature covered, the latter dominates the more recent literature. The early literature focusing on the internet and data traffic, and energy use, found that despite an increase in data traffic, energy use could be kept down as a result of technological advancements. The more recent literature highlights that it is not likely that in the future increased data traffic will be offset by improved energy efficiency in the sector. Instead, energy use is expected to increase, unless measures are taken. However, several studies also show that the expected increase in energy use and GHG emissions can be mitigated by more efficient use of current and further development of technology, including networks for transmissions. Whether this will lead to a reduction in GHG emission to a large extent depends on the electricity sources used, i.e. produced using fossil fuels or greener sources. In the following subsection, we will discuss recent findings from a few selected articles. We will then in the following sections of this report summarize and discuss the findings from this systematic literature review in more detail, complemented with findings from other relevant literature on the topic. Table 3 provides the list of studies from the systematic literature review with short descriptions of the studies.

2.2 Summary of selected recent studies

In this section, we summarize some of the most recent and relevant contributions and start by Cheng et al. (2022) who examined the deployment of 5G networks in the UK using an agent-based model. In addition to studying spatial dimensions related to this deployment they also study the associated effects on energy consumption and carbon emissions. Using a 10 year scenario, ending in 2030, their simulations show that in the UK the 5G radio access network will consume more than 2.1% of total electricity and through this energy consumption lead to close to 1 million tons of carbon emissions. One reason for this increase in carbon emissions is that the power consumption of 5G base stations is about four times higher than 4G base stations (but which better efficiency in terms of data transmission). However, a main driving factor is the demand for services related to the 5G networks. Cheng et al. examine three mobile data growth scenarios; low demand, medium ("business as usual"), and high demand. They show that under all scenarios 5G power consumption is expected to increase, inducing a corresponding increase in carbon emissions. To mitigate the negative environmental effects of energy use the authors stress the importance of continuing the switch to greener energy sources.

Madlener et al. (2022) examines the potential for using regulation with the purpose to save energy generated by video streaming. This is motivated by the massive growth in data traffic related to video streaming and its effect not only on energy use and induced GHG emissions but also on network congestion. Using a bottom-up approach decomposing between devices, transmission networks and data centers, Madlener et al. conduct simulations based on three scenarios; "business as usual" (BAU), a pessimistic scenario, and an optimistic scenario. To exemplify, the BAU scenario assumes a continuation of current trends, including energy efficiency improvements, the pessimistic scenario assumes low energy efficiency improvements and high data consumption compared with BAU, and the optimistic scenario assumes higher energy efficiency and greener energy sources. The analyses show that both under BAU and the pessimistic scenario, energy use and GHG emissions from video streaming will increase significantly. According to their simulations, for data streaming, access network is and will stay the main contributor to energy consumption (followed by devices). The analysis then shows a great potential of regulation for electricity savings and related reductions in GHG emissions. The type of regulation examined includes various forms of technical regulation, such as restricting streaming resolution or improving energy efficiency. For instance regulators may act to foster the transition from 4G to 5G. But the authors also point to the potential for pricing measures like transit fees for data traffic to improve long-run incentives.[4] However, they believe that regulatory intervention will be needed in any case.

Other studies take a more global approach to ICT. Özpolat (2022) studies the link between national internet use in G7 countries between 1990 and 2015 and national environmental degradation. The motivation for the study is the two opposite effects ICT can have on GHG emissions. On the one hand, ICT may lead to a decrease in GHG emis-

[4]See Jullien & Bouvard (2022) for an analysis of traffic cost sharing.

sions due to less need to travel, more efficient use of resources, etc. On the other hand, the ICT sector in itself requires energy to function which results in GHG emissions, and widespread use of ICT may lead to an increase in demand for products in different sectors which will also increase GHG emissions. Therefore, using panel data and controlling for different aspects expected to affect the environment, Özpolat aims to examine whether internet use is negatively correlated with environmental degradation and also to identify the causal relationship. Instead of focusing in GHG emissions Özpolat uses ecological footprint as a proxy for the negative environmental impact from internet use, which is an index that "measures how much nature people need to produce goods and services that they use to survive" (p. 12835). It is found that, controlling for total energy use, for Germany, Italy, Japan, UK and USA internet use is negatively correlated with ecological footprint, but that for France the correlation is positive. Causality tests suggest a bidirectional relationship between energy use, internet use, and ecological footprint, each of these dimensions seemingly affecting the evolution of the others.[5] A suggested causality is that "energy consumption can lead to more internet use and internet use decrease environmental degradation". Unfortunately, the paper only identifies statistical correlations but does not investigate the mechanisms that could explain these correlations.

