A long road ahead: a review of the state of knowledge of the environmental effects of digitization

Gauthier Roussilhe[a*], Anne-Laure Ligozat[b], Sophie Quinton[c]
[a] *RMIT*, Royal Melbourne Institute of Technology, Australia
[b] *Université Paris-Saclay*, CNRS, ENSIIE, LISN, France
[c] *Université Grenoble Alpes, Inria, CNRS, Grenoble INP, LIG, France*
[*] *Corresponding author at:* 124 La Trobe St, Melbourne VIC 3000, Australia.
Email address: gauthier.roussilhe@student.rmit.edu.au

Abstract In this brief review, we report on the state of knowledge and its limitations regarding the environmental footprint of the digital sector. While the final energy consumption and the related carbon footprint of information and communication technologies (ICT) are well studied, other environmental factors and some phases of the life cycle are still poorly understood. New connected equipment and services currently being deployed make such assessments even more complex. In addition, more research is needed on the indirect effects of ICT (*i.e.* substitution, optimization and various rebound effects). Indeed, recent reports tend to ignore or minimize the negative effects of digitization. Because indirect effects depend on external factors such as regulations, prices, socio-cultural contexts, etc., extrapolations are extremely uncertain. Methodological elements have been proposed to perform such evaluations, but there is still a long way to go.

Keywords *Sustainability, ICT, Environmental Footprint, Digitization.*

1 Introduction

While the environmental effects of digitization have been studied since the 1990s [19], many questions are still open. The current environmental emergency and the need to transition rapidly towards more sustainable societies, combined with the ever increasing development, deployment and use of information and communication technologies (ICT), are making this topic particularly important today. This review intends to provide a broad overview of the current state of knowledge in the field. As it is often the case (see for example [23] and [7]), we will first discuss the *direct* environmental effects of ICT, namely those that result from the life cycle of the underlying equipment (end-user devices, networks and data centers). We will then address *indirect* effects, *i.e.* the (positive or negative) environmental effects of the digitization of other sectors and activities, e.g. through efficiency gains or rebound effects. We conclude with a discussion of gaps in knowledge and future research directions.

2 Estimating the direct effects of digitization

So far, most global assessments of the direct environmental effects of ICT have focused on electricity consumption (including manufacturing and use phases) and greenhouse gas (GHG) emissions (also called carbon footprint) – leaving out other major effects such as material or water footprint, but also pollutions. As a result, our review covers the same limited scope.

The most prominent publications on this topic are: Andrae & Edler [2] which is known to be outdated and superseded by Andrae [1], Malmodin & Lundén [32] and Belkhir & Elmeligi [4]. While they are based on the same breakdown of ICT equipment into data centers, telecommunication networks and end-user devices, these studies have different perimeters. By unifying the scopes considered in [2], [32] and [4], Freitag *et al.* [15] argue that GHG emissions from the ICT sector ranged from 2.1 to 3.9% of global emissions in 2020 (1.2 to 2.2 GtCO2e). Carbon footprint estimates and projections are computed using a mix of top-down views based on global numbers (worldwide data traffic, hardware shipments, etc.) and bottom-up estimates obtained mostly using life cycle assessments (LCAs).

The wide range of ICT's carbon footprint estimate, and most importantly the disagreement over the associated trend — Malmodin & Lundén [32] believe that it will stagnate in coming years, while Andrae [1] anticipates an increase — is explained by differences in the scope chosen, *e.g.* whether to include IoT, cryptocurrencies and other new services, in assumptions (about energy efficiency, ICT decarbonization etc.) but also in extrapolation methods: Malmodin & Lundén project trends based on equipment sales while Andrae & Edler's projections are based on the evolution of data traffic. While the former is too narrow in scope to anticipate future uses and services, the latter is known to be inherently flawed because increasing traffic does not necessarily lead to a similar increase in footprint due to improved equipment efficiency. In a recent paper, Pasek *et al.* [35] identify six key factors that make estimating the carbon footprint of ICT and its future trends complex or even impossible: access to industry data, bottom-up *vs.* top-down assessments, system boundaries (scope), geographic averaging, functional units (*e.g.* KWh/GB or KWh/subscriber), and energy efficiencies.

