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BEHIND THE FIGURES: understanding the environmental impacts of ICT and taking action

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This study was prepared under the direction of Frédéric Bordage, founder of GreenIT.fr.

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The case studies were prepared and written by Lorraine de Montenay, with contributions from Julie Orgelet, Frédéric Bordage, Etienne Lees-Perasso, Damien Prunel, Caroline Vateau, Romain Mahasenga and Sofia Benqassem, and the expertise of Michel Bénard, Jacques Combaz, Claire Downey, Laura Draetta, Fabrice Flipo, Guillaume Pitron and Gauthier Roussilhe whom we thank for the quality of their contributions and their participation.

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Case studies methodology

For some of the most recent technological innovations in ICT, which is the case for Artificial Intelligence for example, the data to measure what are the environmental impacts of these technologies is not enough available to estimate in a quantified approach the environmental impacts of these technologies at the scale of Europe in a multicriteria life-cycle assessment (LCA). Yet, **it is not because there is a lack of data that there are no environmental impacts**. We still wanted to address these subjects even if they could not be integrated in the LCA, to limit the blind spots.

As the aim of this study is to make the understanding of the environmental impacts of digital technology accessible to a large audience, we wanted to give the general public the opportunity to become more familiar with the scientific method of life cycle analysis and to understand, beyond the figures of the life cycle analysis, what are the main environmental issues linked to digital technology.

To ensure a global comprehension of the environmental impacts of digital technologies and bring an answer to these difficulties, we wrote 8 case studies.

The case studies were selected to represent the key topics that allow us to understand **how the digital ecosystem works today and the environmental issues it raises for today and tomorrow.**

We divided the case studies in two categories: case studies focused on technologies and case studies focused on environmental impacts.

The “tech” case studies are on the following subjects:

1. The Internet of Things (IoT) and connected objects

2. Artificial intelligence

3. Cloud

4. 5G

5. Autonomous vehicles

The “environmental effects” case studies are on the following subjects:

6. Rebound effects

7. Raw materials

8. E-waste & circular economy

How are case studies composed?

Each case study begins with a “key data for magnitude” header, which allows to browse quickly what are the key stakes in a broad perspective, at a global or the European scale.

For each case study, the summary enables to understand the key points developed in the case study.

Each case study is also provided with a definition section: this section will help non-tech-experts to understand key technology definitions, or key environmental notions in the case of environmental case studies.

The heart of each case study is then to explain why the technology addressed is a lever or a hindrance for climate and the environment, as well as highlighting some key findings or when possible, some examples of solutions. In the case of the environmental case studies (rebound effects, raw materials, e-waste & circular economy), the impacts and the principal stakes for Europe are addressed.

During the 4 months of research and writing of those 8 case studies, we also interviewed some experts outside our team, bringing a complementary overlook at the different topics explored. Their contribution are made available to the reader in the box “the expert’s view”, for each case study in which we have been able to involve them. We specially thank them for their time and their various and always qualitative contributions, which brings perspective to our case studies: Michel Bénard, Jacques Combaz, Claire Downey, Laura Draetta, Fabrice Flipo, Guillaume Pitron, Gauthier Roussilhe.

Bring rigorous yet accessible case studies to read

We wanted to ensure that our case studies were rigorous and accessible to anyone who is novice in the understanding of the environmental impacts of ICT or more advanced.

To ensure our case studies were rigorously written, we looked as much as we could at critical reviewed life-cycle assessment studies to support our words, and at the state-of-the-art knowledge on the different topics. We were also as transparent as possible on the sources of the data, by providing our sources in the footnotes, when possible, with a hyperlink to the resource. We relied as much as possible on publicly accessible data. Moreover, the case studies were cross-reviewed by at least 3 different people from our team and the expert interviewed for each case study with an interview (6 case studies over 8).

To make our case studies accessible to anyone, we made a compromise between being synthetic and giving enough details to be transparent on the logical chains. Our case studies are about 9 to 13 pages each, which allows the reader to choose its right level of detail: the reader can have a quick reading, by focusing on the “data for magnitude” header at the beginning of each case study, the figures, and quotations, or have a more in depth reading from the beginning to the end of the case study. A reader that would like to have the most in depth understanding of a specific subject addressed in a case study could easily develop complementary knowledge by following the links to the sources we used.

From inter-relations between the case studies topic to a finding: interdependency from one technology to another

As each topic addressed in case studies open many doors on other topics, we had to limit the field of our work to not change our project in a Wikipedia of the environmental footprint of the ICT (which would be great but represents a huge work that was neither the aim nor compatible with the scope of our work). However, we found many interlinks between the different topics addressed in the case studies, that we have highlighted, to facilitate navigation from one case study to another. At the end of this work, the observation that we make is that there are, beyond the simple interconnections between these subjects, real links of dependence from one technology to another, and that we find in these studies of cases.

Case study digest

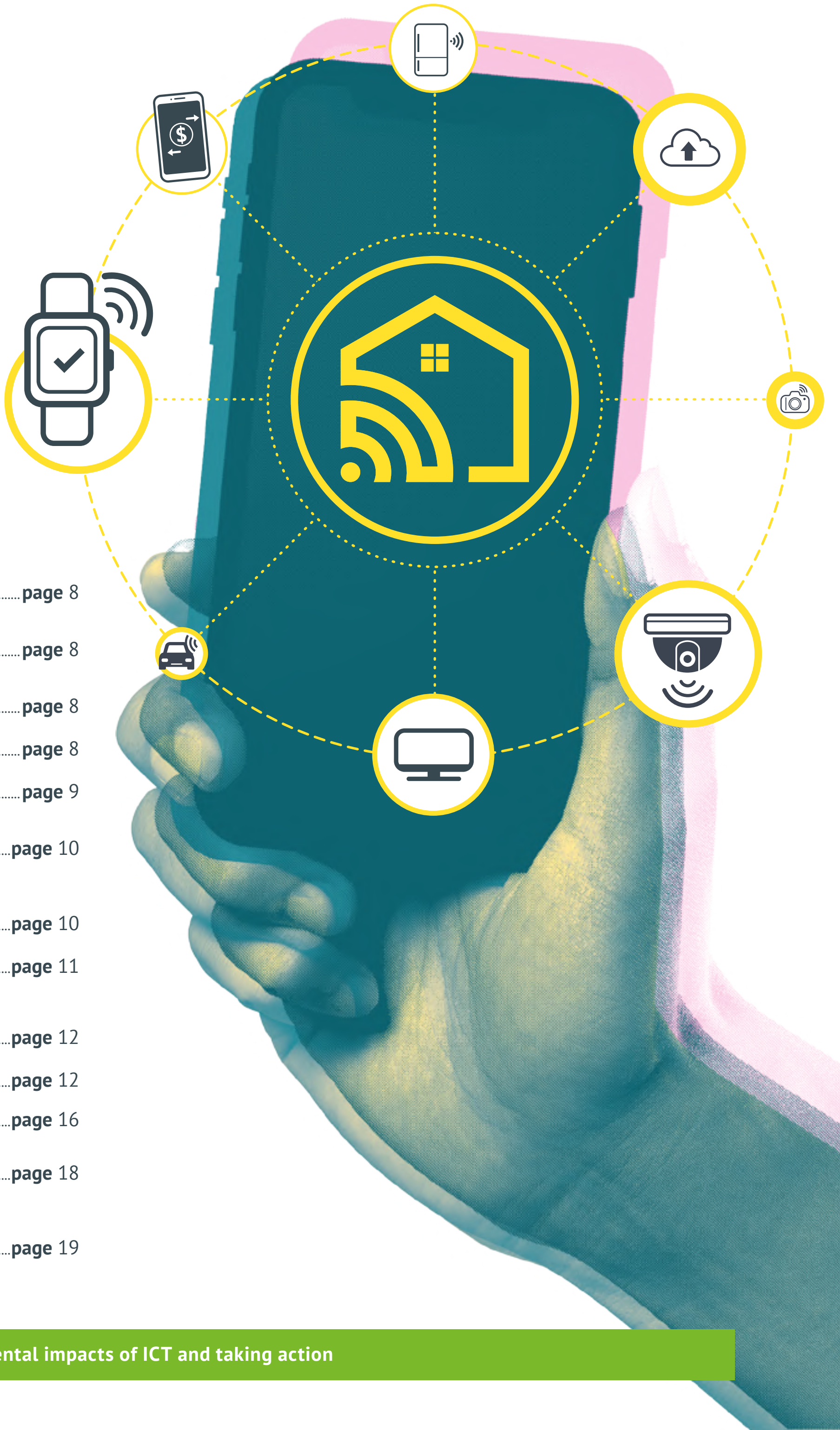
TECH CASE STUDIES		
IoT and connected objects	p. 7	The IoT is expending quickly but is only at the very beginning of the rise expected. **The IoT rise contributes already and will contribute to endanger both the climate and the stock of critical resources** that is used to manufacture both ICT and sustainable development technologies (electrical vehicle batteries, photovoltaic panels).
Artificial Intelligence	p. 20	Artificial Intelligence processing and learning is very energy intensive. **Eliminate unnecessary data acquisition and processing, plus take into account the real cost of 'free applications' or 'free data'** are two keys to reduce and regulate the AI greediness.
Cloud computing	p. 31	In the **short term**, the priority is to limit the zombie servers with major economic benefits. In the **long run**, integrate sovereign clean cloud in a digital plan, ensure edge computing is not killing the mutualisation benefits of cloud for some milliseconds saved, stimulate users' goods practices.
5G	p. 43	If 5G precipitates the production of more terminals and connected objects, these effects will undeniably exacerbate mining and contribute to the unsustainability of the digital sector.
Autonomous Vehicles	p. 55	**Autonomous vehicles are mostly found to increase vehicle distance travelled and reduce the share of public transport and slow modes of transport. This could exacerbate GHG emissions.** To avoid this predictable rebound effect, user behaviours must be considered in policy-making decisions in a wider vision of the transport infrastructure evolution.

ENVIRONMENTAL EFFECTS CASE STUDIES		
Rebound effects	p. 65	Efficiency in technology is systematically associated with large scale systemic rebound effects when sobriety measures are not immediately associated to it. **Both user behaviours and economic players strategies must be considered in policies to prevent rebound effects.**
Raw materials in ICT	p. 77	**Raw materials used in ICT are non-renewable. The stock of mineral and metals is limited, unequally accessible on the planet.** EU autonomy cannot be ensured by mining within the EU. Raw material extraction and refining has enormous and various environmental impacts which means even in the greener cases, extraction and refining provoke multiple and frequent environmental disasters. **Metal extraction and refining is the second most polluting human activity on Earth just after lead-battery recycling.**
E-Waste & circular economy	p. 90	It is necessary to **increase the collection of equipment (still working or not) to stimulating the circular economy and stimulate industry interest for recycling.** The Bale convention is still not respected by the EU though the **EU have short term sovereignty interests to keep and recycle the WEEE inside the EU.**

TECH CASE STUDIES:

- IoT and connected objects
- Artificial Intelligence
- Cloud computing
- 5G
- Autonomous Vehicles

IoT and connected objects



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Key data for magnitude

20%
of the total digital transformation spendings is in IoT devices for more than half the companies in Europe[i]

12bn
IoT devices actively connected worldwide in 2019 (half the devices)[ii]

31bn
IoT devices actively connected expected worldwide for 2025[ii]

84bn devices expected worldwide in 2030[iii]

71%	**6%**	**16%**	**2%**
of devices are expected to be M2M devices[iii]	of devices are expected to be connected TVs[iii]	of devices are expected to be smartphones[iii]	of devices are expected to be tablets and PCs[iii]
12% of data traffic[iii]	**15%** of data traffic[iii]	**53%** of data traffic[iii]	**20%** of data traffic[iii]
x44 in 12 years[iii]	**x16.2** in 12 years[iii]	**x34.8** in 12 years[iii]	**x7.4** in 12 years[iii]

Data traffic is expected to be multiplied by 18.4 between 2018 and 2030, driven by the IoT and smartphone[iii]

[i] Accenture, *Digital Industrial Transformation with the Internet of Things*, 2017
[ii] IoT Analytics, *State of the IoT 2020: 12 billion IoT connections, surpassing non-IoT for the first time*, Press release, November 19, 2020
[iii] McKinsey Global Institute, *Connected world: An evolution in connectivity beyond the 5G revolution*, February 2020, p.36

Summary of the case study

The IoT is a young and complex technology area, regrouping a miscellany of connected electronic devices which are difficult to define and count and increasingly difficult to measure in terms of their environmental impact as they are diversifying ever more quickly and experiencing exponential growth.

In the first section of this case study, we will explore what the IoT is and what kind of connected devices go to make it up. In the second section, we will provide an overview of the environmental issues related to the IoT and its exponential rise. With two concrete examples found in the literature we will see that one of the main IoT-related issues is the entropy of raw material resources used to manufacture electronical compounds as more and more connected devices are manufactured, and that even when smart devices can be used to limit greenhouse gas emissions, the question of impact transfer must be considered at least with regard to raw material resources.

Since most IoT devices are intended for the consumer market or industry, and the proportion of connected devices that will serve to limit and reduce environmental impacts of human activities is still difficult to predict, can the IoT be designed to actively shape a sustainable future? Our recommendation section offers some leads.

Definitions

What is the IoT?

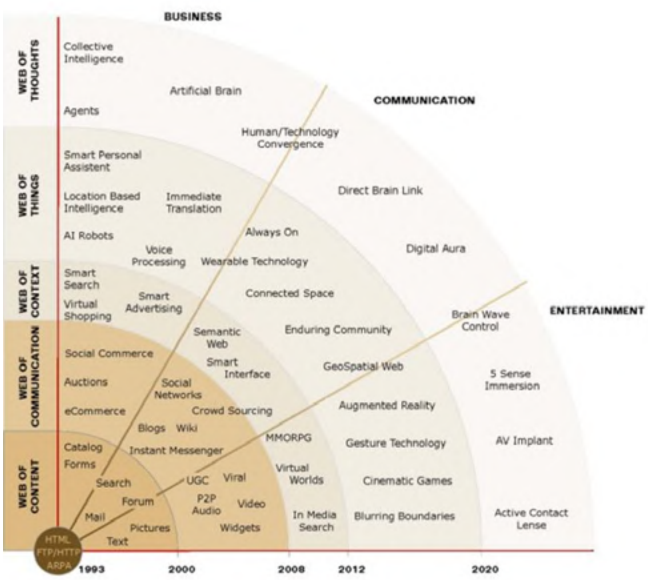
The Internet of Things (IoT) is defined by the ITU as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies".[1]

1 https://www.itu.int/en/ITU-T/gsi/iot/Pages/default.aspx (last retrieved: 02/04/2021)

The aim of the IoT is to connect devices, called connected objects, to the Internet and to one another. Connected objects are a wide category that can be divided into:

- **Personal devices:** Connected speakers, smartwatches, Bluetooth speakers, VR/AR glasses, etc.
- **Connected home devices:** For energy management, connected home alarm systems, connected home appliances such as fridges, robot vacuums, etc.
- **Public IoT and smart city devices:** Security cameras, traffic monitoring devices, energy distribution and grid optimisation, sensors to collect, analyse and share data to improve urban planning, etc.
- **Health and medical care devices:** For monitoring blood pressure, sugar level, body weight, etc.
- **Industry and manufacturing devices:** Automated quality control systems, production monitoring, etc., to enhance operational performance and increase productivity.

The web expansion: from web of things to web of thoughts



Source: ©TrendONE 2008 by Nils Müller; www.TrendONE.de

- **Transportation and mobility devices:** Connected vehicles, telematics and fleet management for vehicle diagnostic or monitoring (battery monitoring, tore pressure monitoring, driver monitoring, etc.)

> *"Connected personal computers, tablets, and smartphones are NOT considered IoT, although these may be part of the solution setup."*
>
> Source: *IoT Analytics*

Main concepts

- **Connected objects or smart objects:** Objects connected to the Internet with a set of functions enabling the object to improve its features thanks to data and software updates provided through the Internet.

A smart device has three types of hardware component: initial object components, smart components, and connectivity components.

- **Initial object components** include the product's mechanical and electrical parts that exist even when the same object is not a connected object (fridge, camera, speaker, etc.)
- **Smart components** consist of the sensors, microprocessors, data storage. In addition to this hardware component basis, the smart device may include software (which is not a component) that contributes its share of "intelligence" through its operating system and enhanced user interface, allowing control of the device.
- **Connectivity components** include the ports and antennas enabling wired or wireless connections with the product.

Intelligence (software and hardware sensing components) and connectivity give an object or product four new capabilities: monitoring, control, optimisation, and autonomy, each one building on the preceding one.[2]

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2 https://hbr.org/2014/11/how-smart-connected-products-are-transforming-competition (last retrieved: 05/04/2021)

A smart device is not an isolated object: to be "smart", the device also relies on a network to communicate and operate with other devices or to feed it data, but also on local (edge computing) or remote (data centres) computing units.

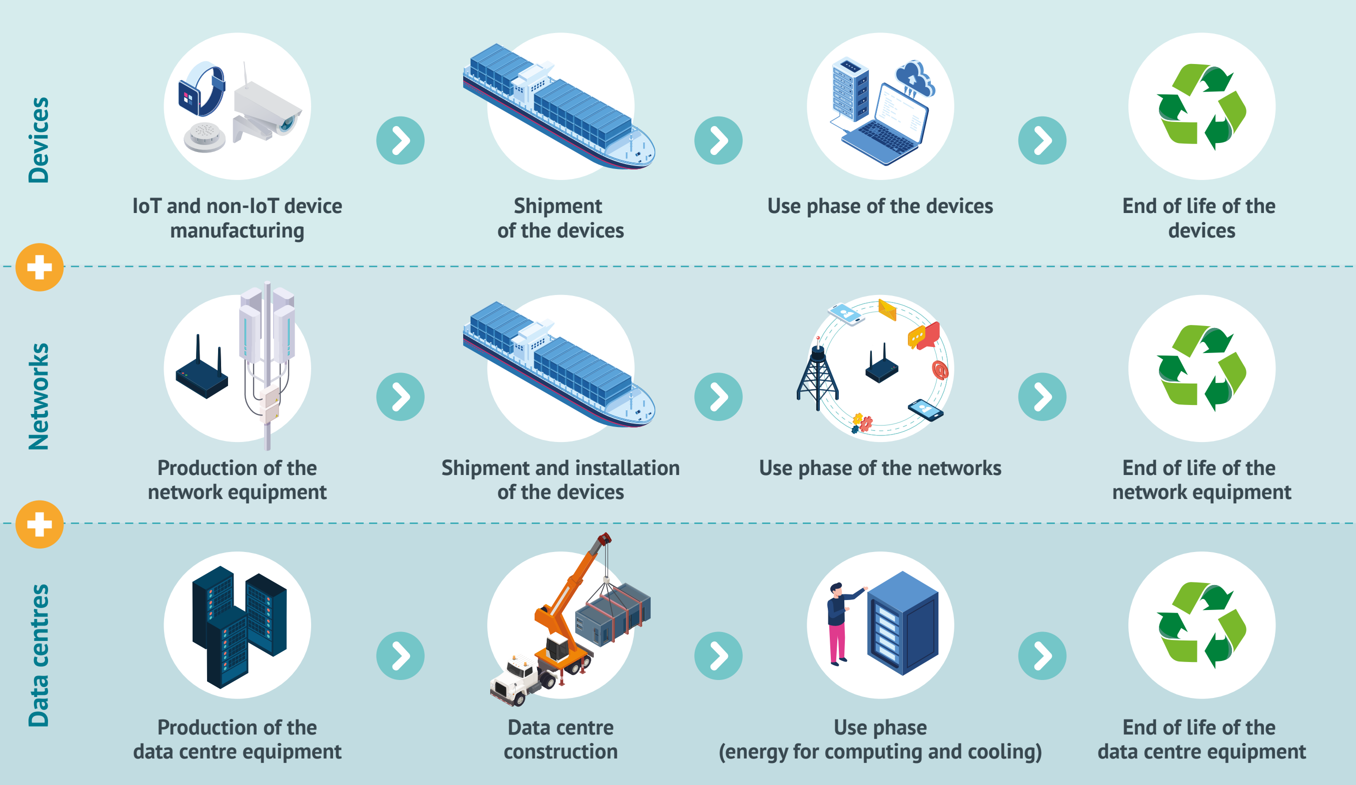
Environmental issues related to IoT applications

Looking at the miscellany of device types in the IoT, the lack of life cycle assessments for connected objects, and the fact the IoT is a very fast-moving industry, it is almost impossible to provide a complete overview of the environmental impacts related to it. In this section, we will see that the information provided by the existing life cycle assessments on some of the connected devices invites us to consider the overall environmental benefits and costs in a multicriteria approach and to limit impact transfers when considering designing a smart device to be environmentally friendly. We will also see that as more and more connected devices are manufactured, each device contributes to the production and the diffusion of e-waste containing rare and precious materials. Lastly, we ask ourselves what the foreseeable consequences of the future rise of the IoT are.