The research question in Zhao et al. (2022) is similar to the one in Özpolat (2022), that is to examine the ICT sector's effect on energy efficiency and environmental sustainability. Data from eight emerging Asian economies (Bangladesh, Malaysia, the Philippines, Thailand, Sri Lanka, China, and India) over the period 1991 to 2019 are used. Broadband and mobile cellular subscriptions are used as proxies for ICT use, and GHG emissions are used as the measure of the ICT sector's environmental impact. Again the approach consists of identifying statistical correlations (within and accross periods). The study finds some differences in the effects stemming from broadband and mobile cellular subscriptions, but the overall general conclusion suggests that an increase in the use of internet and mobiles has led to increased energy efficiency and a negative impact on GHG emissions. Hence, the study finds that ICT in emerging economies can "help to enhance energy efficiency and improve environmental quality" (p. 12204). However, the causality tests also show a bidirectional relationship between GHG emissions and internet use. The authors do stress the importance of government policies to promote clean energy and to curb out-of-date

[5] The Granger causality test is a statistical test for determining whether the realization of one variable is useful in forecasting the future realization of another variable.

inefficient technologies for the mitigation of any negative environmental effects from the ICT sector.

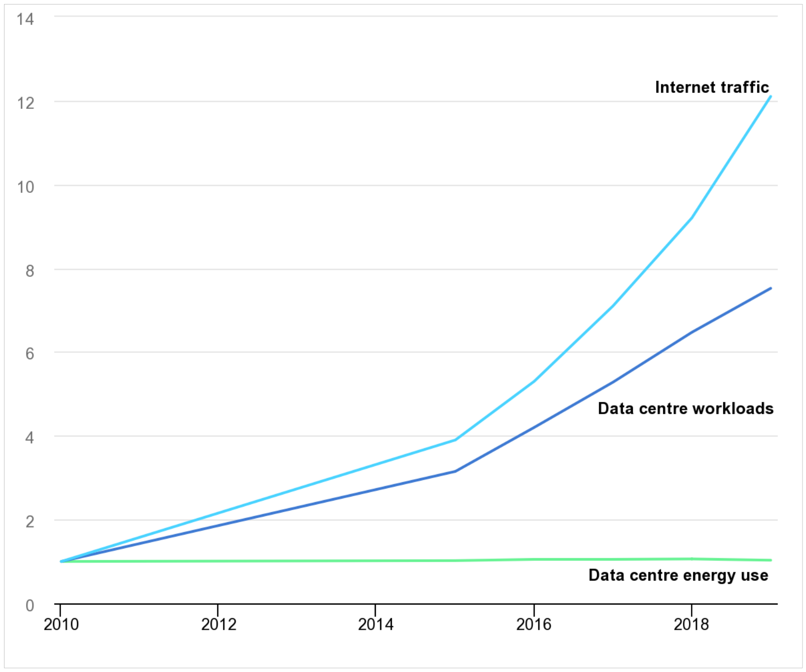
Yilmaz & Uysal (2022) examine the role of the ICT sector on GHG emissions among OECD countries. The motivation for the study is again the mixed evidence in the literature on whether the total effect of the ICT sector is to increase or decrease GHG emissions. Compared to Özpolat (2022) and Zhao et al. (2022), the countries included are less homogeneous when it comes to their level of internet usage, which provides an important contribution. Whereas a strong correlation between energy consumption per capita and GHG emissions is found, a small but positive correlation is found between the percentage of the population using internet and GHG emissions. Yilmaz & Uysal (2022) find for OECD countries that ICT penetration (measured by the percentage of the population using internet) has a positive effect on GHG emissions only up to the 40th quantile (less than 40% of the population using internet). Above that level, the effect is no longer statistically significant. Moreover, below the 40th quantile, the impact is decreasing. Hence, according to this study, ICT has the potential to mitigate GHG emissions, once a certain threshold of usage has been reached. However, as for others, the paper stresses the need for government interventions in the form of regulation or investments to mitigate any negative effects from the ICT sector and to encourage it to go greener.

3 Information technology and the environment

3.1 Demand for data

Figure 3 illustrates the rapid increase in internet traffic, data center workloads and energy use over the last decade. As shown in the figure, the growth in internet traffic has been exponential and this is a result of a combination of technological innovations and changes in people's behavior (Sandvine 2020). Hugely popular streaming services like Netflix and YouTube illustrate the success of this combination. The data workload has had a similar growth as internet traffic, while during the period, technological progress allowed to contain the energy consumption of date centers. Data infrastructures handle emails, cloud computing services, social networks, data services for businesses, hospitals, universities, etc. Transmission infrastructures and data centers, that simplistically can be described as warehouses filled with servers, are the backbone of the internet (Zaman et al. 2019). The value of the public cloud services market worldwide has also shown tremendous growth from US$ 60 billion in 2009 to US$ 240 billion in 2020.[6]

Figure 3: Global trends in internet traffic, data centre workloads and data centre energy use, 2010-2019



Source: IEA (2020*a*)

3.2 Data centers

As mentioned data centers have been the main focus of the earlier literature. They originated in the the United States in the mid 1940s with their main task being to store military information for the government. Today they are used to centralize, store, process, and disseminate data. Many of the centers are located in big cities where private demand for data traffic is the highest. For instance, almost 200 data centers are located in and around London, UK.[7] People often fail to recognize the buildings filled with servers that actually represent the cloud, and ensure the data traffic, as these facilities are often discretely hidden in highly secured buildings. Moreover, the link between abstract concepts like "cloud computing" or "data" and physical buildings may be hard to conceptualize for many people.