2.1 Data centers

There is an ongoing debate specifically about data centers, in particular regarding whether the observed and expected increase in data traffic will translate into an increase in data center electricity use[1]. Recent work by Masanet *et al.* [33] estimates worldwide electricity consumption of data centers at 205 TWh in 2018, a modest 6% increase compared to 2010, despite a ten-fold increase in data traffic. In contrast, based on data sets from the European and German data center industry, Hintemann and Hinterholzer [22] estimated worldwide energy consumption of data centers at around 400 TWh in 2020. The difference between these two figures can be explained by differences in the estimated number of hyperscale data centers (which are particularly efficient), and "differences in scope (e.g. including or excluding crypto mining), methodologies and assumptions" according to the International Energy Agency (IEA), which recently estimated that data center electricity consumption in 2021 was between 220 and 320 TWh [24] (without including cryptocurrencies).

In addition to electricity, water consumption and related water stress have been pinpointed as a major issue for the data center industry [34, 42], as well as the renewal rate of IT equipment which is likely to increase its manufacturing footprint [18].

[1]Note that this leaves out other life cycle impacts such as energy consumption due to manufacturing.

2.2 Networks

Like for data centers, studies on networks are generally focused on electricity consumption as the use phase represents a significant part of their carbon footprint (around 80%) [31]. Malmodin and Lundén [31] assessed the carbon footprint of ICT networks, up to 169 MtCO2e and 242 TWh in 2015. By synthesizing most of the available studies on this subject, Coroamă [10] estimates this consumption at 340 TWh in 2020. He points out the lack of coherence of the available results, e.g. a divergence factor of 5-26 between bottom-up and top-down studies. The IEA estimates that energy consumption of networks was between 260 and 340 TWh in 2021 [24].

However, these studies do not account for manufacturing impacts that are yet to be better understood. Given that the carbon footprint of the 700,000 5G base stations installed in China was estimated at around 17±5 MtCO2e in 2020 [13] – accounting for manufacturing, transport, construction and use – with the use phase accounting for an estimated 9.8 MtCO2e, such impacts are clearly significant.

2.3 End-user devices

The environmental footprint of end-user devices is generally assessed through LCAs. The global footprint is then obtained in a bottom-up fashion by estimating the number of devices of various types that are manufactured (based on sales number), in use (based on estimates of the average lifespan of such devices) and discarded in a given year, and multiplying these numbers by the corresponding impact of each type of device. Clément *et al.* [9] performed a review of available LCAs of smartphones and tablets which showed the importance of the manufacturing phase, and specifically that of integrated circuits (ICs), in the environmental impact of devices. There are no up-to-date data for computers and displays (see [6, 14, 45] for older studies).

Looking more precisely at key components such as ICs, Bardon et al [3] and [40] estimate that the environmental footprint of more advanced technological nodes (below 10nm) is increasing, possibly due to new manufacturing processes. Beyond these familiar devices, a whole new range of devices are appearing with the advent of the Internet of Things (IoT). Pirson and Bol showed that the carbon footprint of IoT edge devices with different hardware profiles can vary up to a factor of 158× [39]. Many other devices are poorly accounted for. For instance, electronic devices (ICs, sensors, etc.) used in other sectors, such as the car industry, are understudied, although they are at the core of new mobility solutions. Kemp *et al.* [26] or Sudhakar *et al.* [44] estimate that electronic equipment could represent an important part of the life cycle GHG emissions of an autonomous electric vehicle.