IoT: a lever to achieving the objectives of reducing environmental impacts?

In some cases, IoT applications are intended to help reduce the environmental footprint of human activities, such as when using both IoT and AI to monitor traffic to reduce air pollution, or for optimising industrial manufacturing or predictive maintenance. Nevertheless, in most of the cases described in the literature, the environmental impacts of the solution itself are not assessed, making it impossible to judge whether the overall impact positively impacts our environmental footprint or not (see our case study on AI).

Simplified life-cycle vision of the IoT



Focus on a comparative LCA of three cases of kitchen hood*

In 2018, an Italian team ran a comparative life cycle assessment of three cases of kitchen hood:

- System A: conventional extractor kitchen hood
- System B: smart extractor kitchen hood
- System C: smart filtering kitchen hood with an additional smart aspiration system

This LCA clearly points to the fact that a significant reduction of climate change impact category is possible, with some trade-offs. In the discussion, the researchers explain that "*from a general perspective, the introduction of strategies for the reduction of the energy consumed along the entire product life cycle determines a significant contraction of the related impacts. However, if specific impact categories are observed (e.g., in this case "Human Toxicity" and "Metal Depletion"), the use of electric and electronic components weights adversely on the environmental behavior. Furthermore, for the analyzed cases, the decrease of energy consumption comes at the expense of good air conditions, which are penalized from lower aspiration flow and reduction of air exchange.*"

This means that although the energy consumption of the kitchen hood is limited throughout the hood's life cycle from production to end-of-life, this decrease in consumption is offset by a limitation in its primary use, and there is an impact transfer to consider regarding metal depletion and human toxicity.

The study clearly indicates that not only one, but a plurality of environmental parameters should be considered when designing smart devices to avoid impact transfer: "*According to the current analyzed product configurations, from an environmental point of view, the use of certain materials, such as rare and precious metals, should be reduced. In parallel, strategies to consider also further "environmental" parameters need to be carefully adopted in the development of smart devices, thus avoiding "impact" transfer, which cannot be neglected in a wide concept of environmental sustainability.*"

* V. Castorani et al., *Life cycle assessment of home smart objects: kitchen hood cases*, 2018

In other still rare cases such as the one opposite, a life cycle assessment allows us to see in what way connected devices (here, connected extractor hoods) could help reduce, or at least, limit, our environmental footprint.

It is not possible to judge all the cases of use of connected devices on the basis of one case; however, other life cycle assessments on smart devices or more broadly functioning units in the IoT often tend to draw similar conclusions, showing that the reduction in impact of an IoT object compared to a non-IoT functional unit is not always clear or can be very limited and may result in impact transfers, most notably raw material depletion and hazardous waste production.[3]

Regarding the speed of development of the IoT and the variety of connected devices, the number of studies aimed at understanding the sustainability of the IoT solutions for smart measuring and more generally the environmental impact of the IoT is still low. More systematic measurement of the environmental impacts of new connected devices would allow us to better assess and quantify the conditions in which connected devices and the IoT could be a lever to reduce environmental impacts, or at least contribute to the reduction of these impacts by limiting impact transfer.

3 Lelah A, Mathieux F, Brissaud D, *Contributions to eco-design of machine-to-machine product service systems: the example of waste glass collection*, 2011; Bonvoisin J, Lelah A, Mathieux F, Brissaud D, *An integrated method for environmental assessment and ecodesign of ICT-based optimization services*, 2014; Ingemarsdotter, E., Diener, D., Andersson, S. et al., *Quantifying the Net Environmental Impact of Using IoT to Support Circular Strategies—The Case of Heavy-Duty Truck Tires in Sweden*, 2021

IoT: a hindrance to achieving the objectives of reducing environmental impacts?

Currently, a tsunami of connected objects is sweeping through our daily lives and this boom is not without consequences on the environment. The meteoric rise of the IoT raises three main environmental issues:

1. The environmental impacts of the manufacturing, usage and end-of-life of each device
2. The environmental impacts of data processing (via data centres or edge computing)
3. The possible rebound effect (Jevons' paradox) of the IoT

Focus on the example of the LCA of the Samsung Galaxy Watch*

A life cycle assessment report published in 2020 shows that more than 22 substances are used to manufacture the Samsung Galaxy Smartwatch (46 mm). The minerals and metals (magnesium, iron, copper, chromium, nickel, manganese, and zinc) make up more than 90.56% of the concentration, while non-metallic elements (such as silicon and sulphur) account for about 8%, and hazardous substances (such as lead, arsenic, bromine and mercury) for no more than 900 ppm.

This study also assesses three different user scenarios for the use stage (based on a 3-year use): a high-consumption scenario (power user), an average user scenario (regular user) and a green user scenario, showing that the highest-consumption scenario can almost double the carbon footprint of the smartwatch compared to the greener use case.

* H. Vo, J. Kattleus, S. Karki, S. Shopneel, *Life Cycle Assessment Summary Samsung Galaxy Watch*, 2020

An overview of the environmental impacts of the manufacturing and end-of-life of each device

When assessing the environmental impacts of a connected object in a life cycle assessment, both the smart and connectivity components are taken into account. Components that would have been part of the object even if it had not been "smart" are also included, unless the aim of the LCA is to assess the environmental impacts of ICT (if these components are not electronical components).

Sensing and connectivity components contain a wide variety of raw materials such as magnesium, iron, copper, silicon, chromium, nickel, etc. (see our case study on raw materials). For example, an LCA of the Samsung Galaxy Watch (46 mm), shows that more than 22 substances of concern are used to manufacture the watch (see example opposite)[4].

Although the findings of this study concern only one type of connected watch and one type of device among the galaxy of connected objects, they are a reminder of where the main environmental impact areas of connected objects are (primarily during the manufacturing phase), which is the case of most ICT user devices such as smartphones, laptop, tablets, etc.

> *"The IoT is not only a multitude of connected objects, but also the entire Internet infrastructure that enables these devices to connect with one another and with the rest of the world. This means that millions of servers, kilometres of copper cables and optical fibres, Internet boxes, etc. have to be added to the equation."*

4 Xiuyan Li, K. Lu, *Improving sustainability with simpler alloys*, Science, 2019

The extraction and use in manufacturing of these raw materials contribute greatly to greenhouse gas (GHG) emissions, but also to water and raw material depletion.

Moreover, connected objects characteristically disseminate tiny quantities of numerous critical raw materials all around the world after being used to produce a variety of small, connected objects. Once these materials are extracted, processed, and used to manufacture small components, some in alloys, their recyclability rate decreases dramatically (**see our case study on raw materials**). Currently most designers of connected objects do not take the environmental impacts into account when designing the objects, which is a lost opportunity for regulators to ensure effective traceability and recycling of this diffuse e-waste.

An overview of the environmental impacts of data processing

A systemic view is needed

When running a life cycle assessment with a complete functional unit in mind, for example "*Automatically trigger the watering of a lawn taking into account the humidity of the soil and the weather forecast*", it is also necessary to include the calculation time of the weather forecast servers, the servers to which the object is connected which constitute its brain, the entire network infrastructure, etc. at pro-rata temporis – that is, the percentage of time the equipment is used for that specific purpose – or another allocation method such as CPU performance.

Overview of best fitting technologies for investigated IoT applications

Appl. Area	Application	Edge Device	ANT+	Bluetooth	Bluetooth Smart	DECT ULE	Z-Wave	ZigBee	802.15.4-2011-based	EnOcean	WiFi	Low Power WiFi	Ethernet	GPRS	3G (UMTS)	3G+ (HSPA)	4G (LTE)	LoRa	Sigfox
Smart home	Smart lightning	Smart LED bulb	Y	N	B	Y	Y	Y	Y	Y	N	Y	X	X	X	X	X	X	X
		Gateway	X	X	X	X	X	X	X	X	Y	B	Y	Y	N	N	N	X	X
	Home automation	Sensors	Y	N	Y	Y	Y	Y	B	B	N	Y	N	X	X	X	X	X	X
		Actuators	Y	N	Y	Y	Y	Y	B	B	N	Y	N	X	X	X	X	X	X
		Camera	X	X	X	X	X	X	X	X	Y	X	B	X	Y	Y	Y	X	X
		Gateway	X	X	X	X	X	X	X	X	Y	X	B	X	Y	Y	Y	X	X
	Smart appliances	Smart appliance	Y	N	B	Y	Y	Y	B	B	N	Y	N	X	X	X	X	X	X
		Gateway	X	X	X	X	X	X	X	X	Y	B	Y	Y	N	N	N	X	X
Smart mobility	Smart roads	Roadside unit	X	X	X	X	X	X	X	X	B	X	X	X	X	X	X	X	X
	Smart street	Street luminaires	X	X	X	X	X	X	X	X	X	X	X	Y	N	N	N	B	B

Best Available Technology Possible Technology Not Recommended Technology x Not Appropriate Technology

Source: European Commission, *ICT Impact study, Final report*, prepared by VHK and Viegand Maagoe for the European Commission, July 2020, p.156

IoT and energy consumption

The IoT is constitute of a multitude of connected objects. By adding up all these devices, it already represents an important final energy consumption in the ICT. Our LCA study founds that IoT devices in the EU-28 in 2019 represents about 28 TWh of electric consumption over the year.[5] The IoT is not only a multitude of connected objects, but also the entire Internet infrastructure that enables these devices to connect with one another and with the rest of the world, including a miscellany of networks used for the IoT such as ZigBee, Bluetooth Smart, EnOcean, LoRa, Sigfox, etc. (see table p.13), which all have different characteristics.

This means that millions of servers, kilometres of copper cables and optical fibres, Internet boxes, routers, repeaters, antennas, etc. have to be added to the equation – and all this equipment has to be manufactured, supplied with electricity, in some cases cooled, etc.

The evolution of energy consumption of ICT in the recent years is highly dependent from many efficiency innovations on the network and data centres infrastructures, but also highly sensible to behaviours of users if they buy more ICT equipment and use them often. In that way, the case of the rise of IoT devices is impressive as the IoT end-users' devices only already contribute to about 10% of the final energy consumption of the ICT in the EU-28.[6]

Data traffic and data computing

Data traffic and data computing are two different aspects of connectivity and so their environmental impacts are quite different.

Data management is a crucial aspect of a controlled and acceptable development of the IoT. Edge computing allows various sensors and connected objects to compute data at the nearest point, without having to use a data centre. Edge computing development is therefore concomitant with the development of IoT.

On the one hand, edge computing limits use of the network, but on the other, data centres have made significant progress in recent years regarding their consumption impact thanks, for example, to the rise of hyperscale data centres and colocation and an increased load rate which is synonymous with efficiency gains (see our case study on cloud). As the load rate of a data centre is much higher than that of an edge computing unit, it is not certain that smaller, decentralised, and possibly very numerous, edge computing units would ultimately be as effective as data centres in limiting the environmental impact of data processing.

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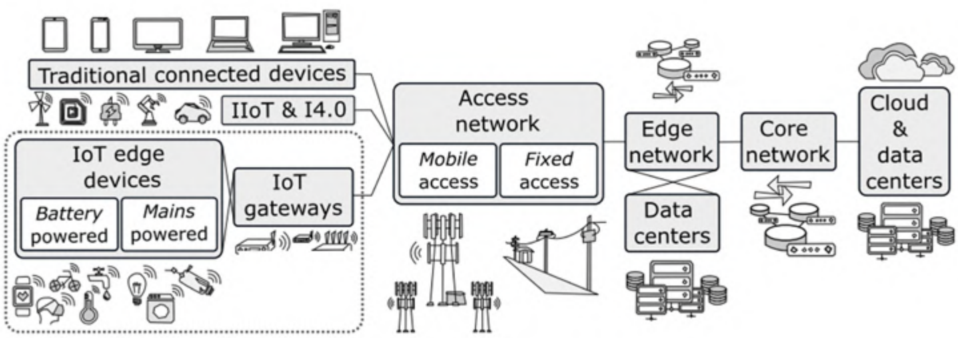
5 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

6 See our LCA study results: Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

Schematic network representations of the IoT, adapted from Pirson & Bol, 2021



Data computing, especially edge computing, is constantly maturing, making it difficult to predict the exact scale of the expansion of the IoT and consequently its overall footprint in terms of material and energy consumption. However, the hype around the IoT is likely to be boosted by 5G in the coming decade (**see our case study on 5G**). Moreover, as 5G is capable of supporting much higher data transmission rates than low-power networks (LoRa, Sigfox), and because the variety and complexity of IoT applications is expected to rise, data consumption by the IoT is very likely to explode in the years ahead.[7]

But to understand how large a share data represents in the environmental footprint of one functional unit in the IoT, it would be necessary to carry out systematic, or at least regular, life cycle assessments on specific functional units in the IoT field.

The huge potential rebound effects of the IoT

The IoT is currently being structured to allow connected objects to be part of a complete ecosystem, consisting of:

- **Devices:** M2M, sensors, user devices, etc.,
- **Networks:** wireline such as fibre, or wireless such as LoRa, NB-IoT, 5G, LTE, Bluetooth, etc.,
- **Services:** Big Data, platform as a service, AI applications, etc.

The IoT enables new uses and potential efficiency and productivity gains which can pave the way for a powerful rebound effect (see our case study on rebound effects).

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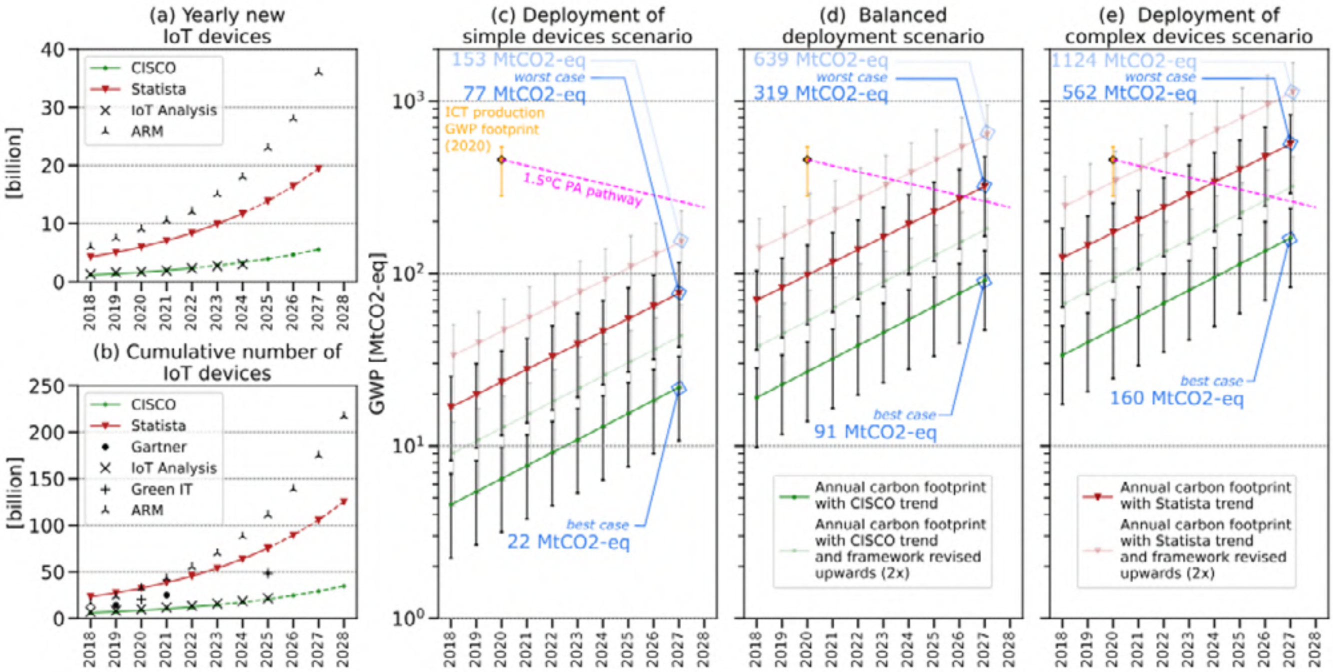
7 McKinsey Global Institute, *Connected world: An evolution in connectivity beyond the 5G revolution*, February 2020, p.36

Yearly deployment of new IoT devices, diagram from Pirson & Bol, 2021



Source: *Yearly deployment of new IoT devices*, diagram from Pirson & Bol, 2021 . "(a) Yearly deployment of new IoT devices computed based on the trends in (b) which represents the cumulative number of IoT devices, according to most popular market studies and predictions. Dashed lines are personal extrapolation [of the authors]. (c-e) Macroscopic analysis of the *annual* carbon footprint generated by the production of IoT edge devices for different massive IoT deployment scenarios, based on (a). Shaded curves show the results if our framework is revised upwards by a factor 2x to account for the truncation error. (c) Scenario 1 *deployment of simples devices* considers a majority of simple devices in the deployment i.e. a=90% of light harware profiles, (d) scenario 2 b*alanced deployment* considers a balanced mix of simple and complex devices i.e. a=50%, (e) scenario 3 *deployment of complex devices* considers a majority of complex devices i.e. a=10%."

The expert's view

Laura Draetta is an environmental sociologist. She first completed a PhD at the École des Hautes Études en Sciences Sociales (EHESS). She has been an associate professor at Telecom Paris for 15 years and simultaneously carries out her research at the Interdisciplinary Institute on Innovation (joint research unit of CNRS). She is co-holder of the RD-ID Chair created at Telecom Paris in partnership with Thales to investigate the theme of responsible digital identity. Her research and teaching focus on the interconnections between technology, environment, and society. She is particularly interested in both responsible innovation and public controversies relating to digital innovations (RFID, smart meters, facial recognition, 5G). Since 2019, she has been a Research Fellow at University of California Berkeley, Center for Science, Technology, Medicine and Society. She works as an Ethics expert with the European Commission and was appointed by ANSES[i] to participate in the collective expertise on smart meters and 5G.

In the project *Trace of ICT: Information technologies and waste management*[ii], you worked on an early case of connected objects, RFID tags. What did the project consist of?

We were interested in the paradox that characterises RFID tags and their specific use in waste management: the risk of generating new waste when the aim is to manage existing waste better. The RFID tag, almost invisible, is often inseparable from the object into which it is incorporated. When the latter reaches the end of its lifecycle, it risks being disposed of with the RFID tag that identifies it. In this case, the tag in turn becomes waste. RFID tags raise the issue of their recyclability because of their small size (difficult to see) and because of the difficulty of separating tags from the objects that embed them. In glass bottles for example, the RFID tag is melted into the mass, which makes it impossible to recover.

This paradox at the origin of the project became an increasing issue in relation to the Internet of Things, which envisions a society where any object can be identified remotely.

The issue arose as much from the point of view of the supply of raw materials as of their recovery.

The project also revealed a fairly significant lack of interest in the issue among manufacturers. The tendency of manufacturers was to highlight the strengths of RFID rather than its weaknesses and to transfer the problem of its environmental impact to their customers. Scientists were more aware of the issue and were interested, for example, in the dematerialisation of RFID tags (tags without antennas or chips). This project led to the publication of a book in 2012[iii] and the coordination of an international workgroup on digital traceability with all stakeholders.[iv]

You also work on controversies linked to smart techs. Why – how – does a controversy arise? How can we remedy it?