[6]Statista, (Link) (Accessed June 21^{st}, 2021)

[7]For locations of data centers in the world, see, e.g., (Link). (Accessed on June 1^{st}, 2022)

The size of data centers vary from 30 m^2 for small computers room in average-sized companies to several hundred thousand square meters, with the largest data center located in Tahoe Reno, Nevada, covering an area of almost 670 000 m^2.[8] Even if internal company server rooms can also be classified as data centers, we usually think of data centers as supporting data services provided to firms, individuals and institutions. This includes hyper-scale data centers, which according to the International Data Corporation (IDC) are centers with more than 5,000 servers and space of at least 10,000 ft^2 (ca. 930 m^2). These hyper-scale data centers provide advantages in terms of energy efficiency, and represent about 40% of the traffic of total data centers according to recent data (Shehabi et al. 2016).

3.3 Data, energy and the environment

Data processors and servers run 24/7 and need constant electricity to power them. Since processors and servers produce heat they need cooling systems to avoid corrupt data, crashes, or server damage, which requires energy. This results in GHG emissions with estimates based on data from OECD countries suggesting an elasticity of 0.82, i.e. a 1% increase in electricity demanded results in an increase of 0.82% of CO_2 emissions (Köppl-Turyna et al. 2021). It has been estimated that data services consume up to 3% of the worlds' electricity and account for 2% of all carbon emissions (Lee et al. 2020, Liu et al. 2020).[9] The exact energy consumption is, however, uncertain with different studies coming up with different results. For instance, estimates by IEA suggested that data centers' energy consumption in 2019 amounted to 195 TWh (IEA 2020*a*), whereas the EURECA Project claimed that in Europe alone, the consumption is around 130 TWh (Bashroush 2018), which suggests a global energy consumption significantly above 195 TWh. However, the uncertainty on the exact amount of energy consumed does not change the fact that data services require large amounts of energy which contributes to GHG emissions.

As shown in Figure 3, whereas the internet traffic and data workload have grown exponentially, the energy use has remained constant. This may seem surprising, but

[8] Analytics Vidhya provides a list of the 8 largest data centers, see (Link) (Accessed on June 1^{st}, 2022)

[9] The total IT sector (including computers, and other equipment to handle information) has been estimated to consume about 7% of the world's electricity, which is expected to rice to 13% by 2030 (Avgerinou et al. 2017).

several factors have contributed to this. Central to the increase in energy efficiency is that service providers have incentives to reduce their energy consumption as it makes up an important share of the companies' costs, estimated to be around 40% (IEA 2020*a*). One very important factor contributing to increased energy efficiency is the sector's investments in research and development to develop intelligent software able to anticipate the need to use energy efficiently. As a result, during the growth in internet traffic and data worload, data services have benefited from what is refereed to as "Moore's law", i.e. "The principle that the speed and capacity of computers can be expected to double every two years, as a result of increases in the number of transistors a microchip can contain." (Moore et al. 2005). Moreover, a major source of energy consumption is the cooling of servers, and one way to address this has been to locate server infrastructures in dry and cool places where the natural conditions reduce the amount of energy required to run the servers (Avgerinou et al. 2017). Further, as discussed above size matters with hyper-scale service providers being more efficient than others due to economies of scale, better equipment, and more efficient cooling techniques.[10]

Despite these gains in efficiency there are still further potential gains. The energy efficiency of data centers is usually measured in power usage effectiveness (PUE). A value of PUE = 1 means that the total energy used equals the amount of energy used by the IT equipment. Hence, a value equal to unity suggests that no energy is "wasted." The average PUE has been estimated to be around 1.8 (NREL 2022). Further evidence suggesting that there is still room for improvement is the findings by Bashroush & Lawrence (2020) who found that 65% of the power used by IT equipment in data centers was used to process only 7% of traffic due to aging, non-efficient, equipment. Notice also that studies focusing on data centers ignore the implications of their location for transmission infrastructures and the quality of services.