2.4 Challenges due to new digital technologies

Emerging digital technologies such as blockchain or Artifical Intelligence (AI) represent new challenges for assessing the environmental effects of ICT. For instance, as the use of AI is becoming ubiquitous, the environmental impact of training natural language processing (NLP) models has become a source of concern – see for example Strubell *et al.* [43] and Patterson et al [37, 38]. While these studies roughly follow the division between data centers, networks and end-user devices, the terms used and the areas of focus differ. AI/ML applications look at the training phase generally done in data centers but rarely integrate the use phase on various devices, called in this case the inference phase. Furthermore, the manufacturing phase is not always taken into account.

Gupta *et al.* [18] emphasize the increasing part of manufacturing in the life cycle of computing and AI in particular while Wu *et al.* [47], Kaack *et al.* [25] and Ligozat *et al.* [28] advocate for more extensive evaluations of AI systems, taking into account the whole life cycle of equipment, the different phases of AI, and its indirect effects. New digital technologies and their uses influence the expansion of digital infrastructures and could increase the absolute global environmental footprint, regardless of the efficiency of the equipment that supports them. These effects must therefore be studied in a broader framework than that of an isolated technology deployment.

3 Estimating the indirect effects of digitization

Different classifications have been proposed to describe the indirect environmental effects of digitization. In 2006, Hilty *et al.* [21] proposed a classification between 1st order effects related to the life cycle of a product or service, 2nd order effects related to the efficiency and substitution effects of a service, and 3rd order effects related to behavioral and structural changes brought about by a service. Hilty and Aebischer [20] proposed a new version of this classification in 2014 with the LES model, with the L standing for life-cycle impact, the E for enabling impact (benefits of using ICT services) and S for structural impact (socio-economic impacts of ICT). Horner *et al.* [23] summarize the different categorizations that have been proposed in the past: indirect effect of a single service (efficiency, substitution, direct rebound), indirect effect of complementary services (indirect rebound), economy-wide and society-wide indirect effects. For the sake of simplicity, we use here the first classification used by Hilty *et al.* by separating the enabling effects, i.e. the benefits resulting from the use of an ICT service, and the rebound effects, whether they are direct, indirect or socio-economic wide.

While enabling effects are well understood in the form of efficiency or substitution, rebound effects require further explanation. A rebound effect is identified as a positive impact (less resources consumed, more efficient process) on a service or product which leads to an increased demand on the latter or beyond. Coroamă and Mattern [12] identify several types of rebound effect that could apply to digital technologies: a direct rebound effect (optimization of a product leads to an increased consumption), a backfire (when the rebound effect is more impactful that the original solution), indirect rebounds (when the rebound happens out of the original scope), time rebound (linked to the cost of time-saving technologies), and macro-level rebounds (economy/society-wide). Moreover, Bieser and Hilty notice that structural effects (macro-level rebounds) are mostly ignored in the literature. [7]

3.1 Enabling effects

To the best of our knowledge, no scientific publication so far has provided an assessment of the global (current or potential) enabling effects of digitization for GHG emissions mitigation[2]. Still, two claims have been widely shared amongst stakeholders and tech companies since 2015: that digitization could reduce global GHG emissions by up to 20% (12 GtCO2e) in 2030 according to GeSI [16], a partnership of companies from the ICT sector; and that mobile communication technologies enabled the avoidance of 2.1 GtCO2e in 2018 according to GSMA [17], the association representing the interests of mobile operators worldwide. Both reports show major methodological flaws and their results should be used with extreme caution, as we explain below.

[2]Note that a few scientific studies do exist at the macro (but not global) scale, *e.g.* Malmodin *et al.* [29].