The controversy surrounding a new technology is in fact a mode of public, informal technological assessment that is complementary to the formal techno-scientific assessment provided by •••

i https://www.anses.fr/en/content/presentation-anses (last retrieved: 28/06/2021).

ii In French, Trace de TIC: https://journals.openedition.org/terminal/1801?lang=fr (last retrieved: 28/06/2021). This interdisciplinary research project was based on collaboration between sociologists from Télécom Paris (Campus Sophia Antipolis) and industrial engineering researchers from Mines Saint-Etienne (Campus G. Charpak Provence), and it was supported by the ADEME. The project looked at the potential of RFID technology in waste management and its ecological viability.

iii DRAETTA Laura, DELANOË Alexandre, *RFID, une technologie controversée : ethnographie de la construction sociale du risque*, Collection Mondialisation, Hommes et Sociétés, ed. Lavoisier, 2012

iv This workgroup, which was a thinktank within the Observatory for Responsible Innovation, included manufacturers, regulators and academics in the ICT sector. Members of this thinktank have been working on how this promising RFID technology can be deployed in a responsible manner to address privacy, health and environmental issues. The workgroup held a colloquium in Paris and produced a position paper.

••• institutional expertise. It raises new doubts and concerns which widen the field of representations of the proposed technology.

We often hear the call to 'do more educating'. But this 'lack of knowledge' image is inappropriate. It has been shown, with supporting data[v], that people concerned by a new technology are often fully informed and exposed to techno-scientific communication. Education is not necessarily the remedy for stopping or preventing controversy, since it risks answering questions that have not been asked and not answering the right questions.

While not a miracle solution, bringing all the stakeholders to the same table is already progress. The difficulty lies in identifying the relevant stakeholders, which is often where things go wrong, because it is done from the perspective of the promoters, whether industrialists or institutions. Often, citizens are seen only as consumers, and rarely as citizens, and are left out.

Ignoring a controversy has serious consequences. It creates mistrust of the promoters of new technologies. Also, questions that emerge during a controversy will return if unanswered and fuel a new controversy. Controversy is an unanswered question.

v Bucchi M. & Neresini F., 2002, *Biotech remains unloved by the more informed*. Nature, 416: 261.
Raimi K. & Carrico A., 2016, *Understanding and beliefs about smart energy technology*. Energy Research & Social Science, 12: 68-74.

"This paradox [of more environmental impacts created by a technology used to limit environmental impacts] became an increasing issue in relation to the Internet of Things, which envisions a society where any object can be identified remotely.

Laura Draetta

A very recent study submitted for review in 2021[8] that assesses the embodied carbon footprint of IoT devices finds that their heterogeneity makes it very difficult to estimate the absolute carbon footprint of the production of IoT devices, with worldwide results ranging from 22 to 1,124 MtCO2-eq/year in 2027 depending on the deployment scenarios (see figure p. 15) – by way of comparison, the global carbon footprint of ICT production in 2020 lies between 281 and 543 MtCO2-eq.[9]

The study underlines that these trends are in conflict with the Paris Agreement, even in the case of deployment of the simple devices scenario ("*likely to generate concerns after 2030*"[10]). The same study underlines that the IoT meets several conditions that encourage the development of rebound effects, creating "*a fertile ground for rebound effects*"[11].

The future that is emerging for the IoT is thus one of an impressive acceleration in the production and use of connected objects, with a resulting increase in the environmental impacts associated with it. As we have seen, this multiplication of impacts comes on the one hand from the impacts related to the manufacture of connected objects and on the other from the impacts related to the use of these connected objects, but also from the

8 Pirson T., Bol D., *Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach*, 2021
9 Freitag C., Berners-Lee M., Widdicks K., Knowles B., Blair G., and Friday A., *The climate impact of ICT: A review of estimates, trends and regulations*, 2021
10 Pirson T., Bol D., *Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach*, 2021, p.12
11 *Ibid.*, p.13

processing of data and the use of network infrastructure and devices that need to be added to the equation.

Conclusion

The IoT is expected to rocket in the years ahead, yet the benefits it promises will not come without environmental burdens, which are still being overlooked. In the meantime, the few life cycle assessments on IoT devices point out the risk of worsening the current environmental situation; they often conclude by stating the critical need for more life cycle analyses to ensure that decision-making processes focus on the benefits of the IoT without transferring impacts and causing the potential savings to backfire. There is therefore a pressing need to consider the overall environmental benefits and costs in a multicriteria approach and to limit impact transfers when designing an environmentally friendly smart device.

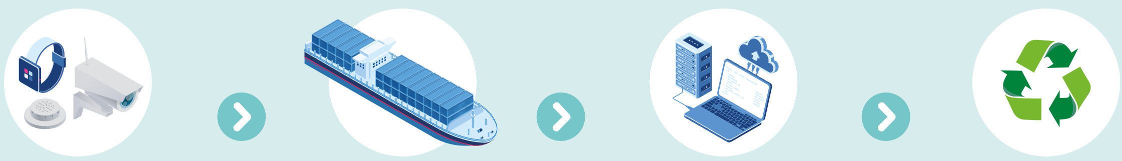
As more and more connected devices are manufactured, we have also seen that each device contributes to scattering some materials used to manufacture these devices, which are often not recyclable[12] (**to learn more, see our case studies on raw materials, e-waste & circular economy**). Moreover, the anticipated huge rise in both the number of connected device units and data traffic underlines the need to set priorities and limits to ensure that the IoT will not be a hindrance to achieving the objectives of reducing environmental impacts, such as global warming, that it will stay in line with the Paris Agreement and not in conflict with it. But also to reduce the depletion of resources that are limited and critical; and finally, to address health and geopolitical sovereignty issues.

Currently, most designers of connected objects do not take the environmental impact into account when designing the objects – or at least not systemically – sometimes even when these objects are intended to reduce humanity's environmental footprint. Eco-design may be a first prerequisite to limiting the environmental impacts of the IoT, but regarding the ongoing exponential rise of the IoT, even if eco-designing connected objects is a necessity will it be sufficient to limit climate change and critical raw material depletion?

Our recommendation section outlines some recommendations for a digital evolution for the IoT which is compatible with the Paris Agreement and the Green Deal.

12 https://www.environnement-magazine.fr/recyclage/article/2015/12/01/46697/quelle-fin-vie-pour-les-puces-rfid last retrieved: 04/06/2021; https://staceyoniot.com/sustainability-is-the-elephant-in-the-iot-room/ last retrieved: 08/07/2021

Simplified vision of environmental impacts related to the IoT



Recommendations for a digital evolution compatible with the Green Deal

Where the IoT is concerned, it is **compulsory to eco-design connected objects in a systemic approach, bearing in mind how they are manufactured and how they interact with their environment.** The connected objects are prioritised for critical uses, such as medicine, and restricted to cases where their overall benefits are proven in order to limit their environmental footprint. To guarantee this environmental gain, a multicriteria life cycle assessment is carried out to verify the overall environmental benefit in a cost-benefit comparison; this is done systematically before the solution can be presented as environmentally friendly, and information is provided to users.

The economic model of the IoT used for efficiency diagnostics and monitoring has been designed to promote a pooled approach to diagnostic services in which the same sensors are used in different locations for a given period and travel around. This limits the risk of disinterest in use of the sensors which occurs after a certain time and enables them to be reused elsewhere once good practices are in place, thereby greatly reducing their environmental impact. One example is the case where the IoT was used to ensure safety on a construction site and made it possible to reduce raw material depletion by 60 per cent, greenhouse gas emissions by 67 per cent and water consumption by 75 per cent thanks to pooling and the circular model approach[i]. Another positive aspect of this model is that it can be used both for BtoC or BtoB, and that when applied to BtoC, it helps limit the digital divide and the perception of monitoring as an intrusion of privacy.

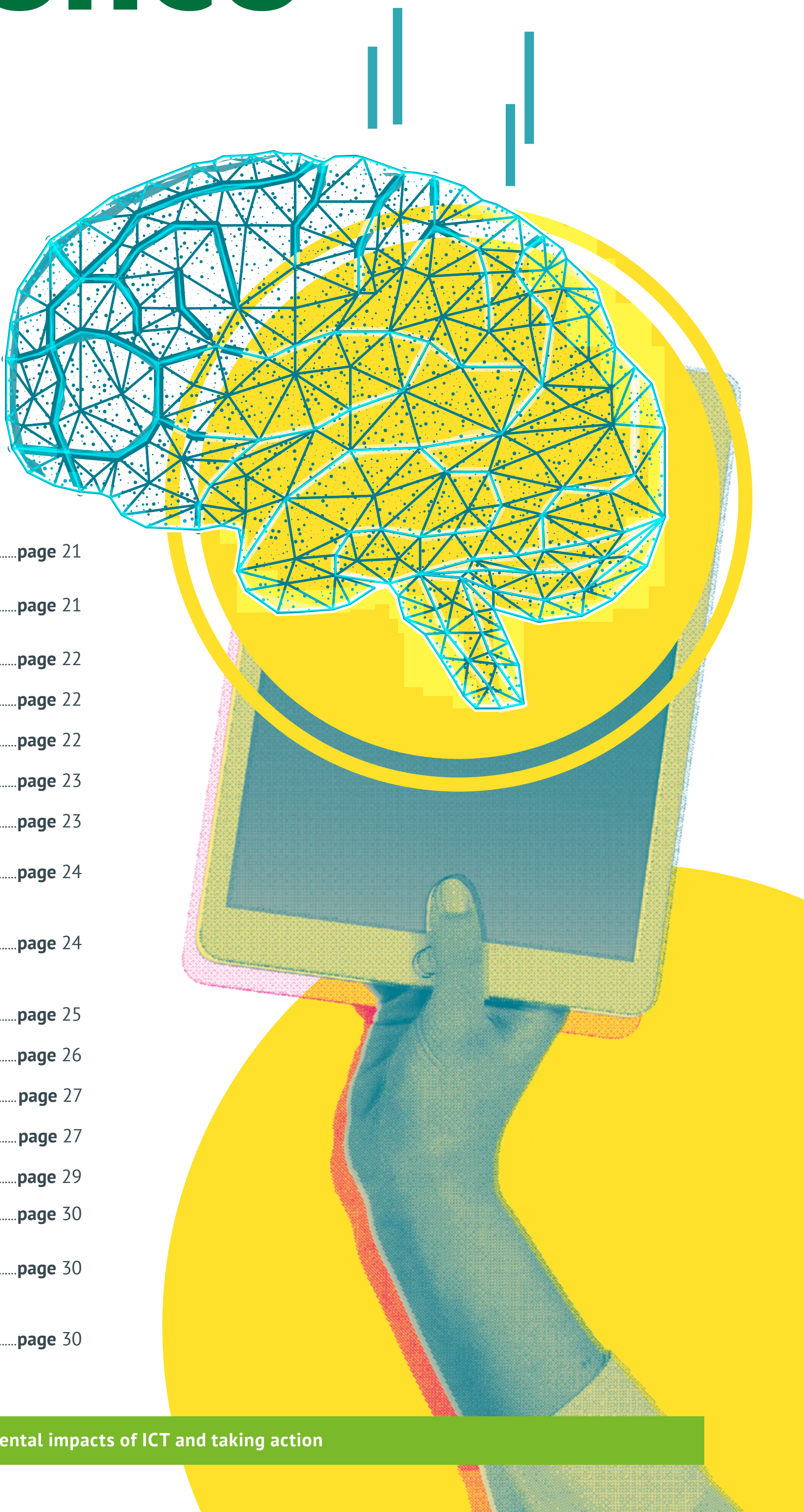
European funding supports the environment-friendly design of high- and low-tech cross-fertilisation innovations: these use the best of both approaches to eco-design solutions that offer the greatest sobriety. Disruptive innovation includes not only technical innovations but also innovative models that enable cooperative and resilient approaches to be developed while strengthening the circular economy in Europe, with a positive impact on Europe's sovereignty as well as climate.

Communication interfaces (API) of connected objects are mandatorily in opensource to allow users to retain the use of their connected objects, even if the service is no longer supported by the original manufacturer, and to provide opensource software updates.

To ensure clear and up-to-date knowledge for the purposes of strategic and political decision-making, multicriteria LCA studies are regularly funded at the European scale to cover the IoT market, both overall and covering specific categories of connected objects, initially the most manufactured and the heaviest.

i French SME use case of ELA Innovation, from the GreenConcept ADEME Operation, between 2017 and 2019: http://www.greenconcept-innovation.fr/wp-content/uploads/2020/02/ELA_INNOVATION_fiche_Ademe_GreenConcept2409.pdf

Artificial Intelligence



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Key data for magnitude

270% growth in adoption of AI by businesses (in four years)[i]

22% of AI start-ups, are located in Europe[ii]

x5 growth (and more) is anticipated for AI semiconductors than for the rest of the market between 2017-2025[iii]

Currently, AI is mainly used in a way that increases our impact:

70% B2B services, is the distribution of AI start-ups in Europe, compared to 64% worldwide[ii]

only 3% of European AI start-ups are related to the Energy (2%), the Agriculture (1%) or Government Urban Management (0%) sectors[ii]

As AI relies more on hardware and data than the rest of the ICT, it runs the risk of an increased dependence of Europe on China and the USA

40 to 50% of total value from the technology stack could be captured by semiconductor companies, although they currently account for 20 to 30% from PCs and 10 to 20% from mobile, as AI applications rely more on hardware as a core enabler of innovation[iii]

[i] Gartner, *Gartner Survey Shows 37 Percent of Organizations Have Implemented AI in Some Form*, Press release, 21 January 2019
[ii] Roland Berger and Asgard, *Artificial Intelligence – A strategy for European startups Recommendations for policymakers*, 2018
[iii] McKinsey & Company, *Artificial-intelligence hardware: New opportunities for semiconductor companies*, 2018

Summary of the case study

This case study provides a general overview of what artificial intelligence (AI) is, what possibilities the recent advances in AI provide, and how it can be a lever or a hindrance to achieving the objective of reducing environmental impacts, based on the available literature. Firstly, we will provide a few definitions that will give a better idea of what AI covers in terms of current usage to help us to understand what AI is and what its current applications are. Secondly, we will explore the burning question: "Is artificial intelligence a lever or a hindrance to achieving the objective of reducing environmental impacts?". At the same time, we will explore in what ways AI is currently helping reduce environmental impacts, although further development and research are needed if it is to make any significant contribution, since the number of cases today are few and the data is insufficient to measure the global benefit for the climate and the environment. We will also take a closer look at the general process followed by AI to show the areas where it has environmental impacts and where these vary the most.

This will enable us to make two main observations about the environmental impact of AI. Firstly, the increasing use of end-user or sensor equipment presents an ever-greater challenge to efforts to limit rebound effects and therefore the environmental impacts of AI applications in the years ahead. Secondly, an increase in computing capacity may limit greenhouse gas emissions during the machine-learning training process yet increase the environmental footprint of AI hardware, as previously used but less powerful hardware becomes obsolete even more quickly.

This also puts the spotlight on the need for greater regulation of AI to ensure that the EU embraces opportunities for frugality and data sovereignty, which is necessary to avoid a further increase of its environmental impacts.

Definitions

The notion of artificial intelligence is entering everyday language just as artificial intelligence is about to permeate our daily lives, from leisure to the professional world, including online shopping, as a profoundly disruptive technology.

What is artificial intelligence?

Abbreviated AI, artificial intelligence is a generic concept referring to "*any machine or algorithm that is capable of observing its environment, learning, and based on the knowledge and experience gained, taking intelligent actions or proposing decisions.*"[1] In this way, AI mimics the capabilities of the human mind and how humans interact with their environment.

The first methodological developments in artificial intelligence date back to the 1970s, with the development of expert systems.[2] It should be noted that expert systems, despite huge investment by several industries, never achieved any successful business outcome, and were therefore abandoned at the end of the 1970s. A long 'AI-winter' then took place, and it was only in the 2000s that research in AI resumed. Since then, significant advances have been achieved by machine learning (ML), and more specifically these advances were made possible by the increasing availability of data and computing power. Tremendous business successes have been achieved with recommendation systems, especially in areas such as e-commerce and ads. Other successes have taken place in industrial areas such as computer vision and predictive maintenance.

These astonishing advances are likely to be only the beginning of what AI should be able to do in the future: the development of the IoT (see our case study on the IoT & connected objects), sensor technologies and the volumes of data used to train the algorithms will boost the capabilities of AI and AI applications in society.

Main concepts

To better understand the concepts underlying artificial intelligence, here are some of the main concepts explained in brief:

- **Machine learning (ML):** Machine learning is a subset of AI which allows it to learn by itself, as it reprogrammes itself throughout the learning process. There is a major paradigm shift here: whereas classical programming uses rules as input to provide an answer as an output, machine learning uses data as input to provide an answer as an output. Here, the systems using machine learning are trained rather than explicitly programmed. Machine learning is better able to work with and learn from structured labelled data and is still struggling with unstructured and unlabelled data.

- **Neural network:** Neural networks are the backbone of deep learning algorithms. Their structure and name are inspired by the way biological neurons interact by signals in the human brain. They work in multiple successive layers. Once neural networks are trained and fine-tuned for accuracy, they can process data at an extremely high speed to provide results.

- **Deep Learning:** "Deep", as in deep learning, refers to the number of layers in a neural network. Deep learning can ingest and process both structured, labelled data and unstructured, unlabelled data.

- **Data:** Quantitative or qualitative information, mostly used for calculations, interpretations and understanding of a fact. Data is at the basis of machine learning.

- **Big data:** Data sets on a larger scale involving data from multiple sources, in large quantities, often in real time. The use of recent advances in network technologies and smart sensors for collecting data enables big data to supply machine learning.

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1 European Commission, *Artificial Intelligence – A European Perspective*, Joint Research Centre, 2018
2 Russell, Stuart; Norvig, Peter. *Artificial Intelligence: A Modern Approach*, 1995

Some non-exhaustive examples of AI applications

Today there are many forms of AI applications. Some of them do not require very advanced AI, others are particularly technologically disruptive. Here are some non-exhaustive examples of what AI can offer today:[3]

- **Handwriting recognition:** The ability to recognise and digitally transcribe handwriting. This application of AI was one of the first modern AI applications in the late 1990s. Today this application is commonly used in the banking industry.

- **Speech recognition:** The ability to recognise speech and transcribe it as text by digital means. Speech recognition capacity drives dictation software on various terminals, from smartphones to connected speakers, including computers with dictation software, GPS, or TV voice remotes. Natural language processing (NLP) is usually the next step after speech recognition.

- **Natural language processing (NLP):** The ability to understand, interpret and generate human text. NLP is used in digital assistants such as connected speakers (e.g. Alexa) or smartphone digital assistants (e.g. Siri). It can also be used in some chatbots. Some NLP, used for example in the analysis of customer experience reviews, relies on sentiment analysis to detect mood and subjective qualities in language.

- **Image recognition:** The ability for the AI to identify and classify any values (items, actions, human) based on an image. Image recognition is mostly used for machine-based tasks such as analysing and granting access. Some examples of image recognition can be found in ID recognition (facial and fingerprint), in autonomous cars and robots, or in medical and financial analysis.

- **Real-time recommendation:** The ability to process data and deliver recommendations based on user preferences, previous user consultations, or any other parameter. It is commonly used to provide similar or appealing content, purchasable items, or any other kind of information related to potential requests, needs or interests.

- **Dynamic ride-share systems:** A system matching multiple variables (distance, time, quality of the service, etc.), that can be based on AI to provide the most optimal service, mostly for car sharing. This system is also used for short runs and deliveries, such as food delivery.

- **AI-based household robots:** Robotic devices used at home that use artificial intelligence to simplify and optimise specific tasks. They usually learn from where they operate based on their characteristics and level of technology. Surveillance robots and vacuum cleaners are a major example of household robots.