4 Implications from COVID-19 and other trends

The COVID-19 pandemic has led to changes in people's daily lives and habits (Feldmann et al. 2021). The immediate impact was that people were forced to stay at home more, which had an impact on data consumed. For instance, Feldmann et al. (2021) found an

[10]One server in a hyper-scale data center is estimated to be able to replace 3.75 servers in a non-hyper-scale data center (Shehabi et al. 2016).

overall increase in traffic of 15-20% within the first weeks of lockdown, with increases during peaks of up to 200%. Another study showed that internet traffic grew by 40% between February 1st and April 19th, 2020 (Sandvine 2020). A big driving factor was the increase in streaming which increased from 55% of the total internet traffic in 2019 to 80% in 2020. Another driving factor was the increase in working from home which induced growth in video conferencing (e.g., Zoom) and VPNs (e.g., 35% of all Americans worked from home in the US in May 2020 (Bick et al. 2020)).

This increase in data consumption, and hence energy use, was offset by companies switching from "in-house solutions" to using external service providers. The motivation for this switch was to provide better and more reliable network access to employees working from home (IDC 2020), but an additional bonus was an increase in the efficiency of the companies' data energy consumption. Hence, the pandemic accelerated the process of transferring data processing to more efficient service providers, but with the consequence of increasing traffic.

The increase in teleworking also meant a reduction in commuting, with a significant decrease in CO_2 emissions from transportation, given the fossil fuel dependency of most vehicles. Teleworking resulted in an increase in energy usage from data demand, more cooking and heating at home, and reduced transportation, resulting in a net negative effect on CO_2 emissions (IEA 2020*b*). This could suggest that a significant increase in data consumption, and hence, a related increase in energy use, due to teleworking is not problematic since it will be offset by reduced CO_2 emissions from transportation. However, evidence from the transportation literature also suggests the existence of a constant travel time budget, whereby individuals allocate a stable amount of time for transport (Stopher et al. 2017). For instance, if teleworking induces individuals to live further away from their work places, total travel time and CO_2 emissions from transport may not be reduced. Whether the constant travel time budget is still applicable with teleworking is an empirical question, but this is a reminder that more energy usage due to data consumption related to teleworking may indeed lead to an increase in CO_2 emissions.

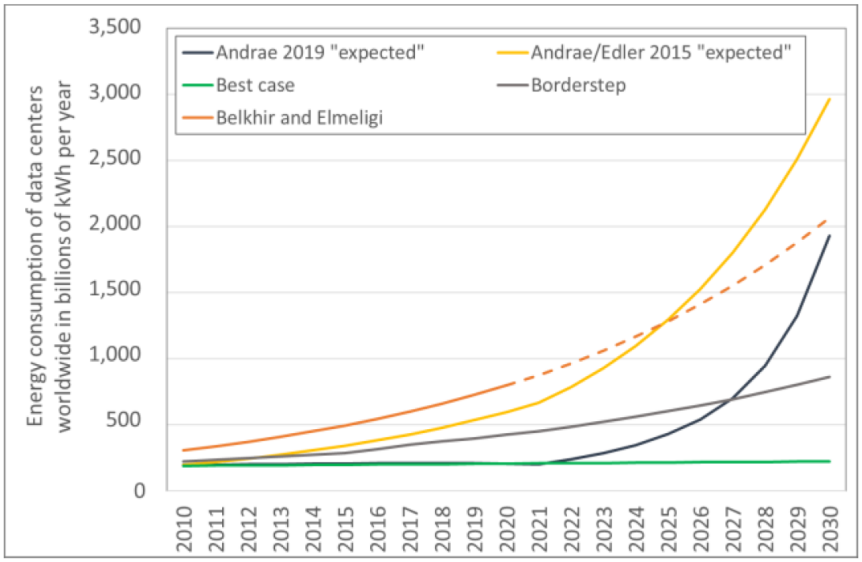
Another important driver of data consumption is the sector's ability to innovate. For instance, mobile data traffic increased by 55% between 2016 and 2017, which was facilitated by the new technology at the time (4G) (Widdicks et al. 2019). The introduction of 5G will significantly improve the energy efficiency of the networks compared to 4G technology, but it will also allow users to consume more at higher speed, which may further increase demand for data, and hence may lead to increased energy use and GHG emissions (Li et al. 2018, Madlener et al. 2022). Other innovations are data-hungry, like the blockchain technology[11] and artificial intelligence (AI). The former is a groundbreaking technology with potentially broad applications like medicine (Krittanawong et al. 2020). The latter is a rapidly evolving general-purpose technology with also broad applications, one example being autonomous cars. The common denominator for these two new technologies, and the reason why they are expected to play an important role in the future of the data industry, is that they both require extensive use of data. There is a risk that such data-hungry technologies will increase the sector's energy use and GHG emissions. For instance, Bitcoin's blockchain and its impact on the environment due to the huge amount of electricity that is required to make it work has already lead to controversies (Badea & Mungiu-Pupăzan 2021).