The GeSI report proceeds by extrapolation from industrial case studies and conversations with experts. For a given digital solution, the authors select a few GHG abatement levers and corresponding impacts, weigh them by an adoption rate (different for OECD and non-OECD countries) and compare the result to a baseline scenario based on IPCC and WRI projections. As an example, they estimate a potential of avoided emissions for mobility at 3.6 GtCO2e by 2030, based on the hypothesis that digitization could reduce car production by -15%, fuel consumed by -30%, and all freight (maritime, road, air) between -20 and -30%. Similarly, GSMA's estimates are obtained by multiplying, for each case studied, an avoided emission factor by the number of smartphones in use (or machine-to-machine connections) to obtain a global estimate. The largest source of avoided emissions relates to accommodation sharing (AirBnB, Couchsurfing), up to 221 MtCO2e avoided in 2018. This result is based on an avoided emission factor of 56.2 kgCO2e per smartphone, obtained through the answers of 6,000 smartphone users to an online survey and a single study commissioned by AirBnB in 2014 comparing GHG emissions of shared accommodation *vs.* hotel. Of the 2.1 Gt of potential emissions avoided, around 10% are thus obtained by a global extrapolation of the responses of this sample of 6.000 people.

The complexity of performing macro-studies, pointed out in [29], is also addressed by Malmodin and Coroamă [30] who pinpoint shortcomings due to extrapolations from case studies — in particular, the fact that the representativeness of these case studies is critical but rarely discussed. For instance, if a pilot project or a case study works somewhere under specific conditions, this result cannot be extrapolated until you manage to reproduce the same conditions: a smart thermostat works better in an well insulated house, a bike-sharing app is more effective once you develop a biking infrastructure and so on. Furthermore, there is no guarantee that indirect effects, whether positive or negative, are maintained over time, so it is better to keep assumptions and a baseline scenario conservative.

Other issues that appear even at smaller scales, which are discussed by Coroamă *et al.* [11], Bergmak *et al.* [5] and Rasoldier *et al.* [41] include: ignoring life-cycle impacts (*i.e.* the environmental footprint of the ICT service/product under study), and structural impacts (rebound effects, society-wide effects); and overlooking the fact that the success or failure of an ICT service depends on factors outside of the ICT sector (policies, price, culture, etc.). Methodologies to address this are proposed from the perspective of a single service in [11] and [41], and from the perspective of multiples services and companies in [5].

In the light of all these issues, it appears clearly that the existing grey literature focuses on positive effects, while ignoring or minimizing possible negative outcomes.

3.2 Rebound effects

Rebound effects are particularly hard to track as they can apply from the micro to the macro scale. Coroamă and Mattern [12] note that "the mechanisms behind rebound effects in general, and thus of digital rebound as well, are essentially non-technical in nature. Their roots reside in economics and in human behavior." Following this observation, Lange *et al.* [27] study if ICT reduces energy demand, including direct and indirect effects. Their conclusion points out two energy-reducing effects (increase of energy efficiency and sectoral change / tertiarization) and two energy-increasing effects (direct effects and economic growth).

At a smaller scale, it is possible to observe rebound effects. For instance, based on English travel patterns from 2005 to 2019, Caldarola and Sorrell [8] estimate that while teleworkers take fewer trips than non-teleworkers, they travel farther, suggesting that teleworking does not reduce travel. On a similar topic, Ward *et al.* [46] study the effects of switching from private vehicle travel to transportation networks companies (TNCs) such as Uber or Lyft. Based on a Monte Carlo simulation of 100,000 passenger trips in six U.S. cities, they estimate that shifting from private vehicle travel to TNCs reduces air pollutants by 50-60% on average, but increases fuel consumption and greenhouse gases emissions by 20% due to deadheading, and external costs by 60% due to congestion, crashes and noise. Rebound effects can help us understand where digitization cannot be a solution in today's society, but studying them could also help figure out in which social, economic, technological, political conditions digitization could actually work.

Studies that focus on enabling effects generally avoid studying rebound effects because of their complexity and because they depend on behavioral or structural changes. For instance, the authors of the GeSI report [16] discussed previously also estimate a rebound effect of 1.37 GtCO2e that is not deducted from the 12 GtCO2e total of potential avoided emissions due to the fact that "the science behind rebound is generally tricky and a matter of debate." This argument is however debatable since enabling effects such as the energy savings obtained by a smart meter (taken into account in the GeSI or GSMA estimates) are equally complex: a smart meter does not in itself guarantee energy savings, it is the potential changes in behavior enabled by the visualization of consumption data that could lead to avoided GHG emissions. There has thus been so far a double standard when it comes to modeling indirect effects. This needs to change if we want to estimate potential net effects, integrating both enabling effects and rebound effects.