KDOG vs LYNA used for breast cancer detection

To limit environmental impacts, AI must complement existing low-tech options. For example, KDOG can be used at random for breast cancer detection, then LYNA used more precisely to detect Breast Cancer Nodal Metastasis:

- **KDOG is an experimental screening method for breast cancer** relying on the extraordinary capabilities of the canine sense of smell: dogs are trained to detect cancer by sniffing sweat-soaked compresses. This simple method is inexpensive, non-invasive, and painless. With only 6 months of training, the dogs are able to reach a success rate of more than 90% at first passage and 100% at the second passage.
- **LYNA (Lymph Node Assistant) is an experimental Google AI based medical assistant** trained to detect tumours by image recognition. In tests, it reached up to 99.3% slide-level accuracy. Even if it is not yet perfect, LYNA achieved better performances than pathologists in tests. Further investigation will show whether the algorithm improves diagnostic accuracy.

3 Examples of uses enabled by AI are quickly evolving and would be arduous to list. Here, we have preferred to provide a selection of the most frequent cases to date, rather than trying to make an exhaustive or near-exhaustive list, which would in any case be hard to read and rapidly obsolete.

- **Autopilot technologies:** A system that uses multiples variables (GPS technology, image recognition, collision-avoidance technology, robotics, and natural language processing) to guide an engine, such as in planes and cars. Autopilot technologies existed previously, but AI enables autopilot engines to go further, for example for military purposes. Autopilot technologies are highly dependent on the quality of the sensors and on the response time.

- **Predictive maintenance:** The ability to anticipate maintenance and more specifically on what part and how it should be performed, based on the data collected on the conditions and the tasks performed, and machine learning from previous failures.

Currently in 2021, we can divide artificial intelligence capabilities into "good enough", "under research", and "fictional": good-enough capabilities are already in use for e-commerce applications, with existing business successes such as ad targeting systems or recommendation systems on well-known platforms such as Amazon or Netflix. For such "good-enough" applications, performances like 92% to 95% accuracy or customer satisfaction are acceptable considering the objective (recommendation of a film, or a pizzeria, or a shirt). Note that such "good-enough" performance range is unacceptable for medical objectives, such as the prediction of a health accident, which would require "mission critical" performance (99.9%, or 99.99%, etc.)

Predictive maintenance is an area in which artificial intelligence has made much progress and is currently reaching the "good-enough" state for market.

Applications related to human perception, such as image recognition, audio & video analytics, handwriting recognition, are also progressing towards the "good-enough" category. Most of them exist as opensource algorithms.

Currently, the more complex the artificial intelligence capabilities, the less operational they are. For example, natural language understanding (NLU) has already made huge progress during the past decade thanks to deep learning and the reinforcement of learning processes, but it is still necessary to process huge amounts of data to obtain better results.

Nowadays, more complex artificial intelligence technologies and capabilities are being developed, such as quantum computing and social robots respectively, but this progress is still too recent to forecast how AI will evolve in the future.

Environmental issues related to AI applications

Many potential AI applications are only just starting to emerge. However, they are already having a significant impact on the capacities deployed in terms of IT and technology (IoT, datacentres, computing power, etc.). This impact is synonymous with tempting promises for economic players and research, but is already contributing to increasing the environmental impact of ICT. In some cases, AI can be used for optimisation purposes, making it possible to further reduce the consumption of resources, optimise distances travelled to reduce them to a minimum, or even prevent breakdowns by performing predictive maintenance.

As AI appears more and more as an enabler, will it be a lever or a hindrance to achieving the objectives of reducing environmental impacts?

Artificial Intelligence: a lever to achieving the objectives of reducing environmental impacts?

In some cases, AI can be used as a lever for optimisation, making it possible to reduce the environmental impact of the use of certain machines or products within specific industries.

This is the case of predictive maintenance, which has made much progress in recent years, thanks in particular to the knowledge acquired by AI of the different types of failure and how to anticipate them. Predictive maintenance is now capable of increasing the period of use of hardware and components, allowing intervention prior to breakage.[4] It can reduce waste, thanks to better conditions of use of the machines, and reduce maintenance costs since maintenance is increasingly carried out only when predicted by predictive maintenance, and only focused on parts with possible malfunctions. However, to date, we have found nothing in the literature that enables us to compare the advantages/disadvantages regarding environmental impact for a more in-depth case study.

Another example of optimisation enabled by AI is the cooling of datacentres. Google revealed in 2016 that it had successfully given control of the cooling of several of its datacentres to DeepMind, an AI algorithm, reducing its datacentre cooling bill by 40%.[5] While energy consumption by datacentres was a pressing issue for the tech industry during the past decades, significant efforts have been made to improve their energy efficiency. Cooling now accounts for a small amount of a datacentre's energy use (see our case study on the cloud). As computing needs, network traffic and storage capacity have exploded in recent years, the energy efficiency of datacentres has been multiplied by 4, which amounts to an increase in datacentre consumption of only 6% in 8 years.[6]

In a paper published in 2019 by the Ellen MacArthur Foundation and Google, with research and support from McKinsey & Company, a primary exploration was drafted of the intersection of the emerging megatrends, AI and the circular economy.[7] This paper presents the initial steps towards identifying cross-sector circular economy applications for artificial intelligence. However the case studies are not sufficiently detailed to compare the advantages and disadvantages on environmental impacts at this stage.[8]

Looking at the upcoming evolutions of AI, energy actors anticipate that it has a role to play in optimising the integration of variable renewable energy (VRE) technologies into power systems. AI is being used or tested for VRE integration to improve renewable energy generation forecasting, maintain grid stability and reliability, improve demand forecasting, optimise energy storage operations, etc.[9]

The role of AI is progressively evolving from a facilitating and optimising tool to a central contributor to smart and fast decision-making. As this metamorphosis is ongoing, is it possible for AI to be both an enabler of technological and economic progress, while being respectful of the environment and helping to achieve the climate objectives of the Paris Agreement?

Artificial intelligence: a hindrance to achieving the objectives of reducing environmental impacts?

To understand if AI is a lever or a hindrance to achieving the objectives of reducing environmental impacts, it is necessary to understand the ongoing process when an AI algorithm is at use.

AI applications may involve completely different kinds of hardware, yet it is impossible to have a life cycle analysis approach which quantifies the overall environmental impacts of AI.

However, by understanding the general process followed by AI, it is possible to draw a picture of the areas where the environmental impacts of AI can vary the most.

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4 Bosch ConnectedWorld Blog, *Industry 4.0: Predictive maintenance use cases in detail* (last retrieved 02/03/2021); AI Multiple, *Predictive vs Preventive: In-depth Maintenance Guide*, 2021, (last retrieved 02/03/2021)

5 DeepMind, *DeepMind AI Reduces Google Data Centre Cooling Bill by 40%*, 2016, (last retrieved, 02/03/2021)

6 Koomey, Jonathan et al., *Recalibrating global data center energy-use estimates*, Science 28 February 2020 (last retrieved 02/03/2021)

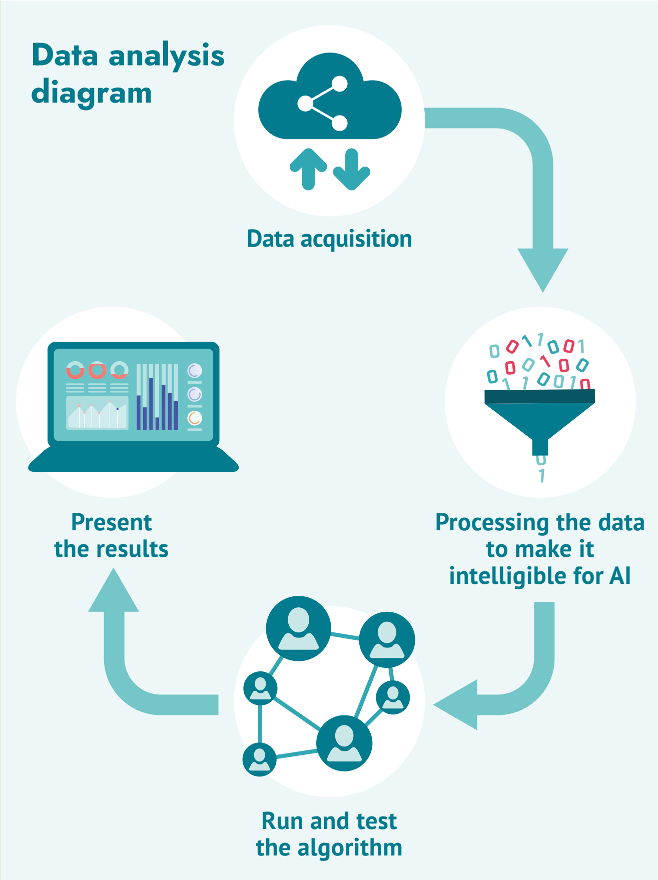
7 Ellen MacArthur Foundation, *Artificial intelligence and the circular economy - AI as a tool to accelerate the transition*, 2019.

8 This paper deals with cases in which there is insufficient information to begin an analysis. The cases reported are an initial approach to what could be developed and do not correspond to cases currently deployed or mature enough. To go further, more detailed cases would be necessary.

9 IRENA International Renewable Energy Agency, *Innovation landscape brief: Artificial intelligence and big data*, 2019

The classic data analysis diagram is also valid for AI:

1. Data acquisition
2. Processing the data to make it editable by AI
3. Run and test the algorithm
4. Present the results



"The more complex the training objective of the AI is, the more data is needed to train the algorithm to obtain accurate results."

1. Data acquisition

To feed AI and train it, a certain amount of data must be collected. The two key prerequisites for data collection to train AI are the same as for documentation and data for research purposes: the data must be of good quality and abundant.

Quality data

AI needs to be supplied by the highest-quality data possible to train the algorithm and provide accurate results. A weak algorithm trained with high-quality data will provide more accurate results than a strong algorithm trained with poor quality data.

"Sensors used for data collection have themselves an environmental impact, which is globally multiplied by the numbers of sensors needed to provide the data."

Abundant data

The more complex the training objective of the AI is, the more data is needed to train the algorithm to obtain accurate results.

Today, a large portion of the machine-learning process done by AI uses large amounts of data. This data needs to be collected, refined to be editable by AI, and then processed to eventually output results.

Depending on what, how and where the data is collected and where it is stored, the environmental impacts related to the use of AI may vary greatly:

What kind of data is collected? Is it thousands of hours of HD videos? Is it 64x64-pixel images? Is it neat and organised Excel tables? The more abundant the data, the greater its environmental impact is likely to be.

How is the data collected? Is it collected by sensors? Is it collected by online consumer behaviour observation (mouse tracking, click tracking, visit time tracking...)?

For example, sensors used for data collection themselves have an environmental impact, which is globally multiplied by the numbers of sensors needed to provide the data.

Behaviour trackers have also an impact on the computing resource requirements of a webpage, which potentially results in additional requirements when the page is loaded using a weak Internet connection; a live transmission itself can be very energy-intensive (**see case study on the cloud**).

Where is the data collected and secondly, where is the data stored? Is the data collected all around the world, with each item of user data in the cloud in multiple datacentres (see our case study on the cloud)? Is the data collected and processed locally with a small processor? (see our case studies about IoT, or autonomous cars). If the data is collected and gathered from all around the world, its environmental impact may be greater than if the data is collected and processed locally with a small processor, but it depends on many parameters.

"Anticipated growth five times that of the remainder of ICT semiconductors would proportionally affect raw material resources. Thus, the challenge of restricting the use of AI-related equipment to essential uses may be one of the most critical future challenges facing ICT."

Source: McKinsey

A study published by McKinsey in 2018 anticipates that in the years ahead, "most compute growth will stem from higher demand for AI applications at cloud-computing datacentres". This study also anticipates growth five times greater for AI-related semiconductors than growth in the remainder of the market between 2017 and 2025.[10] The emerging opportunities revealed in this study are related to the hardware components used for data collection, transfer and storage (AI-optimised storage systems, emerging non-volatile memory, high-speed interconnection). All together, these elements are triggering alarms as to the exponential rise of high-tech equipment, which is already posing the biggest challenge to mitigating the environmental impacts of ICT (see LCA analysis).

Anticipated growth five times that of the remainder of ICT semiconductors is contrary to the UN's Sustainable Development Goals.[11] It would proportionally affect raw material resources, which are already depleting at tremendous speed, and risk causing significant rebound effects in terms of greenhouse gases[12], which would be the reverse of the objectives sought by the Paris Agreement and the European Green Deal.[13] Thus, the challenge of restricting the use of AI-related equipment to essential uses may be one of the most critical future challenges facing ICT.

2. Processing the data to make it editable by AI

As seen above, data used by AI must be of good quality and abundant. Data is not always communicated in a clean and organised way, ready to be processed by AI. In many cases, the data has to be refined, either automatically or manually, for the AI to be able process it.

Whether processed manually or automatically, this is not the part of the process that causes the greatest environmental impact, as the impacts are those of the equipment used to refine the data, pro rata temporis. On the other hand, it represents an essential and very time-consuming part of the work carried out by data scientists and covers many AI challenges such as avoiding bias.[14]

3. Run and test the algorithm

To understand this step in the process, a distinction must be made between the scenario where the algorithm learns, and the one where the algorithm executes a decision.

In the learning scenario, the algorithm is "data-hungry": the more it is fed with quality data, the more efficient it is

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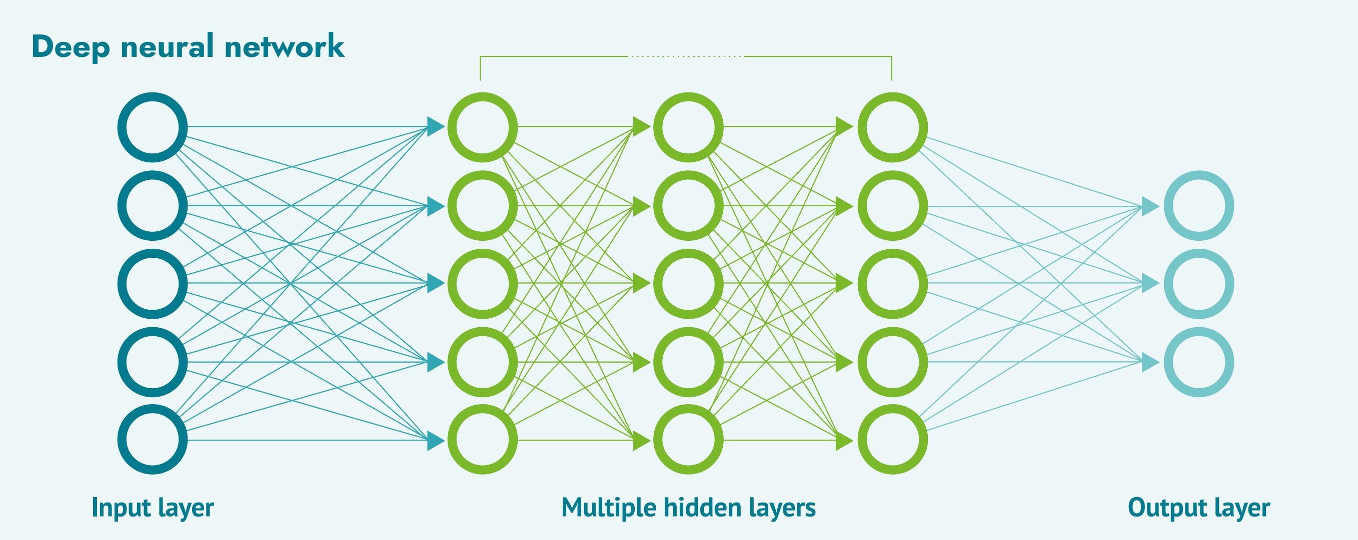
10 McKinsey & Company, *Artificial-intelligence hardware: New opportunities for semiconductor companies*, 2018
11 *https://www.un.org/sustainabledevelopment/sustainable-development-goals/* (last retrieved: 29/06/2021)
12 Due to the exploitation of resources, the consumption of equipment, **see case study on raw material**
13 *https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en* (last retrieved: 29/06/2021)
14 We will leave aside the question of the multiple bias possible due to mis-selection of data, which is important for understanding the work of data scientists regarding AI, but less crucial for identifying the areas that may have the greatest environmental impact.



likely to be. This phenomenon is called "the unreasonable effectiveness of data".[15]

The scenario in which the algorithm executes a decision represents almost nothing compared to the scenario in which the algorithm learns, but is dependent on an efficient learning scenario to exist. In the case of edge computing, the algorithm can be executed locally without a connection to the cloud, which limits the use of bandwidth. In the case of a well-trained and optimised algorithm (i.e. used for autonomous cars), the processor is on-board, close to the sensors, so does not require a connection to run.

Neural architecture search in natural language processing: an example of a heavy impact on greenhouse gas emissions

In a paper published in 2019 by the University of Massachusetts Amherst,[16] researchers found that the energy cost of the AI training process grows proportionally to model size and can dramatically increase when neural architecture search, an incremental process that goes through an exhaustive round of trial and error, is used to increase the model's final accuracy.

Indeed, they found that the model they studied with the highest cost had a carbon footprint of roughly 1,400 pounds of carbon dioxide equivalent without the tuning process of neural architecture search, and emitted more than 626,000 pounds of carbon dioxide equivalent with this tuning process, which corresponds to approximately 284 tonnes of carbon dioxide equivalent: "nearly five times the lifetime emissions of the average American car (and that includes manufacture of the car itself)."[17]

This study, one of the rare firsts in the field, highlights for the first time how important the carbon footprint of AI can be during its learning process. If a similar study were to be carried out concerning AI trained on European territory, it would however be necessary to consider the European energy mix, which is different from that of the United States used in the University of Massachusetts study. However, not only the energy consumption should be considered, but also the environmental impact indicators. If there were to be a life cycle assessment on one functional unit in an AI training process, the environmental impacts of the different items of equipment used during the overall process would have to be considered.

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15 Norvig, Peter et al., *The Unreasonable Effectiveness of Data*, 2009; Sun, Chen et al., *Revisiting Unreasonable Effectiveness of Data in Deep Learning Era*, 2017; Google AI Blog, *Revisiting the Unreasonable Effectiveness of Data*, 11 July 2017 (last retrieved 01/03/2021)

16 Emma Strubell and al., *Energy and Policy Considerations for Deep Learning in NLP, University of Massachusetts Amherst*, 2019

17 MIT Technology Review, *Training a single AI model can emit as much carbon as five cars in their lifetimes*, 6 June 2019 (last retrieved 01/03/2021)

The expert's view

Michel Bénard has been a private consultant since early 2018. He is an expert at Innosuisse and provides investment due diligence and technology assessment for private customers. Michel Bénard did his Master's degree and PhD at Telecom ParisTech, and has held R&D, business, and management positions at IBM, EPFL, HP and Google.

"The initial AI work took place in the 1970s and 80s, mainly thanks to the efforts of the oil and gas industry to develop and use so-called expert systems for oil exploration. However, for several reasons (scarcity of quality data, limited computing power and rigid, rule-driven algorithms) these first efforts did not result in any technical success and no business outcome could be achieved. As a result, AI then went through a 'winter period'.

In the early 2000s new AI projects were launched with better and more data, much higher computing power and new data-driven machine learning algorithms. Success came rapidly, and since then AI implementations for ads and recommendation systems have been working according to industry and user expectations, generating tremendous business successes (in e-commerce, online entertainment and social networks). Encouraged by these successes, other industries have developed and deployed AI with some initial success, for example in predictive maintenance and computer vision. Other sectors (healthcare, e-education, etc.) are also currently experimenting with AI, and initial results look promising.

In most cases, powerful AI needs large amounts of quality data, and in the case of some algorithms, such as neural networks, performance is increasing almost unreasonably with data availability. Also, the learning phase of these algorithms requires very high computing power to obtain good performance. These requirements generate high demand for energy, which has to be provided to AI-dedicated datacentres. Such a problem is not new, and the computer hardware industry has been working for decades on its energy bill. New efforts were recently launched, new sustainable energy sources have become part of the energy supply, and energy-driven optimisation techniques are being developed to minimise the power consumption of datacentres. These efforts have to be relentlessly pursued.