Figure 4 shows that there is a risk that data centers will not be able to continue to meet the increase in data traffic and workload with energy efficiency gains, and instead that energy consumption will increase. Bashroush & Lawrence (2020) suggest that even if there is room for innovation that will lead to less efficient old equipment being replaced by new one, innovation and energy gains are slower than what they used to be. Koomey & Naffziger (2015) also suggest that "Moore's law" may no longer be applicable, with 2,7 years to double the capacity instead of 2 years. Hence, the ICT sector's contribution to GHG emissions may be significantly higher in the future if no measures are taken.

Even though the ICT sector consumes energy, it may have a negative effect on GHG emissions through its impact on different sectors of the economy, and there may be other positive environmental effects resulting from data usage. As discussed above, an increase in data demand may be offset by reduced emissions from transportation. Moreover, the spread of ICT can also lead to green development through improved energy efficiency and more efficient use of resources in general (Wang et al. 2021, Özpolat 2022). For instance, Özpolat (2022), based on an empirical analysis of the G7 countries, found that a 1% increase in internet usage is associated with a reduction of 0.3% of environmental degradation. However, since the ICT sector in itself requires energy some evidence suggests that it initially will increase emissions due to the increase in energy demand before it will lead to reduced emissions through its cross-industry efficiency gains (Saud et al. 2022, Wang et al. 2021, Zhao et al. 2022). Hence, it follows the trajectory of the

[11] For a description of blockchains: (Link) (Accessed on June 10^{th}, 2022)

Figure 4: Uptime Survey results on the average annual PUE of large DCs from 2007 to 2019



Source: Hintemann & Hinterholzer (2019)

environmental Kuznets curve (Mäler 2001). Moreover, evidence also suggests that even if the ICT sector has the potential to reduce emissions such a development depends on how electricity is produced, fossil fuel or renewable energy sources, and to what extent the sector will experience technological development leading to higher energy efficiency (Mohammad Aldossary 2022, Guo et al. 2021, Ben Lahouel et al. 2022, Özpolat 2022, Wang et al. 2021, Zhao et al. 2022).

5 Self-regulating and regulation

5.1 Self-regulation and green consumers

As described above, our dependence on ICT is likely to increase which will result in more demand for data. However, the operators of data services have a self-interest in being energy-efficient, and there is also room for increased energy efficiency in the sector. As described, cooling servers consume a large proportion of the energy used to process data. By placing servers in locations with a dry and cold climate, service providers can reduce their costs, as less energy is required to run the servers (Avgerinou et al. 2017, Zheng & Cai 2011). The location provides "free" cooling services, which results in a lower PUE for such services (i.e. more energy efficiency), and since less energy is used, there are less

Table 1: Energy sources and GHG

Energy source	**Emissions in gCO_2e/KWh**
Wind	10
Hydroelectric	20
Nuclear	150
Oil	510
Coal	950

Ferreira et al. (2019)

GHG emissions (everything else equal). Hence, the interest of the firm to reduce its costs aligns with the social desire to reduce GHG emissions. However, these colder locations are often in rural areas, which means that the servers will have to be located far from users.

Data centers and network infrastructure managers can also aim at becoming "green" by innovating to become more energy-efficient, and/or using greener sources of energy, like renewable energy (Uddin & Rahman 2012, Renugadevi et al. 2020, Syed et al. 2021). For instance, using algorithms that enable the servers to run more efficiently by adjusting to changes in demand can save energy, resulting in less emissions. Faucheux & Nicolaï (2011) estimated that "green IT" could save 15% of CO_2 emissions compared with "business as usual" in 2020, and Patón-Romero et al. (2017) found for an university context that green IT could save 52% of CO_2 emissions, approximately equal to savings of 7,261 tons of CO_2. As shown in Table 1, replacing fossil fuels with renewable energy also has the potential to significantly reduce the carbon footprint of the sector.

However, despite the many potential measures by the industry to improve energy efficiency there is still a significant risk that the increase in internet traffic will lead to increased energy consumption with an increase also in GHG emissions. One way to address this risk is to influence individuals' and organizations' data creation and/or consumption. Many individuals and organizations are not aware of the effect their internet usage has on the environment. Would raising awareness be sufficient to influence their behavior, or are regulation or financial incentives necessary? Studies have shown that consumers are willing to pay a premium for green telco products (e.g., EY 2020, Friedrich et al. 2021). However, such studies are often based on survey answers, which means that it is uncertain whether consumers would actually be willing to pay more for "green products", or accept new types of contracts that would incentivize less data consumption.