4 Gaps in knowledge and future research directions

In its last report [36], the IPCC Working Group III mentions: "At present, the understanding of both the direct and indirect impacts of digitalisation on energy use, carbon emissions and potential mitigation is limited." Our brief review of the current state of knowledge is in line with this statement.

Table 1 lists the gaps in knowledge that we have identified in Section 2 regarding the direct environmental effects of digitization. Data from manufacturers, whether American, European or Asian, are not available for public research, resulting in the environmental factors related to manufacturing being understudied. End of life (EoL) is even less understood because of the lack of traceability of end-of-life equipment and the geographical dispersion of formal and informal treatment of e-waste, while significant pollution can take place at the local level. Besides, because global studies have focused on the ICT sector, there are no environmental assessments of ICT products that go directly to other sectors (*e.g.* chips for the automotive industry). Finally, providing a reliable estimate of the environmental footprint of a digital service is still a complex exercise, especially with new services being promoted every year (metaverse, etc.).

Indirect effects of digitization are even more complicated to assess. Global studies from the industry mostly focused on positive impacts, presenting only partial and unreliable estimates. Research about indirect effects of digitization raises many methodological questions that are still open. We have summarized in Table 2 the gaps in knowledge and recommendations for future work discussed in Section 3.

While ICT are at the core of most critical infrastructures and human activities, the role they can play to mitigate GHG emissions remains unclear. More research is needed to identify under which multi-faceted conditions (taking into account territorial specificities) a digital solution can have positive effects, and under which it has negative effects, meaning it is better not to deploy it or even to "un-digitize" it depending on the situation. Last but not least, one should acknowledge that our times require urgent action and that answers to many questions raised in this paper may not get scientifically sound answers quickly enough. One crucial question that remains is then: what do we need to know to make decisions?

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Table 1: Summary of the gaps in knowledge regarding direct effects of digitization, based on [32], [4], [1] and [15].

	Historical focus	**Gaps of knowledge**
Life cycle stages	Use phase	Raw material extraction, manufacturing, maintenance, EoL
Environmental impact indicators	Final energy consumption, GHG emissions	4 studied out of 19 recommended by the European Union Product Environmental Footprint
Infrastructures	Data center, networks, end-user devices	Edge computing, IoT / IIoT, telecom satellites (no data), network deployment, etc.
Services	Data transfer (esp. streaming)	IA / ML life cycle, AR / VR related services, blockchains (esp. manufacturing), etc.
Geographical areas	North America, Europe	Asia for manufacturing, EoL (worldwide)
Sectors	ICT / E&M sector	All sectors except ICT / E&M sector

Table 2: Summary of the gaps in knowledge and methodological recommendations regarding indirect effects of digitization, based on [7], [11], [41], and [12].

	Historical focus	**Gaps of knowledge (G) and recommendations (R)**
Life cycle impacts of ICT solution	Use phase	Impact transfers to other life cycle phases (G)
Environmental impact indicators	Saved energy consumption, avoided emissions	Negative effects are mostly ignored (G)
Baseline choice	Business-As-Usual (worst case scenario)	Counterfactual scenarization / Time perspective including efficiency gains, induced demand, etc. (R)
External social, economic, environmental factors inclusion	Mostly ignored or implicit hypotheses	External conditions in which an ICT solution can have and cannot have a positive impact (G/R)
Input data	Small-case and uncertainty due to lack of availability	Better open data policies and governance / limited extrapolation of uncertain data (R)
Extrapolation method	Global extrapolation from small scale leading to misestimates	Use of a conservative extrapolation factor / refer to a present effect / study based on random sampling scheme / avoid global extrapolations or limit the scale (R)
Rebound effects	Mostly ignored	Need for future assessments of rebound effect including more than just ICT service usage (R)