Moving forward, there is important work ahead for AI to become more pervasive:

- Becoming able to address and solve mission-critical tasks, such as detection of diseases, prediction of natural disasters and of equipment failure,
- Getting more explainable, especially if it is to address mission-critical tasks in health, mobility or industrial applications,
- Greater energy optimisation by eliminating unnecessary data acquisition and processing, or by taking into account the real cost of 'free applications' or 'free data'.

i The results of the project can be found on the following website: http://www.rediscoverycentre.ie/research/q2reuse/

ii Ina Rüdenauer, Siddharth Prakash, *Ökonomische und ökologische Auswirkungen einer Verlängerung der Nutzungsdauer von elektrischen und elektronischen Geräten*, Öko-Institut und VZBV, 2020

4. Present the results

Finally, the results (usually predictions) provided by the model must be presented. The environmental impacts can, again, vary tremendously depending on how the results are to be used:

- Are the results sent to another ICT device in a machine-to-machine (M2M) approach?
- How many devices are there? Are they permanently connected to the Internet to be able to function, and with what technologies?
- Are the results presented to a human viewing them using a conventional laptop computer?

The impact at this stage will vary depending on the environmental impacts of the terminals used (computers, connected objects, etc.), and their number.

Conclusion

To date, it is impossible to exactly assess and measure the environmental impacts generated using artificial intelligence: cases of AI used to reduce environmental impacts are still rare and no measurement of the balance of environmental benefits versus cost has been made. Globally, the uses of AI are extremely numerous yet difficult to assess as the field is constantly changing, and many variants need to be considered to measure the environmental impacts on specific cases of use. In the meantime, very few studies have been published: the balance of environmental benefits versus costs is unexplored territory in research into AI.

However, by understanding how AI works, it is possible to get an overview of the most impactful areas. These are mainly the AI training process (especially if a neural architecture search is involved) and data collection if one looks at the greenhouse emissions and raw material depletion, which means compute efficiency will have to be increased.

Looking more precisely at the environmental impact due to raw material resource use, the impacts are related to the semiconductors, chips and equipment used to collect, gather, and process data, which are set to rise sharply; and even more so with devices such as connected objects for data collection by sensors or as end-user equipment. AI is more and more a serious enabler of multiple devices.

The increasing use of sensors will pose an ever greater challenge to efforts to limit the environmental impacts of AI applications in the years ahead. Moreover, a rise in compute capacities can limit the greenhouse gas emissions related to the fine-tuning process in machine learning yet increase the environmental footprint of AI hardware, as it will make previous and less powerful computing hardware obsolete even more quickly, which could cause rebound effects.

Undoubtedly, AI can be considered more and more as an enabler, a critical component of a technology-based economy. It is raising many fundamental questions, one being how to limit its environmental impacts.

Recommendations for a digital evolution compatible with the Green Deal

In a digital evolution compatible with the Green Deal, AI maturity means that AI is used only for optimising critical tasks, with a priority on detecting diseases, predicting natural disasters and equipment failure if, after comparative assessment, no lower-tech alternative is possible with the same levels of success. AI is systematically coupled with low-tech to get the best out of both worlds for the benefit of society and within planetary boundaries. The path to maturity consists of regulating the use of AI in a way that limits the use of resources and takes into consideration future shortages of critical resources for the manufacture of hardware.

AI maturity is rapidly limiting unnecessary data acquisition and processing, and a European directive has paved the way to regulating the use and processing of data by users of 'free applications'. In so doing, the EU has embraced opportunities to achieve frugality and data sovereignty.

Cloud Computing

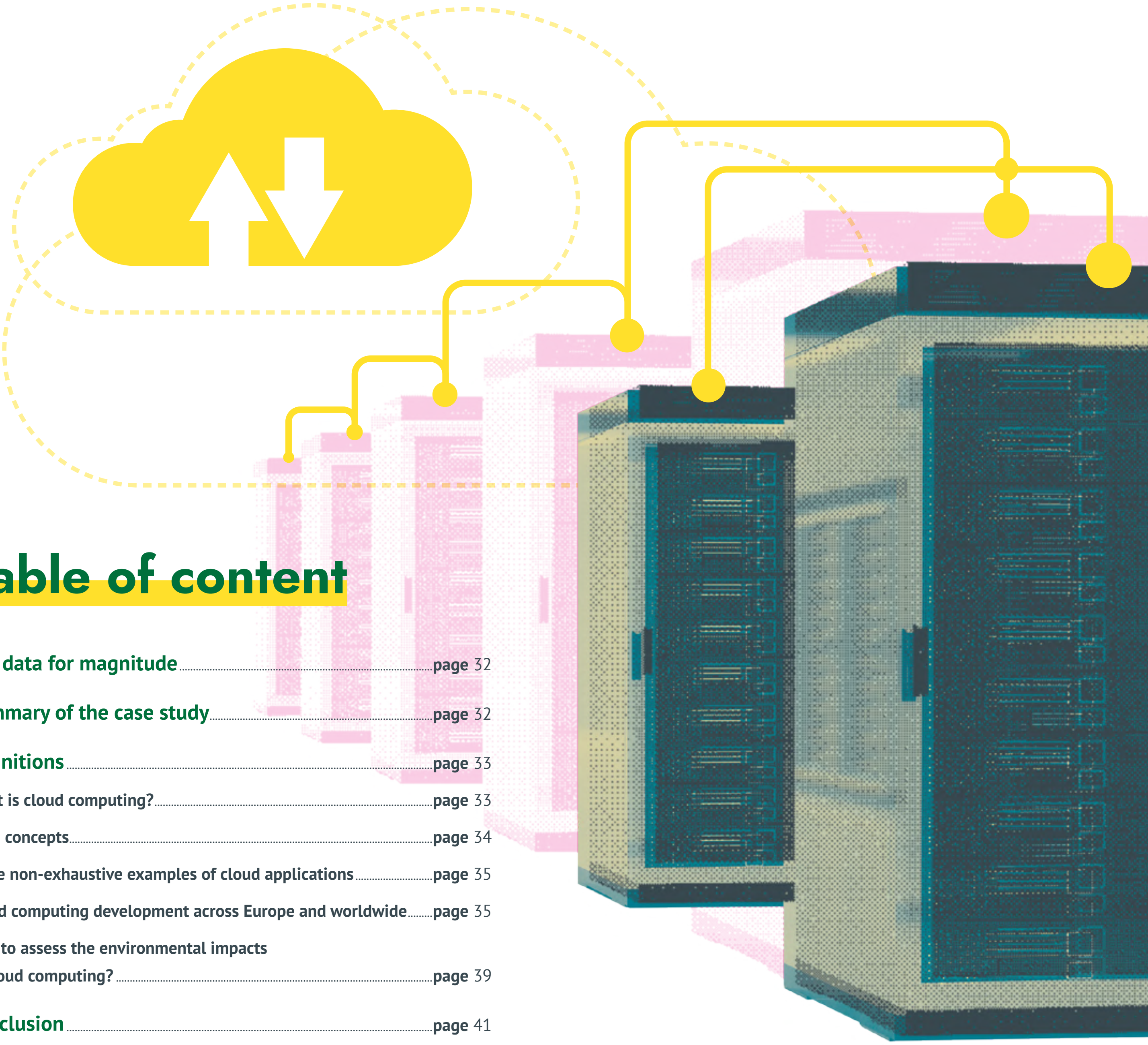


Table of content

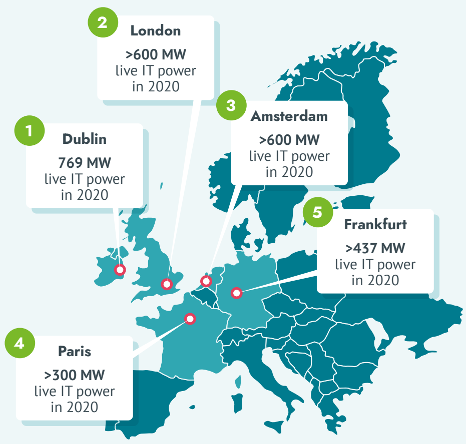
Key data for magnitude

73%
of cloud data centres were public and 27% were private in 2020[i]

36%
of EU entreprises used cloud computing in 2020[ii]

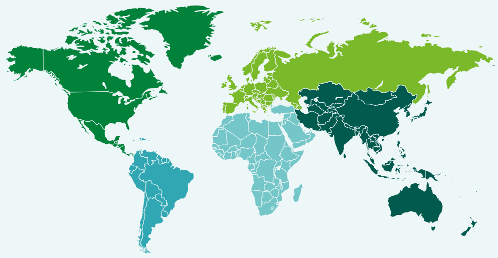
US$44.5bn
is the global market share of infrastructure as a service (IaaS)[iii]

In Europe, the main data centres capacities are in the FLADP cities[iv]



Europe is the 3rd largest cloud market in terms of compute instances[i]

Asia Pacific	37.6%
North America	36%
Europe	20.9%
Latin America	3.2%
Middle East & Africa	2.3%



[i] Cisco Global Cloud Index: Forecast and Methodology, 2016-2021: White Paper, 2018, https://www.cisco.com/c/en/us/solutions/collateral/service-provider/global-cloud-index-gci/white-paper-c11-738085.html

[ii] Eurostat, 2021: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Cloud_computing_-_statistics_on_the_use_by_enterprises

[iii] Gartner, 2020: https://www.gartner.com/en/newsroom/press-releases/2020-08-10-gartner-says-worldwide-iaas-public-cloud-services-market-grew-37-point-3-percent-in-2019

[iv] https://www.datacenterdynamics.com/en/news/europes-flap-markets-have-2000mw-of-data-center-capacity/; https://www.datacenterdynamics.com/en/news/report-dublin-replaces-paris-top-four-european-hubs-accelerate/; Kight Frank / DC Byte

Summary of the case study

Cloud computing is a paradigm shift that has changed the way IT computing and storage resources are consumed. As a consequence, it has also influenced governance within organisations' information systems. This sector is currently experiencing a strong growth. This also means increasing challenges regarding its environmental impacts: while cloud resources seem limitless, those of the planet are not.

Like many ICT tech innovations, the cloud has profoundly transformed organisations: it is depicted as a means for agility, employment, and economic development. What about the environmental perspective?

"The main challenge at EU level is to reconcile sustainability objectives with mass digitalisation via the cloud for a sovereign and eco-responsible cloud."

The principle of the functional economy[1] applies to the cloud: instead of buying and operating an item of IT equipment, users are directly provided with services like computing, storage capacity or appliances, and operate them virtually. At first sight, this saving seems environmentally friendly, especially because it is in the economic interest of cloud operators to not overestimate the resources involved and to extend the lifespan of equipment and infrastructures.

However, the environmental impacts of these services are numerous, such as contribution to climate change,

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1 The functional economy is an economic model based on the development of solutions that combine service guarantees and the functions of use of material goods belonging to the producer.

depletion of non-renewable resources (metals, fossils), water use, energy consumption. Besides, there has been a massive increase in the use of cloud services, which can also be related to bounce (see case study rebound effects) and infobesity effects.[2] Keeping in mind that while cloud resources seem limitless, the resources consumed for ICT are mostly non-renewable ones, and therefore limited, even if some renewable resources are used in the energy mix of data centres' electric consumption.

On balance, how could cloud computing be more of a lever than a hindrance to achieving the objectives of the Paris Agreement and limiting environmental impacts, especially climate change?

The answer to this question requires multi-level measures to enhance transparency, environmental signage, develop best practice standards and raise awareness among all stakeholders about environmental issues, in order to eco-design cloud services.

The main challenge at EU level is to reconcile sustainability objectives with mass digitalisation via the cloud for a sovereign and eco-responsible cloud.

In this case study, we will review the current situation in detail, outline the environmental issues associated with the cloud and define recommendations for a "greener" cloud.

Definitions

The first cloud computing models date back to the 1950s with applications running on shared core mainframe systems. Deployment of the Internet network enabled the development of cloud services by making IT, platforms and applications usable from any type of terminal worldwide.

What is cloud computing?

Cloud computing is a widely used term that brings together a wide variety of services and business models. Used massively both professionally and privately, and because of its ease of use, it facilitates the development of the digital sector.

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2 Infobesity effect is when the volume of information received by a human being exceeds their productive capacity to process this information.

Cloud Computing: Equipment and infrastructures involved

Data centre
Construction and operation
Provides spaces feed with high quality electricity, air conditioning, and a high security level

Hardware
Selection, set up, maintenance and decommissioning of hardware equipment hosted in the data centre (computing, storage, network)

Cloud
Cloud Services design, delivery and operation IAAS, PAAS, SAAS

Usage
Network and end-user devices required to access services

Main concepts

In 2011, the NIST[3] (National Institute of Standards and Technology of the United States), defined cloud computing as "*a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction*."

The NIST is responsible for developing standards and guidelines including minimum requirements, for providing adequate information security for all agency operations and assets.

Cloud services include three types of services:

- **Infrastructure as a Service (IaaS):** The service provisions IT resources as availability of compute, storage and network to the user. In this model, the user has to manage the operating system and the software deployed on the IaaS.
- **Platform as a Service (PaaS):** The service provides infrastructure availability including IaaS and operating systems to the user. The user is still responsible for the software layer.
- **Software as a Service (SaaS):** The service provided to the user is a direct access to applications running on a cloud infrastructure.

Moreover, three different types of hosting are commonly developed for Cloud Services:

- **Private cloud:** Cloud infrastructure is operated only for an organisation. It can be managed by the company itself or by a third party and may exist on- or off-site.
- **Public cloud:** Cloud infrastructure is made available to the general public or a large industry group, and belongs to a company selling cloud services.
- **Hybrid cloud:** Cloud infrastructure is a composition of two or more types of cloud (private, community or public). They remain unique entities but are connected by a standard or patent technology that allows data sharing and cloud applications).

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3 *The NIST Definition of Cloud Computing*, 2012

Definition of cloud computing according to the NIST

On demand self-service
"A consumer can unilaterally provision computing capabilites, such as server time and network storage, as needed automatically, without requiring human interaction with each service provider"

Resource pooling
"The provider's computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand"

Wide network access
"Capabilities are available on the network and are accessible through standard mechanisms that promote use by thin or thick and heterogeneous customer platform (e.g., mobile phones, laptops and digital personal assistants or PDAs)"

Fast flexibility
"Capabilities can be elastically provisioned and released, in some cases automatically, to scale rapidly outward and inward commensurate with demand. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be appropriated in any quantity at any time"

Measured service
"Cloud systems automatically control and optimize resource usage by leveraging a counting capacity at an abstraction level appropriate to the type of service"

Source: https://www.gsa.gov/cdnstatic/Best_Business_Practices_for_US_Government_Cloud_Adoption.pdf

The picture below shows, by user or cloud provider, the control perimeter for each of the three types of service. It represents the areas where users/providers could have a direct impact and implement environmental improvement.

Differences between SaaS, PaaS and IaaS

IaaS	PaaS	SaaS
Application	Application	Application
Data	Data	Data
Runtime	Runtime	Runtime
Middleware	Middleware	Middleware
O/S	O/S	O/S
Virtualization	Virtualization	Virtualization
Servers	Servers	Servers
Storage	Storage	Storage
Networking	Networking	Networking

Managed by the customer: IaaS – Application, Data, Runtime, Middleware, O/S; PaaS – Application, Data. Managed by Cloud provider: all other layers.

To sum up, instead of investing in hardware, companies using cloud computing systems subscribe to an external IT department. The provider takes care of everything from storage, networking, server maintenance to security. By storing their data internally, they must manage these functions themselves.

Some non-exhaustive examples of cloud applications

Amazon Web Services, Microsoft Azure, and Google Compute Engine are among the leading providers of IaaS cloud services.

Google App Engine and AWS Elastic Beanstalk are two typical examples of PaaS. PaaS is also subscription-based which gives you flexible pricing options based on business needs.

A known example of SaaS includes Google G Suite, Microsoft Office 365 or Dropbox.

Cloud computing development across Europe and worldwide

The worldwide public cloud services market grew 24.1 percent year on year in 2020 reaching $312 billion in total revenues.[4]

The use of cloud services is increasing for both personal and professional usage, meaning more computational tasks and higher storage demands by data centres. In the EU-28 countries in 2018, 56 percent of individuals aged 16 to 74 used the internet for social networking.[5] According to Cisco, consumer applications are responsible for about 25 percent[6] of workloads and compute instances in datacentres worldwide. Of these, searches, social networking, and video streaming via cloud applications account for about two-thirds.

From 2016 to 2021 in Eastern Europe, cloud traffic has increased by 38 percent CAGR.[7]

According to Eurostat, more than one in four European companies used cloud services in 2018, especially in the Scandinavian states: Finland 65 percent, Sweden 57 percent, Denmark 56 percent. At the other end of the scale are Bulgaria (8 percent) and Romania (10 percent). [8]

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4 IDC, May 13, 2021: https://www.idc.com/getdoc.jsp?containerId=prUS47685521
5 Eurostat, 2019: https://ec.europa.eu/eurostat/databrowser/view/tin00127/default/table?lang=fr
6 Cisco, 2019: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html
7 Annual Internet Report, Cisco, 2016-2021
8 Eurostat, 2020: https://ec.europa.eu/eurostat/documents/portlet_file_entry/2995521/9-13122018-BP-FR.pdf/a21954b5-3d96-415b-8319-77a24fac10b3

Cloud services are particularly common in office collaboration for email services, file storage and office software. Growth in usage is sustained by mutual growth reinforcement effects between the greater capabilities offered (hardware computing performance, more storage, increase in communication speed) and the opportunities for using more powerful emerging applications and software.[9]

Will cloud computing be more of a lever than a hindrance to achieving the objectives of the Paris Agreement and limiting environmental impacts, especially climate change?

Cloud computing is based on the pooling of IT resources within data centres where they are optimised by virtualisation and energy-monitoring processes. On the one hand, because it enables a pooling of resources, this technology reduces the amount of resources involved and thus the related environmental impacts compared to internal IT server rooms in organisations. On the other hand, and contrary to what is sometimes imagined, it is not stored in actual meteorological clouds but stays firmly on Earth in data centres and data traffic running through optical fibre cables. This means that cloud growth is accompanied by increased demand for material resources, and therefore greater environmental impacts.

Firstly, the computer equipment we use generates significant environmental impacts, especially during the use and manufacturing phases. Regarding data centres, the manufacturing and use of computing equipment contribute far more to climate change, use of resources (minerals and metals) and ionising radiation than the manufacturing and use of storage equipment (**see our LCA report**[10]).

The main advantage of cloud services is that they easily provide additional capacity and manage peaks in activity (for instance e-purchases at Christmas). In addition, cloud services can facilitate the work by providing easy access to appliances, digital workspace and IT systems. The use of the cloud is generally accompanied by high security expectations, sometimes resulting in an oversized physical infrastructure. Sometimes, this oversizing can be a symptom of poorly developed governance.

> *"Institutional changes are key to limiting the environmental impacts of unused cloud resources."*

However, it is possible to use the cloud in an informed way, which can lead to significant environmental gains if best practices and guidelines are followed. For example, in an organisation, the IT manager can start by sizing needs by buying on a "just enough" basis. IT managers can choose a cloud operator that ensures transparency, energy performance, and external recognition, and ask that operator for reporting indicators in order to track its consumption. IT managers can also raise awareness among users internally and communicate about consumption.

We will list the various questions[11] that are asked about the cloud from an environmental point of view and provide some answers.

9 Liguo Yu. 2011. *Coevolution of information ecosystems: a study of the statistical relations among the growth rates of hardware, system software, and application software*. SIGSOFT Softw. Eng. Notes 36, 6 (November 2011), 1–5.