5.2 Regulation

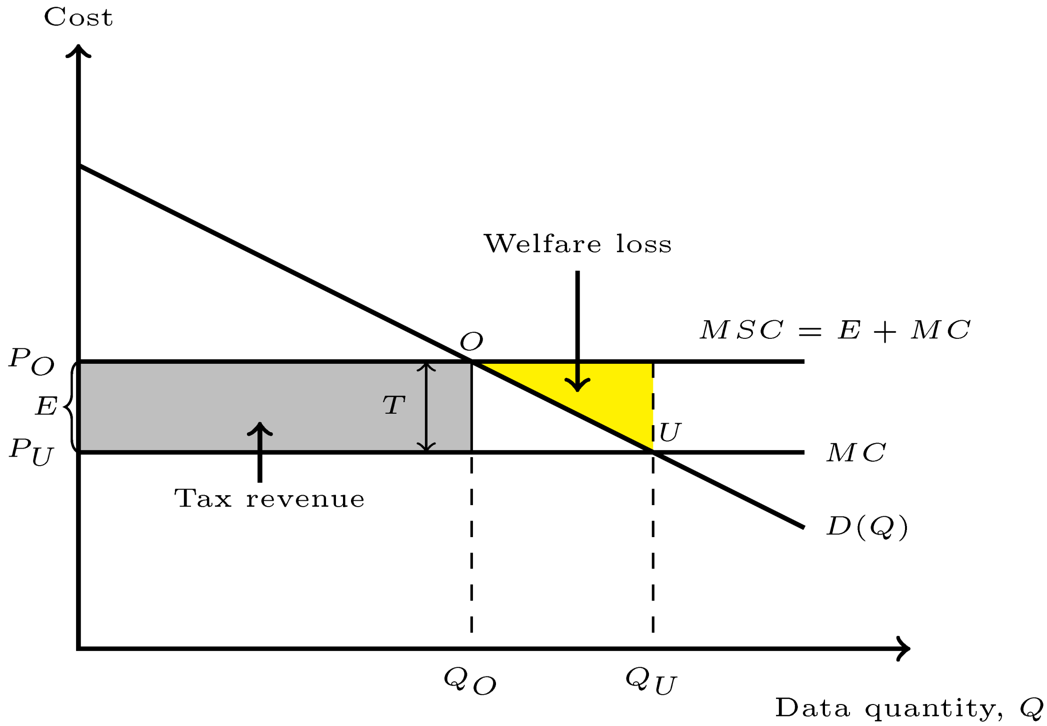
Government intervention is justified when market failures prevent the market from finding a social optimum by itself. When it comes to GHG there is a high risk of excessive emission levels if reducing emissions is costly, or if restricting data consumption has a negative effect on firms' profit. In those cases firms have no incentives to mitigate their emissions, and hence regulation is necessary to address the market failure.

Regulatory instruments are often classified as either prescriptive regulation, also called command and control, or economic incentives. Examples of the former would be restrictions on quantity of data, technology to use, or energy sources (Ben-Shahar 2019). Examples of the latter would be a tax or a fee, or a permits market, related to the GHG emissions from data transmissions. Hence, it would be costly to emit GHG and hence operators would have incentives to reduce their emissions. If the price of GHG emissions reflects the social cost of pollution, it is labelled a Pigouvian fee.

Figure 5 illustrates the principles of a Pigouvian fee for a competitive sector. The downward sloping demand curve ($D(Q)$) reflects the negative relationship between price and quantity of data demanded. The cost of supplying data is represented by MC, which is assumed constant in this illustration (i.e. the supply curve is horizontal). The social cost of the externality is represented by E. The two quantities Q_U and Q_O show the quantity of data consumed in an unregulated market and when the externality has been internalized in the prize. Hence, Q_O is the quantity of the social optimum where the social marginal cost equals the social marginal benefit (represented by $D(Q)$) of data consumption. Figure 5 also illustrates the social cost of not internalizing the externality, represented by the yellow triangle, and the tax revenue from pricing the externality, represented by the grey rectangle.

The internalization of the externality in the price is an economic instrument favored by many economist. Examples of taxation/pricing motivated by externalities are congestion charges and fuel taxes in transportation, and taxes on tobacco and alcohol. The implementation of such charges and taxes can be politically motivated by fiscal considerations, i.e. to raise revenues. However, if the charge/tax corresponds to the externality, i.e. $T = E$ in Figure 5, then it corresponds to a Pigouvian fee that informs the market about the true social cost of the good (MSC). Pigouvian fees are reflected in the "polluter pays principle" (OECD 1995) which postulates that it is fair that those who inflict

Figure 5: Equilibrium in unregulated market and social optimum



Source: Author's (Andersson) own lecture notes.

harm on others should pay for it.