10 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

11 These questions are preconceived ideas listed by the Green IT Alliance in 2014. They provided some answers by analysing the possible environmental benefits of transferring all or part of a company's IS to the cloud to verify the arguments of cloud players on their supposed advantage over the environment. Source: *Alliance Green IT: Is the Cloud Green?*

The virtualisation of equipment allows pooling, optimisation and thus the reduction of physical means (servers, disks etc.) to manage an equivalent amount of data. According to the operators, server consolidation would reduce hardware and operating costs by 50 percent, and energy costs by up to 80 percent.[12]

Yes, but.

There is indeed a pooling optimisation effect. However, the virtual server, whatever its energy effectiveness, does rely on physical infrastructure. Moreover, the use rate of the associated physical server is not optimal immediately and can vary depending on seasonal temperatures (more efficient in cooler temperatures). In addition, it generates a sharp increase in telecom requirements: bandwidth (data centre and customer), equipment, redundancy of access, etc. Moreover, it is important to remember that final energy consumption is not an environmental indicator and that other ones, such as contribution to climate change; resources use, minerals and metals; resource use, fossils; must be investigated.

In the past, each employee had their own personal copy of documents and applications. With the cloud, data is stored only once:

•There is a significant limit on the multiplication of copies and data storage,

•This frees up capacity on the terminals (attachments) and even extends their lifespan.

Yes, but.

Copying and archiving is reduced, but opens the door to a huge rebound effect: ease-of-use encourages the storage of more and more information (longer history, more detailed data, etc.). As a result, the volume of stored data explodes. According to the IDC, "*the amount of data created over the next three years will be more than the data created over the past 30 years, and the world will create more than three times the data over the next five years than it did in the previous five*"[13]. The COVID-19 pandemic is contributing to this figure by changing users' consumption habits.[14] In addition, the original servers are not systematically decommissioned after data migrates to the cloud.

One of the fundamental features of the cloud is usage-based service billing. This mechanism is virtuous because it obliges users to measure their consumption of resources and thus encourages reasoned use.

This is incomplete.

Unfortunately, the granularity of billing (e.g. combination of stored volume, duration of use, internet transit, etc.) makes the business model difficult to predict.

The ease of deployment of new IT resources like virtual servers does not incite sobriety: indeed, when only a few mouse clicks are needed to install more virtual server resources instead of upgrading in house servers physically, it is easy to consume more resources. Moreover, a significant amount of IT "virtual" resources is unused. This point is an issue in environmental efficiency because unused "virtual" assets are still running 24/7/365. Currently, about 30 percent of servers are unused.[15] It has been proven that these zombie servers can be efficiently reduced from 30 percent to 8 percent in just one year if an enterprise takes action when presented with evidence of the magnitude of the problem,[16] which means that institutional changes are key to limiting the environmental impacts of unused cloud resources.

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12 https://www.vmware.com/solutions/consolidation.html
13 IDC, 8 May 2020: Global DataSphere Forecast Shows Continued Steady Growth in the Creation and Consumption of Data.
14 https://www.infoworld.com/article/3586597/cloud-adoption-in-a-post-covid-world.html
15 Jonathan Koomey and Jon Taylor, Zombie/Comatose Servers Redux, 2017
16 https://www.koomey.com/post/159279936533

- The social impacts of the cloud are already visible: avoiding some travels, greater flexibility in working patterns, better work-life balance…

› Yes, but.

However, these benefits should not obstruct negative environmental and social direct and indirect effects: multiplication of computer equipment and their associated environmental impact, increase in infobesity, burnouts and stress related to hyper-connectivity, etc. There is no evidence that teleworking translates into an overall improvement in quality of life, especially if it results in increased working hours and a blurred line between work and private life. Isolation induced by massive usage of telework is also a social risk to consider, especially during the COVID sanitary crisis. Moreover, the partial or total outsourcing of an information governance raises human resources issues: for internal teams (evolution of expertise, strategic vision of IT, etc.), and those of the supplier (place and working condition, etc.).

It is also important to remember that some adverse rebound effects may go against the environmental benefits of cloud computing that working from home enables. For example, if workers have to adapt their home office by building an extension, or if working is associated with more simultaneous air travelling.[17]

- Locating cloud services in high efficiency data centres leads to a reduction of the energy consumptions

› It depends.

Hyperscale data centres have generally a great level of energy efficiency, measured by the Power Usage Effectiveness (PUE), that is around 1.2 versus an average of 1.6 or more in other data centres.[18]

However, because of data duplication in several data centres to prevent from the outage of the first one, this KPI cannot measure the global energy efficiency of cloud services. Moreover, PUE is incomplete to measure the energy effectiveness of a facility: "*The PUE can also send the wrong signals because of ignoring (editor's note: it ignores) the actual effective workload performed. Imagine two facilities: facility A has a PUE of 1.1 and handles 0.5 PB of data, whereas facility B has a PUE of 1.2 and processes 1.0 PB of data on an annual basis. On the basis of PUE alone, facility A would be preferred but facility B requires less energy for processing a similar amount of data, and should be preferred.*

The PUE may also depend on how the measurement guidelines are interpreted. Google explains that the average PUE for all Google Data Centres is 1.11, although they could boast a PUE as low as 1.06 when using narrower boundaries."[19] [20]

- The increase of cloud efficiency could absorb the increase of IT usages and needs

› There is no consensus on this point for the next decade.

Some authors suggest a stable energy need of about 200 TWh worldwide in 2030 when others forecast about 10 times as much.[21] Between 2010 and 2018, the total energy consumption of data centres only increased by 6 percent (from 194 TWh to 205 TWh) while demand was greatly multiplied: this remarkably low result is mainly explained by large energy efficiency gains of data processing and data centre infrastructures. However, Moore's law[22] is expected to stop having an influence very soon (around 2021-2025).[23] A forecasting model of usage impact on data centres' electricity needs highlighted recently

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17 Etude sur la caractérisation des effets rebond induits par le télétravail, ADEME, 2020, https://www.ademe.fr/caracterisation-effets-rebond-induits-teletravail
18 European Commission, ICT Impact study, Final report, prepared by VHK and Viegand Maagøe for the European Commission, July 2020
19 *Ibid.*
20 https://www.google.com/about/datacenters/efficiency/
21 Hintemann R, Hinterholzer S. Energy consumption of data centers worldwide: How will the internet become green? CEUR Workshop Proc.; 2019
22 Moore's law predicts a performance doubling each 2 years. To find more about Moore's law: https://en.wikipedia.org/wiki/Moore%27s_law
23 Shalf J. The future of computing beyond Moore's Law. Philos Trans R Soc A Math Phys Eng Sci 2020;378:20190061. https://doi.org/10.1098/rsta.2019.0061

that, combined, the end of Moore's law and the rise of industrial IoT could cause data centres' energy needs to rise up to 752 TWh in 2030 (about 364 TWh in 2030 for industrial IoT without the end of Moore's law).[24] Moreover, this assumption focuses only on final energy consumption and is incomplete when trying to understand the various environmental impacts of the cloud and data centres, even if it is often the most discussed indicator, as data centres can hold a pressure on the electrical grid.

Pressure on the electricity grid

Data centres consume a great amount of electricity. They can potentially exert an unsustainable pressure on a country's electrical grid. It has already been the case in Ireland in 2021, when the Commission for Regulation of Utilities (CRU) warned in a consultation paper in June 2021 that the country could face power outages if the issue was not tackled.[25] The possibility of prolonged outages caused by energy demand from data centres has prompted EirGrid, the national public power transmission operator, to raise the alarm.

Three scenarios were depicted, the 3rd being considered as "the most balanced and necessary approach":

1. Status quo: considered as unacceptable because it would likely result in load shedding and consumers facing blackouts,

2. A moratorium: "issue a Direction to the system operators to cease processing all data centre connection applications (including modifications) and new connection applications for a number of years"[26],

3. Connection measures, including the priorisation of data centres' connection applications processing in Ireland altogether, based on the following criteria:

• *"The location of each data centre applicant with respect to whether they are within a constrained or unconstrained region of the electricity system;"*

• *"The ability of each data centre applicant to bring onsite dispatchable generation (and/or storage) equal to or greater than their demand, which meets appropriate availability and other technical requirements as may be specified by EirGrid, in order to support security of supply;"*

• *"The ability of each data centre applicant to provide flexibility in their demand by reducing consumption when requested to do so by the TSO in times of system constraint through the use of dispatchable on-site generation (and/or storage) which meets appropriate availability [...] in order to support security of supply;"*

• *"The ability of each data centre applicant to provide flexibility in their demand by reducing consumption when requested to do so by the TSO in times of system constraint, in order to support security of supply;"*[27]

How to assess the environmental impacts of cloud computing?

Having a standardised methodology to assess the global impacts of cloud computing services, and implementing it, is the first step in improving the environmental performance of cloud services. Such a standardised methodology would provide both transparent and public models that would enable researchers and policy makers to work from their own assumptions for the sake of policy-making. Currently, data centres publish very little information, which makes it very difficult to clarify both components' impacts and precise usage categories.

It is also crucial to have a methodology to assess the evolution of environmental impacts linked to migrating from traditional data centres or enterprises' private IT rooms or closets to cloud computing services. This, plus a way to include consequences on networks, equipment and related indirect effects, such as rebound effects.

24 Martijn Koot, Fons Wijnhoven, Usage impact on data center electricity needs: A system dynamic forecasting model, Applied Energy, Volume 291, 2021
25 https://www.cru.ie/wp-content/uploads/2021/06/CRU21060-CRU-consultation-on-Data-Centre-measures.pdf and https://www.lebigdata.fr/irlande-data-centers-pannes-electriques
26 https://www.cru.ie/wp-content/uploads/2021/06/CRU21060-CRU-consultation-on-Data-Centre-measures.pdf
27 *Ibid.*

"If you cannot measure it, you cannot improve it".

Lord Kelvin

Most of the studies looking into the cloud's environmental impacts focus on data centres' energy consumption. This approach is limited because it does not take into account all of the impacts related to the construction stage and end-of-life stage of the equipment involved. Misunderstandings then occur because this methodology leaves aside part of the impacts that can vary depending on IT equipment, data centres lifespan, infrastructure, etc. Even if the use phase usually accounts for most of the impacts in a data centres' environmental life cycle, the main environmental impacts of the cloud cannot be summarised by only looking into final energy consumption. A global approach on the environmental performance of cloud service requires to embrace both hardware and infrastructure and to consider all the stages of the equipment's life cycle.

"Environmental impact studies are mainly based on the energy consumption of data centres instead of complete multicriterial life cycle assessments."

From an environmental life cycle point of view, and considering its contribution to climate change, the use phase is the most impactful, as a data centre must operate 24/7/365. Depending on infrastructure configuration and location, the use phase may be more or less impactful. More specifically, this greatly depends on both cooling needs and on the energy-mix.

Regarding cooling, it is important to note that in many cases, the computing performances of the servers will not be affected if the surrounding air temperature remains around 35 to 40°C.[28] Instead of cooling the data centres down to 20 to 22°C, the ASHREA compliant servers' sets can be used with simple system called **free cooling**[29], which implies important energy savings. If the data centre complies with the most stringent ARSHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standards (A1)[30], the environmental impacts related to cooling will be less important than if the data centre only complies with ARSHAE A4 standards, or even no ASHRAE standards at all. In Europe, the *2019 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency*[31], was inspired by ASHRAE standards.

Environmental impacts (waste, water, resources use (fossil), etc.) may vary greatly depending on the configuration and the location of the cloud infrastructures considered. Regarding the distinction between computing and storage, the cloud's main environmental impacts are related to computing more than storage.

To reduce the environmental impacts of cloud computing, solutions are implemented:

Free cooling, using the data centre's outdoor environment as a source of fresh air. Cold air is directly injected into the cooling air circuit of IT equipment.[32]

Immersion cooling, which consists in immersing the components in a dielectric liquid to cool them down, thus avoiding air conditioning systems and limiting energy consumption.[33]

It is also possible to use the heat from IT components to achieve energy-savings. If the data centre is located near a city, the heat can be used for city heating, as it is currently the case in some cities such as Stockholm

28 https://www.masterdc.com/blog/what-is-data-center-free-cooling-how-does-it-work/
29 https://www.anandtech.com/show/7723/free-cooling-the-server-side-of-the-story
30 http://tc0909.ashraetcs.org/
31 Acton, M., Bertoldi, P., Booth, J., Flucker, S., Newcombe, L., Royer, A. and Tozer, R., 2019 Best Practice Guidelines for the EU Code of Conduct on Data Centre Energy Efficiency, European Commission, Ispra, 2018, JRC114148.
32 Hainan Zhang, Shuangquan Shao, Hongbo Xu, Huiming Zou, Changqing Tian, Free cooling of data centers: A review, Renewable and Sustainable Energy Reviews, Volume 35, 2014, Pages 171-182, ISSN 1364-0321; https://www.buildings.com/articles/27490/6-keys-free-cooling-data-centers
33 https://www.ptisolutions.com/immersion-cooling-the-future-of-data-center-technology/

(Sweden)[34], Mäntsälä (Finland)[35], Odense (Denmark)[36], or to heat a public swimming pool in Paris (France).[37]

Conclusion

To date, the various environmental impacts of cloud services are not documented enough through a standardised methodology. The digitalisation of the economy stimulated a strong development of cloud computing in the past few years. For this activity to be compatible with the objectives of the Paris Agreement to limit climate change, it is crucial to involve the entire value chain (manufacturers, data centre operators, cloud operators, users) and to implement actions for each perimeter, and understand complementarily the environmental impacts of edge computing and of traditional data centres to allow comparisons.

The main environmental impacts are related to the use stage, and computing assignments in particular.

The main issues around the environmental assessment of cloud services are:

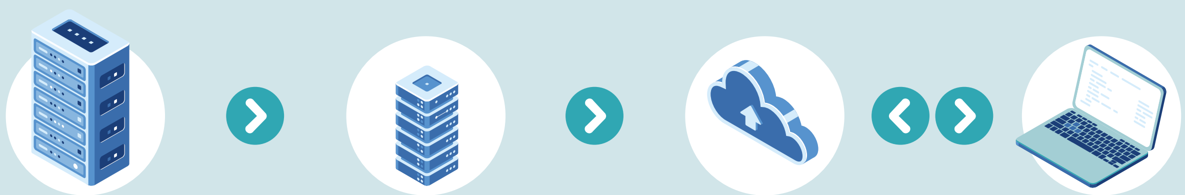
- That environmental impact studies are mainly based on the energy consumption of data centres instead of complete multicriterial life cycle assessments.
- A lack of transparency and opportunities to compare or choose its operator on a comparable basis
- A lack of standardized environmental information for IT equipment
- Studies based on specific stages of the life cycle, or on a single environmental impact, with assumptions and simplifications, which increases the risk of pollution transfers or rebound effect if an eco-design approach is put into place based on them.

The strong growth of cloud computing services has an impact on network load and end-user device renewal.

Publications on solutions to reduce the environmental impacts of cloud computing are often limited to data centre infrastructure. In order to have a global approach on the environmental performance of cloud services, it is necessary to embrace both hardware and infrastructure and to consider all the stages of the equipment's life cycle.

34 https://www.datacenterknowledge.com/design/data-center-firm-expects-halve-energy-cost-recycling-heat
35 https://www.datacenterdynamics.com/en/news/yandex-data-center-heats-finnish-city/
36 https://www.datacenterdynamics.com/en/news/facebooks-denmark-data-center-will-supply-heat-to-city/
37 https://www.greenit.fr/2017/07/25/stimergy-chauffe-piscine-parisienne/

Environmental effects related to Cloud Computing



Data centre
Potentially high impact on **energy consumption and greenhouse gas emissions**, depending on data centre's energy-efficiency

Hardware hosted in data centre
Potentially high impact mainly on **raw material depletion and water** used for the manufacturing process of the equipment used.
High impact on energy consumptions

Cloud services
Potentially very high impact on **raw material depletion, water and greenhouse gas emissions** depending on the IT resources required to provide services but also network and end users' devices

Usage
Potentially high impact on **raw material depletion, water and greenhouse gas emissions** depending on both the energy mix and the end users devices solicitation to access the service

Potentially exponentially high environmental impacts · Potentially very high environmental impacts · Potentially high environmental impacts
Confirmed mitigated environmental impacts compatible with planetary boundaries · Confirmed positive environmental impacts

Recommendations for a digital evolution compatible with the Green Deal

Standards are developed at the UE level based on environmental best practices, impact measurement, and open access to the environmental KPIs of data centres. Implementation of best practices is encouraged as a virtuous behaviour. Raising awareness with informative campaigns and open access to transparent and documented primary data is coupled with environmental labelling of cloud services.

The rebound effects generated by cloud computing are discussed, as well as new emerging technologies related to data computing and transfer, such as edge computing, blockchain or mining. This, in order to shape an ever clearer and comprehensive vision of the environmental impacts on ICT.

As far as possible, data centres' "wasted" heat is reused for urban heat. Data centres with high energy-efficiency and relying on free cooling are also promoted. To this end, subscribing to the Code of Conduct[i] for data centre is highly supported

To be efficient at a global level, it is recommended to encourage the enforcement of several key actions in the UE. Actions should be divided into four levels, each one corresponding to several type of actors.

At the data centre infrastructure level

Improving the environmental impact of a data centre involves developing energy-efficiency and renewable energies. Main actions to implement are:

- Increased efficiency of cooling systems
- Facilitating the reuse of wasted heat
- Massive implementation of eco-design in data centre construction
- Building highly energy-efficient data centres, making it possible to use renewable energies (free-cooling, free-chilling) and reuse wasted heat
- Encouraging subscriptions to the Code of Conduct[ii] for data centre

IT equipment involved in cloud services and architecture level

Improving the environmental footprint of IT equipment involves selecting and managing assets, in order to favour efficient hardware and extend their lifespan, facilitating the circular economy with reuse/repairing of components and equipment. Main actions to implement are:

- Selection of low impact IT equipment
- Optimisation of the virtualisation layer
- Lifespan extension
- Reusing components and favouring the circular economy
- Recycling electronical waste

IIAAS, SAAS and PAAS level

Improving the environmental footprint at the IAAS/ PAAS/SAAS level involves eco-designing services and optimising resources required to run the services at a global level: data centre, network and end-user device. Main actions to implement are:

- Publishing guidelines & standards for an environmental efficiency of cloud computing services et (IAAS, SAAS, PAAS level)
- Promoting the implementation of best practices
- Promoting the development of "low resource solicitation" business models

Cross disciplinary level

At a global level, raising awareness and encouraging the development of a greener cloud requires to:

- Develop standards at an EU level on measurements and best practices
- Follow up on environmental impacts and performance
- Implement a digital environment repository with an LCA approach
- Lead a global informative campaign and raise awareness
- Discuss rebound effects that overcompensate the dematerialisation directly induced by technical progress
- Create "green cloud computing" labels
- Integrate green procurement criteria for cloud services required by public authorities
- Develop innovation to reduce the environmental impacts of cloud services
- Have a global approach of cloud environmental efficiency which includes networks and end-user devices

Research recommendations

Further research studies could be lead, especially regarding the environmental impacts of the different cloud computing services, but also sustainable business models which would tackle the local economic development as well as the social impacts of cloud services.

[i] Code of Conduct, European Commission: https://ec.europa.eu/jrc/en/energy-efficiency/code-conduct/datacentres
[ii] *Ibid.*

5G

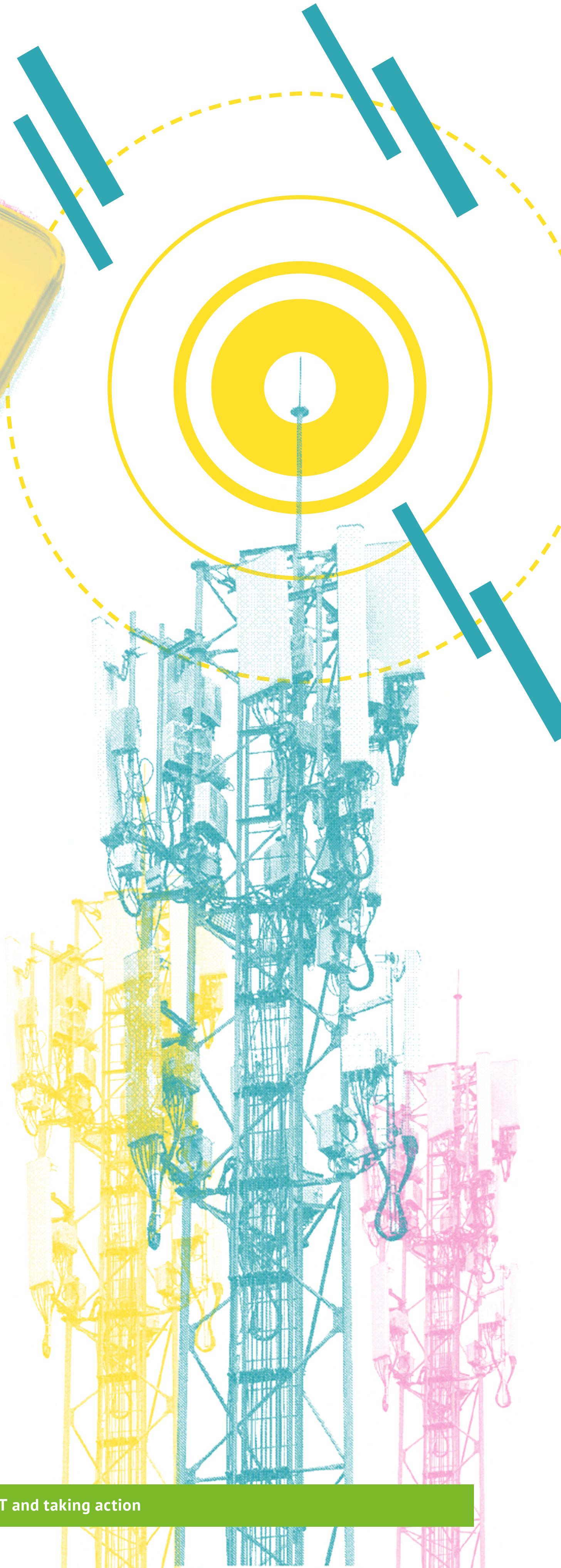


Table of content

Key data for magnitude

90%
nationwide coverage expected by 2026 in Western Europe and between 2026-2029 for Eastern Europe[i]

3rd
largest share of 5G connection will be Europe (29% of total connections)[ii]

10%
of global mobile devices and connection will be 5G by 2023[iii]

Key 5G IoT endpoints expected worldwide

39% of market share in 2023 for connected cars[iv]

32% of market share in 2023 for outdoor surveillance cameras[iv]

11% of market share in 2023 for fleet telematics devices[iv]

only **2%** of market share in 2023 for emergency services[iv]

5G is a major market shift driving the IoT to a ubiquitous level, making more and more equipment an increasing challenge for environmental impacts mitigation

203 million 5G connections
expected in Europe by 2025[ii]

[i] Roland Berger and Asgard, *Artificial Intelligence – A strategy for European startups Recommendations for policymakers*, 2018
[ii] GSMA, *Mobile Economy Europe*, 2018, p.3
[iii] *https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html* (last retrieved: 01/09/2021)
[iv] Gartner, *Gartner Predicts Outdoor Surveillance Cameras Will Be Largest Market for 5G Internet of Things Solutions Over Next Three Years*, Press release, 17 October 2019

Summary of the case study

This case study sets out to explore 5G, a new and complex technology subject for which environmental impacts are still difficult to measure. The purpose of this case study is to help decision-makers and citizens to better understand what 5G is and what we already know about the potential benefits and costs of 5G from an environmental perspective. It is not a matter of being pro or con-5G, but to provide a snapshot of the potential environmental impacts regarding the ICT ecosystem as currently known.

As 5G deployment is currently ongoing, it is difficult to get a precise perspective on this technology: the literature is prolific on the potential of 5G for entertainment and leisure, but we have found no life cycle assessments available that provide insights into the direct environmental impacts of the network and associated devices. This case study shows that the environmental impacts of 5G may be of different kinds: firstly, those related to the number of mobile network antennas to be deployed, which is expected to be about three times higher than for 4G to obtain the same coverage; secondly, those related to 5G devices, with not only a rise in smartphone renewal rates, but also the deployment of billions of connected devices; thirdly, those related to the ensuing explosion of data use.

Our recommendation section will inform overall thinking on 5G compared with other networks to see how to address network and ICT environmental issues better by weighing as well environmental considerations as social acceptance, economic perspectives and European sovereignty.

Definitions

What is 5G?

5G is the 5th generation of mobile telephony. It was designed to achieve high bandwidth at low latency, which means it enables very high-speed travel. This new network builds on previous generations of 3G and 4G networks. It aims in particular to provide ultra-reliable flow and speed. 5G is the basis for the development of massive IoT, autonomous navigation, streamed videogames, augmented reality/virtual reality (AR/VR), full high-speed coverage of crowd events and even smart city cameras.

1980-2020: 40 years of mobile generations

1980	1990	2000	2010	2020
1G	**2G**	**3G**	**4G**	**5G**
Voice	*Voice and text*	*Mobile data*	*Mobile broadband*	*Anything, anywhere, anytime, unlimited*
NMT, AMPS, TACS	GSM, IS-95, D-AMPS	W-CDMA, UMTS CDMA1x EV-DO	LTE	IMT 2020
2.4 Kbps	64 Kbps	384 Kbps	100 Mbps 1 Gbps	10 Gbps
			Gigabit LTE	Multi-Gigabits 5G

Source: IDATE DigiWorld, state of LTE & 5G markets, July 2018

In Europe, 5G is based mainly on three spectrum ranges:

- **700 MHz: This band is currently partially used for 4G. Compared to other 5G bands, the 700 MHz band has low speed but very good penetration inside buildings.** This band will principally support long-distance coverage by 5G (about 5 km or less depending on implementation conditions).

- **3.4 – 3.8 GHz: This range is called the 5G core frequency, as it offers the best compromise between range, speed, and penetration.** It is characterised by a range of 1 or 2 km, and better building penetration than the >24 GHz bands. These antennas will be installed on high points in the urban environment, such as towers, and will in some cases require new supports. They will be divided mainly into 2 types: macro cells (for stations handling more traffic) and small cells (ensuring high throughput at precise locations). Small cells will be mainly deployed in urban areas, to relay the signal to the macro cells.

- **>24 GHz: This band has excellent throughput but little range and difficulty penetrating inside buildings.** To compensate for its low penetration and range, it will rely on an important network of small cells to relay signals to macro cells. It will need a large number of small-cell antennas to ensure very high-speed coverage (1 Go/s). Frequencies of >24 GHz are mmWaves, which makes them well-suited for areas where there are a lot of devices to cover, but in the case of cities, the density of the urban environment has to be offset with multiple small cells.

Other spectrum ranges are under experimentation, including 15 kHz (for IoT specifically) and 5G satellites that could help 5G cover white areas (sparsely populated areas).

Main concepts

- **Small cells:** Small cells are mobile base stations used to boost signals in indoor areas. The deployment of 5G mmWaves within urban areas currently requires thousands of small cell antennas to boost network range. The small cells relay the signal to the macro cells. If the direct path between the small cell and the macro cell is blocked by an obstacle (i.e. a tree) then the small cell can go through other small cells and still communicate with the closest macro cell. To ensure very high-speed coverage this will require a tremendous number of small cell antennas.

mmWaves: Millimeter-wave 5G or mmWaves is the basis of the next generation of mobile applications. High-range bands provide huge amounts of capacity across a limited geographical area. mmWaves was previously shunned for mobile communications because its short-range and narrow wavelengths were susceptible to atmospheric conditions, but as spectrum is a finite resource, attention is now being paid to bands previously considered unsuitable for mobile networks. Many of these bands were allocated to other groups of users, such as the military or public events industry, or are currently used in fields such as scientific research and weapons systems.

Wireless versus wireline technologies: Even if 5G is a wireless technology, it is important to remember that a mobile network antenna is *in fine* always connected to a wireline network to transfer data. This means that if a new frequency improves the data transfer speed, once picked up by the antenna, the data will go into the fibre network. It is estimated that massive deployment of fibre to support 5G will represent an investment of 130 billion to 150 billion dollars over five to seven years in the United States alone[1]. Updating and resizing the infrastructure of servers, power supplies, cables, and fibres, backhaul, etc. is also a part of guaranteeing very high speed.

Multiple-Input Multiple-Output (MIMO): This technology is used to improve the spatial efficiency of wireless networks. As opposed to SISO (Single-Input Single-Output), MIMO technology enables multiple antennas from the transmitter and the receptor to transfer data at longer range and with higher flow.

Beamforming: This technology is used to control and reduce interference. To do so, beamforming, or spatial filtering, combines elements in an antenna array so that signals at specific angles experience constructive interference while others experience destructive interference.

Network slicing: 5G network slicing is a network architecture that enables independent logical and virtualised networks on the same physical network infrastructure. In other words, network slicing can be likened to the possibility of dynamically adjusting motorway lanes depending on the traffic, instead of both directions having the same width, for particular applications. Each network slice is an isolated end-to-end network tailored to fulfil diverse requirements requested by a particular application. The commercial benefit of network slicing is that it can prioritise specific resources (one might require higher speeds, another low latency, etc.) to tailor specific solutions to different industries, but it has a direct effect on net neutrality.

"Advancements in technologies like AI, machine learning, deep analytics, and AR/VR will only be made possible by high-speed connectivity paired with data processing close to the end user."

Rob Kasegrande

Edge computing: Any type of computer programme that brings computation and data storage closer to the request, to save bandwidth and improve response times. Edge computing is often associated with IoT applications, gaming, VR, smart cities, smart industry or connected cars and autonomous cars. Sanket Nesargi, from Deloitte, explains "*Without edge computing, 5G is simply a fast network technology.*"[2] In the same article, Rob Kasegrande adds: "*From a business perspective, 5G and edge computing have a symbiotic relationship. The transformational aspects of 5G are closely tied to edge. Without edge computing, 5G wouldn't be able to meet the promises it is expected to deliver. Advancements in technologies like AI, machine learning, deep analytics, and AR/VR will only be made possible by high-speed connectivity paired with data processing close to the end user.*"

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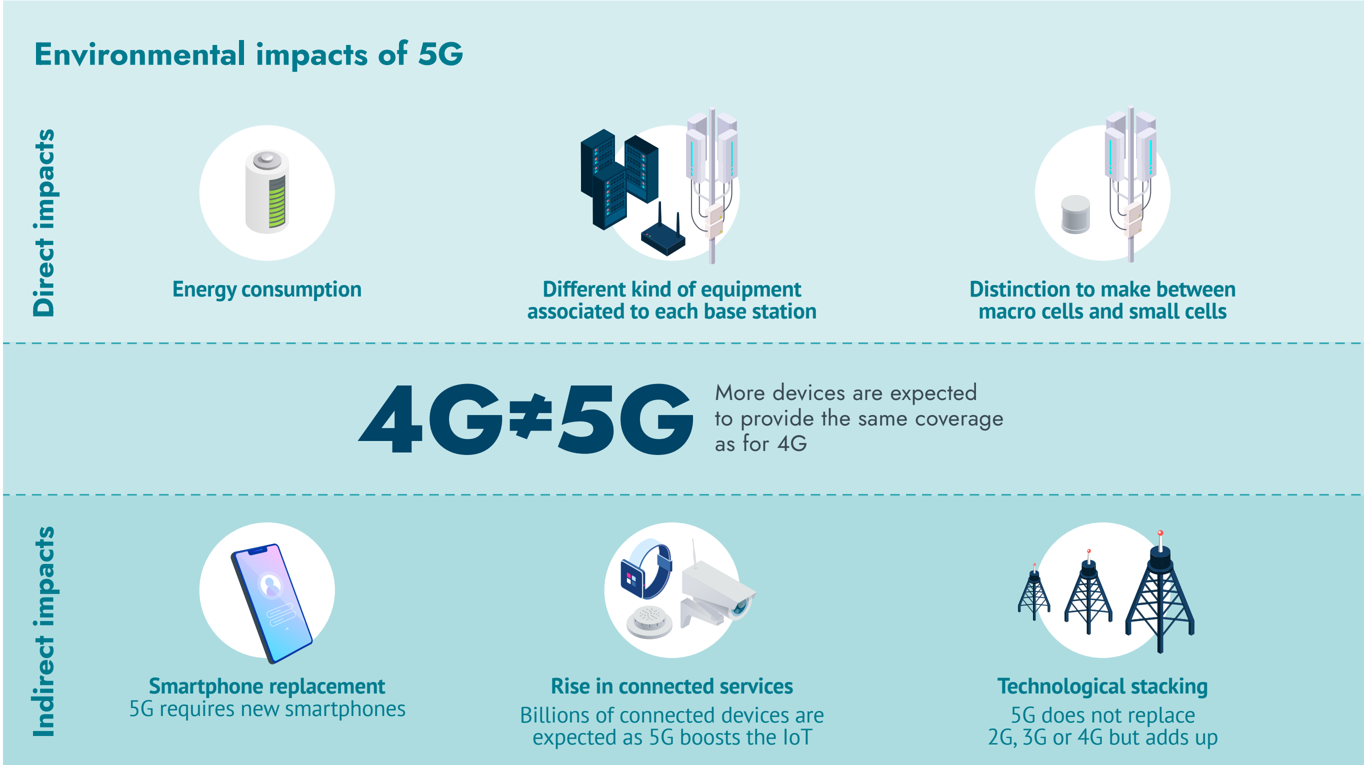
1 Deloitte, *Communications infrastructure upgrade: The need for deep fibre*, 2017
2 *https://www2.deloitte.com/us/en/pages/consulting/articles/what-is-5g-edge-computing.html* (last retrieved: 23/03/2021)

Environmental issues related to 5G



In line with the objectives of the Paris Agreement to attain climate neutrality in the EU by 2050, the European Council endorsed a binding EU target of a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990.[3] In a report on the effects of global warming of 1.5°C published in October 2018, the Intergovernmental Panel on Climate Change (IPCC) specified the cumulative amount of CO2 it was still possible to emit while not exceeding global warming of 2°C by 2100.[4] In 2020, the French General Commissioner for Sustainable Development published a report showing that "taking into account the evolution of the world population by 2100 and respecting a strictly equal distribution of the quantity of CO2 that remains to be emitted, the CO2 "budget" of each Earthman should be between 1.6 t (low assumption) and 2.8 t (high assumption) of CO2 per year between today and 2100, not including residual emissions of other GHGs."[5] Will 5G be a lever or a hindrance to achieving these goals?

Currently, documentation is still too scarce to assess the environmental impacts of 5G networks specifically. However, by looking at the rise of connected objects, which 5G is expected to boost, and the replacement of smartphones required to access 5G mobile network, we can highlight some initial potential areas of impact and key questions to set 5G deployment in the context of sustainability.

3 https://www.consilium.europa.eu/media/47296/1011-12-20-euco-conclusions-en.pdf (last retrieved: 08/04/2021)

4 Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press;

5 Commissariat général au développement durable, *L'empreinte carbone des Français reste stable*, 2020

5G: a lever to achieving the objectives of reducing environmental impacts?

There are two possible ways in which 5G could be a lever to achieving the objectives of reducing environmental impacts: firstly, if 5G use is sufficiently limited not to rush smartphone replacement and does not increase data traffic – or even reduces it; secondly, if the optimisation gains of 5G in the industrial sector offsets the environmental costs of 5G. Will these gains be sufficient to make a positive difference in achieving a reduction in emissions compatible with planet boundaries?

First hypothesis: limited deployment and use of 5G for specific uses

As 5G adds an additional layer to the already existing 2G, 3G and 4G networks for mobile networks, as well as to fibre and DSL, it is unthinkable that a generalisation of 5G will reduce the environmental impact of the networks.

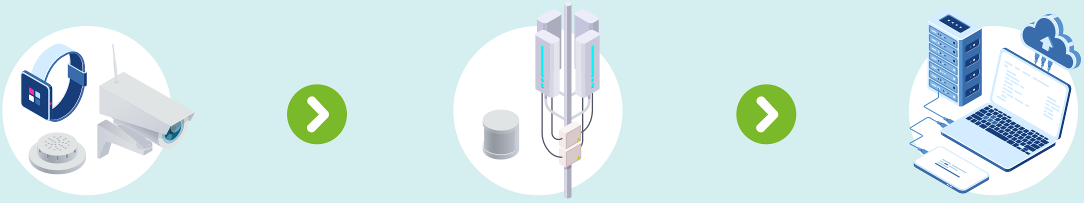
If 5G is sufficiently limited to not drive smartphone renewal and does not increase data traffic, the optimisation gains of 5G would enable a reduction of environmental impacts, as 5G stations are more energy-efficient than 4G stations. However, this scenario would also mean completely disrupting the current deployment scenario of 5G to limit it to specific areas where no other more sustainable option is possible. Moreover, this would also mean abandoning the principal entertainment uses for which 5G is intended.

Second hypothesis: sufficient optimisation gains in the industry to offset the environmental costs of 5G deployment and use

Along with AI[6] and the IoT[7], 5G is often foreseen as an enabler for industrial innovation and optimisation. Currently however, we have not found during the period of our study sufficient documentation and knowledge to be able to judge whether these optimisation gains would be sufficient to offset the environmental costs of the deployment and use of 5G networks and devices. Documents promising environmental gains provide no support for this at present, their costing being exclusively focused on economic and consumer benefits. To be certain that the optimisation gains offset the environmental costs of 5G networks and devices, comparative and consequential life cycle analysis (LCA) needs to be conducted between at least two comparable cases, the difference being whether or not 5G is used to optimise production. As LCA takes into account multiple environmental indicators, such a comparison would avoid shifting, or worse increasing, the environmental impacts from one field to another by choosing a less virtuous solution than it claims.

6 See our case study on Artificial Intelligence
7 See our case study on the IoT and connected objects

5G-simplified illustration



A 5G device (smartphone, connected objects, M2M) emits or receives a signal

Devices are likely to be more resource-greedy and complex

Device numbers soar to reach IoT ubiquity

A 5G antenna receives or emits a signal

More antennas are required to cover a similar area compared to 4G

5G macro cell antennas may be 5G connected to a multitude of small cells

5G antennas may be equipped with complementary devices such as lithium-ion batteries and photovoltaic panels due to peaks in energy consumption

An exponential amount of data travels through backhaul and fibre network to cloud data centres

Cloudlets (small clouds) may be used to process data nearer to the source.

The more data travels and is processed, the greedier it is.

5G: a hindrance to achieving the objectives of reducing environmental impacts?

It is currently too early to precisely predict the environmental impacts of 5G, just as it is too early to precisely estimate how far 5G will accelerate smartphone renewal and accelerate IoT multiplication and what the related rebound effects will be. However, it is obvious that the deployment of 5G will go hand in hand with a renewal of smartphones and an increase in the place of connected objects in our daily lives.

> *"The 5G smartphone race is the most immediate critical issue related to 5G environmental impacts."*

Smartphone replacement: an immediate critical issue

One of the major issues related to 5G is smartphone replacement, as 4G smartphones are not 5G-compatible. Currently, smartphone penetration in Europe is remarkably high.[8] This means that to benefit from 5G, Europeans will have to buy a new smartphone. This will reduce the lifespan of 4G smartphones, which are currently still working perfectly for current uses, and potentially lead to a massive renewal of the European smartphone fleet, even though the environmental impact of smartphones is already high. Our LCA results shows that in the EU-28 in 2019, the smartphones alone contributed to about 9% of the impacts of ICT on climate[9].

Moreover, a 2020 report comparing 4G smartphones and 5G smartphones shows that 5G smartphones embed more components (larger screen, more cameras, 5G modem) and greater calculation power[10], which are likely to increase manufacturing footprint.

These aspects are making the 5G smartphone race the most immediate critical issue related to the environmental impacts of 5G at our current state of knowledge.