Whereas using the pricing mechanism to give incentives to individuals to behave in a more environmentally friendly manner is favored many economists, it is challenging to implement. In addition to the issue of gaining public support for environmental taxes and fees, one issue is whether the tax should be imposed on the demand (on end-users) or supply side. Tudón (2022) finds, studying *Twitch*, that the effect on the platform size is that it decreases less when the suppliers are taxed than when end-users are. Another issue to consider regarding pricing of externalities related to data usage is to what extent end-users are aware of their usage, and how their costs would be influenced by changing their behavior. For instance, many end-users of data are not aware of how their data consumption relates to energy consumption, and since many suppliers offer flat-fee pricing modes this gives the end-users little incentives to be informed, or to reduce their data consumption (Layton & Potgieter 2021). Moreover, another challenge regarding a Pigouvian fee would be that in addition to the GHG there are other externalities. For instance, in periods of peak demand additional users may degrade the quality (e.g. speed) of service of other users, due to network congestion. On the other hand, data usage may also bring positive externalities which may vary from activity to activity which would require differentiated "data taxes" (Bloch & Demange 2018). Hence, the implementation of a pricing scheme to reduce the negative environmental impact from data consumption is challenging, not only regarding political acceptance and administrative costs, but also when it comes to estimating the correct level of the fee.

An alternative to pricing is prescriptive regulation, such as technology standards. For instance, Madlener et al. (2022), in an analysis of potential saving effects on electricity and CO_2 emission from regulation of video-streaming services, focus on prescriptive regulation since they see it as a more feasible option than using economic instruments. In their study, based on three different scenarios (business as usual, grey (pessimistic), and green (optimistic)), they show that regulation can play an important role in energy and CO_2 savings, and that efficiency gains in themselves may not be sufficient due a potential increase in demand for video streaming. An example of regulation in their scenario would be to cap the resolution for video streaming which would reduce the amount of data used. However, prescriptive regulation, as economic instruments, faces challenges to be implemented. One issue when it comes to the ICT sector is that information is often not shared publicly, which makes it both difficult to implement policies that are socially optimal, and to enforce the policies. For instance, as was described above many data centers are small "in-house company data centers" that would be hard to control. Moreover, prescriptive regulation risk discouraging innovations in more efficient data usage, both for services processing the data and networks transmitting the data, as well as for the end-users side.

A third regulatory alternative is voluntary action. This is the approach that has dominated in the European Union (EU). For instance, the guideline the European Code of Conduct for Data Center Energy Efficiency (ECCDCEE) launched in 2008 (EC 2022) encourages data centers to improve their PUE. It focuses on raising awareness of data center operators and owners and push them toward environmentally friendly behaviors. However, it is voluntary so participants will not be forced to implement the guidelines. Avgerinou et al. (2017) found that companies participating had a declining PUE, which suggests that those participating improved their energy efficiency. However, since participation is voluntary those who do participate may be firms with a low cost of improving their PUE, i.e. a selection bias.

6 Discussion and concluding remarks

We have reported the findings from a systematic literature review on data usage in the ICT sector and how it related to energy use and GHG emissions. Data traffic has seen a dramatic increase over recent decades. Globally the data traffic grew from 100 GB per day in 1992 to 2000 GB per second in 2007, and further increased to 46,000 GB per second in 2017, and is expected to reach 150,700 GB per second in 2022 (Madlener et al. 2022). As described, the exponential increase in data traffic has so far not seen an equivalent increase in energy use in the sector. Instead technological advancements improving energy efficiency together with decisions made by the sector to reduce its energy use, like locating data centers to cold and dry locations, have meant that energy demand has been stable. This is, however, not expected to continue, and the increase in data traffic is expected to lead to an increase in energy use in the near future, with a potential increase in GHG emissions from the sector.

Despite the ICT sector in itself contributing to GHG emissions, it has the potential to contribute to a green development. The recent COVID-19 pandemic meant that workers had to work from home and that individuals professionally and privately had to find new ways to interact. This led to an increase in data traffic, e.g. due to an increase in online video meetings, but also meant that fewer trips took place leading to a decrease in emissions from transportation, with a net negative effect on global GHG emissions. Moreover, ICT penetration may also foster innovation and the development of new technologies, etc., in society which could improve energy efficiency, and hence reduce overall GHG emission.

The ICT sector with its data traffic both contributes and can have a negative impact on GHG emissions. As shown by the literature review conducted in this study little research has been conducted on how economic policies can mitigate the negative environmental impacts from data traffic. Thus, this is an important topic for further research. What the literature review showed, though, is that a "business as usual" scenario is expected to lead to an increase of GHG from the ICT sector. To prevent such a development it is important that the sector continues to invest in research improving energy efficiency at all levels, from data centers to transmission networks, and also end-users' equipment, and that it relies even less on electricity produced using fossil fuels.

To this respect, it is worth pointing out that even though a large part of the effect on GHG emissions is due to terminal equipment and data centers, there is a relation with the traffic because data usage and traffic are often complements. In this context, a regulation of traffic that accounts for this complementary may help to empower data providers and induce them to optimize data usage (see Jullien & Bouvard 2022.)

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A Systematic literature review

Table 2: Web of Science: Search results

Energy use and GHG emissions
TS=((Data AND (internet OR cloud OR streaming))) AND TS=(((carbon OR CO2 OR ”green house” OR climate) AND emission*)) AND TS=((energy AND (electricity OR operators OR Calculator OR fossil))) NOT TI=((”Computing” OR management OR algorithm* OR dynamic* OR ”stream” OR techni*))
Result: 150
Data usage and policies to mitigate negative effects from usage
TS =((”data cent*” OR ”data emission” OR ”data exploitation”OR spam*) AND (internet OR stream* OR smartphone OR Ngn OR ”next generation network” OR spam* OR digital) AND (tax* OR regulation OR competition OR pric* OR nudg*) AND (externalit* OR incent* OR induce* OR harm*))
Result: 40

Note: For a description of Web of Science search operators, see (Link)

Table 3: Systematic review of data usage, energy, GHG emissions, and policy

Study	Location	Type	Study objective
Data usage, energy consumption and GHG emissions			
Mohammad Al-dossary (2022)	Saudi Arabia	Empirical research	Propose an eco-friendly approach to control carbon emissions from data centers.
Avgerinou et al. (2017)	Europe	Descriptive research	Evaluate, analyze, and present the current trends in energy consumption and efficiency in data centers in the European Union.
Ben Lahouel et al. (2022)	MENA (Middle East and North Africa)	Empirical research	Investigate the relatiionship between ICT and CO2 emissions controlling for economic growth, foreign direct investment, energy consumption, and trade openness.

Continued on next page

Table 3 – *Continued from previous page*

Study	Location	Type	Study objective
Cappiello et al. (2014)	Europe	Methods article	Develop an approach for the selection of the cloud site for the deployment of applications depending on the environmental impact.
Cheng et al. (2022)	United Kingdom	Empirical research	Empirical examination of the transition to 5G in the UK covering costs and energy usage, including environmental impact.
Ferreira et al. (2019)	Global	Experimental research	Conducted an integrated evaluation of costs and CO2 emissions of the electrical infrastructure in data centers, considering the different energy sources adopted by each country.
Faucheux & Nicolaï (2011)	Global	Review article	Discusses, from an interdisciplinary perspective, the increasing use of green IT and its applications.
Gonçalves et al. (2020)	Global	Review article	Two-tier method to address challenges leading to positively offset carbon dioxide emissions related to mobile networks using a novel approach (tree plantation).
Guo et al. (2021)	United States	Simulation exercises	To propose algorithm to minimize brown energy use, and hence carbon emissions, in data centers while also considering energy costs.
Özpolat (2022)	G7-countries	Empirical research	To examine the effect of internet usage on environmental degradation.

Continued on next page

Table 3 – *Continued from previous page*

Study	**Location**	**Type**	**Study objective**
Patón-Romero et al. (2017)	Global	Methods article	Establishing the characteristics needed to carry out the governance and management of green IT in an organization and performing audits.
Qin et al. (2022)	China	Empirical research	Examine the impact of internet access on household electricity consumption.
Saud et al. (2022)	Global (Belt and road economies)	Empirical research	To examine the role of ICT and financial development in shaping low-carbon environment in selected belt- and road-investment economies.
Shaikh et al. (2020)	Global	Methods article	Provide a new calculator (PEMC) that allow to combine power efficiency, CO_2 emissions, and the total annual costs.
Shehabi et al. (2014)	United States	Descriptive research	Evaluate the approach to estimating primary energy consumption and GHG emissions associated with video viewing through traditional DVD and online video streaming.
Syed et al. (2021)	Global	Experimental Research	Expresses the role of renewable energy in minimizing the environmental impacts of mobile data communications for achieving a greener environment.
Wang et al. (2021)	Global	Empirical research	Examine whether digital technology can reduce carbon emissions, both within the sector itself and its effect on other sectors.

Continued on next page

Table 3 – *Continued from previous page*

Study	Location	Type	Study objective
Widdicks et al. (2019)	Global	Experimental research	Reveal the online activity of domestic watching and provide a detailed exploration of video-on-demand activities.
Zhao et al. (2022)	Asia	Empirical research	Investigates the effect of ICT on energy efficiency and carbon emissions in emerging Asian economies from 1990-2019.
Data usage and policies			
Ben-Shahar (2019)	Global	Review article	Develop a novel framework related to data pollution to rethink the harms the data economy creates, and the way it must be regulated.
Bloch & Demange (2018)	Global	Research	Study data collection by a monopolistic internet platform and how different tax instruments that can be used to reduce the level of data collection.
Jahangard & Shirmarz (2022)	Global	Review article	Descriptive presentation of the literature on green cloud computing techniques, including previous reviews.
Madlener et al. (2022)	Europe	Empirical research (simulations)	Examine the potential from regulation on electricity and CO2-emissions savings of video-streaming services.
Yilmaz & Uysal (2022)	Global (OECD)	Empirical research	Econometric analysis of driving factors of CO_2 emissions among OECD countries with a specific focus on the ICT sector.

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