Rise of connected devices

With 5G, new uses are anticipated, driven by the IoT. Connected devices for personal as well as professional uses are expected to develop, such as AR/VR devices, gaming, 4K and even 8K video streaming, potentially combined with rising tech enablers such as AI (see our case studies on AI and IoT). Cisco anticipates that "*by 2023, IoT devices will account for 50 percent of all net-*

…………..

8 In our LCA study, we used an estimated penetration rate of the smartphone of 92% in the EU-28 in 2019 with more than 473,500,000 units for about 513,500,000 inhabitants.

9 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

10 Gauthier Roussilhe, *Évolution des smartphones 4G vers 5G : Comment évaluer la situation et l'empreinte environnementale*, (in English: *Evolution of 4G smartphones to 5G: How to assess the situation and the environmental footprint*), 2020

worked devices (nearly a third will be wireless)" and that "*a 5G connection will generate nearly 3X more traffic than a 4G connection*".[11]

These uses require increasingly greedy devices requiring numerous components and high energy consumption (computing power, sensors). Just as for 5G smartphones, the multiplication of these components for connected devices is an important issue given the dramatic anticipated increase in connected devices.

The two largest 5G IoT endpoint installed bases worldwide predicted by Gartner are outdoor surveillance cameras and connected cars (see table below).

5G IoT endpoint installed base, worldwide, 2020 and 2023 (thousands of units)

Segment	2020 Volume	2020 Market Share (%)	2023 Volume	2023 Market Share (%)
Connected cars – embedded (consumer and commercial)	393	11	19,087	39
Outdoor surveillance cameras	2,482	70	15,762	32
Fleet telematics devices	135	4	5,146	11
In-vehicle toll devices	50	1	1,552	3
Emergency services	61	2	1,181	2
Others	400	11	5,863	12
Total	**3,522**	**100**	**48,590**	**100**

Rough estimates. Due to rounding, figures may not add up precisely to the totals shown – Source: Gartner (October 2019)

Complementarily, most IoT connections (including 5G but not only) are expected to be done for connected homes & connected workspaces.[12]

"Along with 5G smartphones, the proliferation of connected objects is a high-tech critical environmental issue highlighted by 5G."

This shows that the most important 5G connected devices in the market share are also expected to require numerous on-board components.[13] In the meantime, 5G video surveillance cameras are expected to be increasingly high-definition[14] (Nokia even talks of 4K or 8K video surveillance cameras)[15], which will require additional complexity in terms of component miniaturisation for the camera devices themselves and will also make data traffic management in 5G networks more challenging.

The revolution of connected objects is a particularly serious challenge to efforts to limit the environmental impacts of digital technologies, as connected objects are highly likely to proliferate and gain in complexity. Along with 5G smartphones, the proliferation of connected objects is a critical high-tech environmental issue highlighted by 5G: as they multiply, their use of critical raw material resources increases as well[16] (**see our case study on raw materials**).

What are the environmental impacts of 5G network equipment?

The fact that 5G uses different frequency bands means that it will not necessarily use the same stations as the previous network generations. While for the 700 MHz frequencies 5G will be able to rely on pylons previously deployed for 2G, 3G and 4G networks and the existing fibre network associated, this will not be systematically the case for the other bands: these will require readjustment of the fibre and electrical network according to their smaller range. This will call for an increase in

11 https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html (last retrieved: 24/03/2021)
12 https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html (last retrieved: 01/09/2021)
13 This is because connected cars have numerous sensors and large compute capacity on board to be able to drive safely even in areas not covered by wireless networks, which requires many different components (**see our case study on autonomous vehicles**)
14 https://www.isrmag.com/5g-implications-security-video-surveillance-safe-cities/ (last retrieved: 24/03/2021)
15 https://cities-today.com/industry/5g-video-surveillance-met-smart-city/ (last retrieved: 24/03/2021)
16 Florinda F. Martins, Hélio Castro, Raw material depletion and scenario assessment in European Union – A circular economy approach, 2019

the fibre network and electrical supplies, and additional civil engineering works.[17] Fibre is not the only infrastructure that will need resizing: servers, alimentation cables and backhaul will also need attention. The entire chain is concerned, involving mostly economic costs.

> *"Regarding 5G antennas, I have not seen any LCAs about them, so I cannot quantify their impacts. The new 5G equipment includes MIMOs, which are antennas with more input and output modules than older models. What is the environmental impact of these new types of equipment? In the absence of open data on the subject, we do not know."*
>
> **Gauthier Roussilhe**

Moreover, the decommissioning of 2G and 3G planned on several networks[18] raises other questions regarding the renewal of end-user devices and the non-negligeable risk of increasing the digital divide instead of bridging it.

However, as more cells (macro and small cells) will be required for 3.5 GHz and >24 GHz ranges, we can expect an increase in the environmental impact of the network at least for manufacturing due to the increase in the volume of network equipment deployed to cover a given area – up to three times more antennas to cover rural areas than for similar coverage by 4G.[19]

Energy efficiency of 5G

While there is a consensus that a 5G base station is globally more energy-efficient than a 4G station all things being equal otherwise,[20] it is clear that data traffic will increase tremendously with or without 5G, but even more with 5G: Ericsson Consumer Lab predicts that "one in five users could use 200 GB per month on 5G devices, a 10-fold increase from current cellular data usage"[21] and GSMA even predicts a potential increase in data traffic of up to 1,000 times.[22] Even if the efficiency gains of 5G stations are worthwhile, and energy increase is expected with 5G by the mobile operators: "*Energy increase in 5G, while the jury is still out on just how much this energy increase may be through densification and increased traffic demand*".[23] Efficiency gains are generally offset by greater demand, which is known as the Jevon paradox, or rebound effects (**see our case study on rebound effects**).

This means society has to make a real choice in the years ahead to limit both the expansion of connected objects and rebound effects to ICT uses, and this concerns everyone from policymakers, citizens to economic players.

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17 5G is described as "a game changer, where wireless can no longer exist without wireline" by the FFTH Council Europe (*https://www.ftthcouncil.eu/documents/COM-190313-FibreFor5G-ConvergenceStudy-Presentation-RafMeersman%20-%20v4%20-%20publish.pdf*, p.5, last retrieved 23/03/2021); *https://www.corning.com/in-building-networks/worldwide/en/home/knowledge-center/5g-networks-impact-on-fibre-optic-cabling-requirements.html* (last retrieved: 23/03/2021); *https://www.isemag.com/2020/11/telecom-5g-fibre-power-small-cells-partnerships/* (last retrieved: 23/03/2021)

18 *https://edition.cnn.com/2021/01/07/tech/verizon-3g-shutdown-paused/index.html* (last retrieved: 08/04/2021) / *https://www.att.com/support/article/wireless/KM1324171* (last retrieved: 08/04/2021)

19 Consulting firm Tactis, which participated in 5G trials, investigated the propagation capabilities of 5G on the 3.5 GHz band. To this end, they simulated, on different topologies of the territory, a 5G network in the 3.5 GHz band. They then compared it to the coverage of the simulated 4G 800 MHz band from the same sites. They draw two conclusions: "1. In peri-urban areas, 30% additional sites would be necessary in 5G to maintain coverage and a level of service equivalent to 4G; 2. In a rural environment, it would be necessary to build twice as many sites to have equivalent coverage, and even three times as many sites to deliver a broadband service, at least 8 Mbps. Beyond these coverage concerns, as we can already see in 4G, network densification leading to the creation of additional sites is necessary to absorb the demands for increasing capacity." (*https://www.tactis.fr/simulation-couverture-5g/*, last retrieved: 24/03/2021)

20 Technical publications describe cases of 5G energy consumption in use and explore what network architecture is required to be more energy-efficient (*https://www.ericsson.com/en/blog/2019/9/energy-consumption-5g-nr*, last retrieved: 24/03/2021), other publications report that 5G base stations use a lot more energy than 4G base stations (last retrieved: 24/03/2021).

21 *https://www.ericsson.com/en/reports-and-papers/consumerlab/reports/5g-consumer-potential* (last retrieved: 24/03/2021)

22 *https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/* (last retrieved: 24/03/2021); *https://www.fiercewireless.com/tech/5g-base-stations-use-a-lot-more-energy-than-4g-base-stations-says-mtn* last retrieved: 24/03/2021; *https://www.mtnconsulting.biz/product/operators-facing-power-cost-crunch/* (last retrieved: 24/03/2021)

23 *https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/* (last retrieved: 24/03/2021)

The expert's view

Gauthier Roussilhe is a researcher and designer specialising in the environmental impacts of digital technology. He collaborates with all the players in the field. He developed the Carbonalyzer plugin, holds a number of lectures and courses at EcoInfo (CNRS) and collaborates with GreenIT.fr. In 2020, he wrote a report on 5G and the ecological transition and a shorter study commissioned by HOP[i] *assessing the environmental impact of renewing the smartphone fleet with the arrival of 5G. His latest article, published in March 2021, is entitled "What can digital technology do for the ecological transition?".*

What are the environmental impacts of 5G?

5G is leading to a renewal of the fleet of smartphones, the deployment of sensors and new connected objects which must be 5G-compatible, the construction of new antennas and new datacentres, which will presumably lead to an increase in traffic. Beyond these effects, 5G potentially leads to new uses: we are talking about 4K video for example, virtual reality, augmented reality, video-game streaming from mobile devices. 5G also has the potential to stimulate the advent of autonomous vehicles, although they are not yet ready to become widely used.

Regarding 5G antennas, I have not seen any LCAs about them, so I cannot quantify their impacts. The new 5G equipment includes MIMOs, which are antennas with more input and output modules than older models. What is the environmental impact of these new types of equipment? In the absence of open data on the subject, we do not know.

Regarding the digital sector, we seem to forget that the challenge today is not to freeze emissions at their current level, but to divide them by four. The digital sector as it is today consumes too much to comply with the objectives of the Paris Agreement. The ITU had formulated a plan to reduce emissions from the operator sector to stay below 1.5°C. The ITU recommendation aims for a 50% reduction by 2030 and an annual decrease of 4.2%.[ii]

If I am a citizen just discovering this subject: what are the 3 main points I need to remember about the positive and negative environmental impacts of 5G?

We have to think about where we are taking the digital sector in relation to extraordinarily important, non-negotiable transition issues if we want to achieve the objectives of the Paris Agreement. The public policy question we have to ask ourselves is this: does this infrastructure, this development, allow us to stabilise the world at less than +2°C?

5G is now the embodiment of a debate about the future model for digital development. This debate will take place, whether we like it or not, in relation to autonomous vehicles, video surveillance etc. It raises the question of where we want to take the digital sector and the fact that this can be managed and decided collectively.

Individually, if I consider the environmental impacts as a citizen, it means that 5G should not be a motor for renewing my equipment, and that we must fight politically to know what we can do or not do with the digital sector and even more so with 5G.

i *HOP: Halte à l'Obsolescence Programmée* in French, *Stop Programmed Obsolescence* in English
ii ITU, *Greenhouse gas emissions trajectories for the information and communication technology sector compatible with the UNFCCC Paris Agreement*, 2020, p.11

"This means society has to make a real choice in the years ahead to limit both the expansion of connected objects and rebound effects to ICT uses, and this concerns every- one from policymakers, citizens to economic players."

Conclusion

5G is a complex subject, and there are still too many unknowns to measure its environmental impacts. If the literature has much to say about the economic benefits of 5G for the leisure and security markets, it is silent on the subject of concrete, quantified examples of the potentially positive environmental impacts of 5G, just as it is on the quantification of its direct impacts. Given our current state of knowledge, the most critical environmental impacts of 5G are related first and foremost to the increase in the number of new devices that it requires (both smartphones and connected objects) and the increase in their performance, which requires increasing quantities of raw materials. Increasing our resource needs to manufacture these devices means increasing the EU's dependence on these critical raw materials[24], as well as contributing to their depletion. The rarer these resources, the more energy/water-intensive and therefore polluting their extraction (**see our case study on raw materials**).

"Is it sustainable and useful to have for the same area an ultra-high-speed fibre-optic wireline network, an ultra-high-speed mobile network, and possibly the same via satellite?"

Today, there is no tangible proof that 5G could effectively be a lever to achieving the objectives of reducing environmental impacts given the objectives of its deployment and use. If 5G precipitates the production of more terminals and connected objects, this will undeniably exacerbate mining and contribute to the unsustainability of the digital sector.

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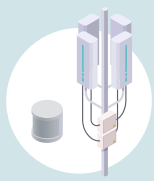
24 https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en (last retrieved: 25/03/2021)

Simplified illustration of areas of environmental impact of 5G

A 5G device (smartphone, connected objects, M2M) emits or receives a signal



A 5G antenna receives or emits a signal

An exponential amount of data travels through backhaul and fibre network to cloud data centres

A 5G device	A 5G antenna	
Devices are likely to be more resource-greedy and complex	More antennas are required to cover a similar area compared to 4G	Cloudlets (small clouds) may be used to process data nearer to the source.
Device numbers soar to reach IoT ubiquity	5G macro cell antennas may be 5G connected to a multitude of small cells	The more data travels and is processed, the greedier it is.
	5G antennas may be equipped with complementary devices such as lithium-ion batteries and photovoltaic panels due to peaks in energy consumption	

Potentially exponentially high environmental impacts · Potentially very high environmental impacts · Potentially high environmental impacts
Confirmed mitigated environmental impacts compatible with planetary boundaries · Confirmed positive environmental impacts

As 5G builds on pre-existing mobile networks, as all the precedent mobile network generations have done, 5G raises the following question: **is it sustainable and useful to have for the same area an ultra-high-speed fibre-optic wireline network, an ultra-high-speed mobile network, and possibly the same via satellite?**

5G may be useful in specific cases, such as for specific industrial purposes and for areas with numerous devices to connect at the same time, but can we afford environmentally to have ultra-high speed everywhere, from any device, with 3 different types of high-speed technology, while bearing the brunt of three times the environmental impacts of high-speed connectivity?

5G is presented by operators as a growth rider. As 5G and next-generation mobile networks shape the urban landscape and increasingly take on a political and societal dimension, mobile network implementations are raising the need for concertation between citizens and regional and local communities, as well as national telecom regulatory authorities. ■

Recommendations for a digital evolution compatible with the Green Deal

At the cross-national level, policymakers from all over Europe jumped at the occasion prompted by concerns about the future mobile network generations to sit **all the actors – from policymakers to citizens, industrialists, NGOs, institutions such as BEREC and its national equivalents, scientists from the tech and medical worlds and the social sciences – down at the same table.**

As a prerequisite to deployment, the scientists pooled their efforts and knowledge to measure the environmental, health and social impacts associated with three deployment scenarios: scenario 1, complete deployment; scenario 2, deployment limited to specific industrial uses; scenario 3: complementary deployment taking into account citizens' needs and eco-design options. Together, they drew a roadmap of the future digital infrastructures in European States, with key guidelines ensuring efficient and rigorous targets to divide by six the environmental impacts of ICT by 2050, with specific targets for user equipment, networks, and datacentres.

This ambitious plan enabled a resilient strategy to be drawn up for ICT in Europe, which limits the overlaying of very-high-speed networks and instead adopts a strategy based on network complementarity and interoperability and addresses the need to bridge the digital divide.

This ambitious digital concertation renewed digital governance and widely involved European citizens, leading to greater trust as the different concerns were addressed and responded to.

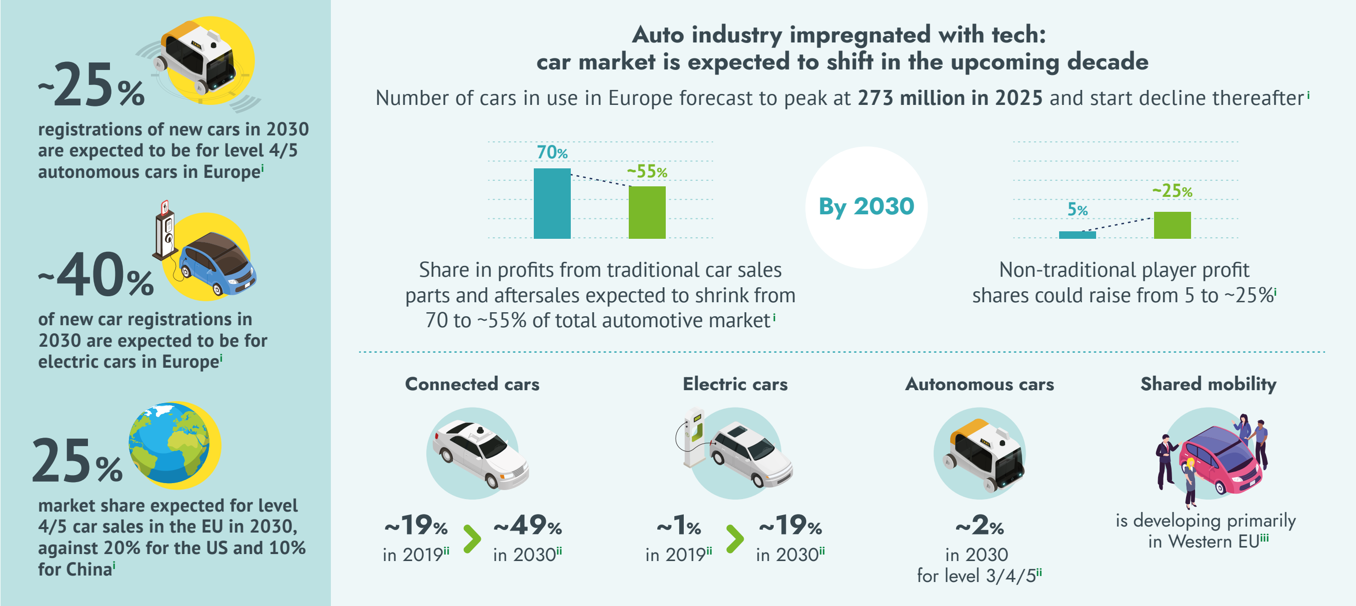
As a prerequisite to European innovation funding, comparative, attributive (direct impacts) and consequential (indirect impacts, induced effects and rebound effects) environmental life cycle analysis studies were made mandatory to measure the benefits versus costs whenever a technology is used to reduce environmental footprint. This applies to 6G funding as well as to funding of any other innovation.

Independent studies were conducted on the health impacts of the 3.5 GHz and> 24 GHz bands to clearly establish whether these waves have adverse effects on human health or not.

Autonomous Vehicles

Table of content

Key data for magnitude



[i] PwC Strategy&, Digital Auto Report, 2019
[ii] BCG, CLEPA and Wolk, At the Crossroads: The European Aftermarket in 2030, 2021
[iii] STARS (Shared mobility opportunities and challenges for European cities), Car sharing in Europe: a multidimensional classification and inventory, 2017

Understand the automation levels

Summary of the case study

Autonomous vehicles are at the intersection of the transport and ICT sectors: they are connected, have an internal computer system to process the data received by their multiple sensors, and they rely more than ever on advanced technologies such as AI, mobile broadband coverage and the IoT. With the development of ICT, many new and innovative applications are being tested with the aim of developing new tech markets. Connected and autonomous cars (CAVs) fall into this category. The hype around this new type of vehicle far exceeds the scale of its entry and mass market penetration. But how can autonomous vehicles change our modes of transport and what challenges must be overcome if autonomous cars are to be more a lever than a hindrance in terms of environmental impact?

Greenhouse gas emissions from transport by car accounted for around 60.4 per cent of total GHG emissions from road transport in the EU28 in 2018, while transport represented 21.8 % of total GHG emissions in the EU28.[1] Autonomous vehicle projects are developing but are not yet on the market due to the absence of a regulatory framework that would allow them to use the roads regularly. In the meantime, the transport sector is undergoing numerous transformations that are also strongly affecting its environmental footprint: the development of the electric car market, the rise of ride-hailing platforms and carpooling are some of the major transformations the transport sector is experiencing.

Definitions

What is an Autonomous Vehicle?

A self-driving car is a vehicle capable of travelling safely by sensing its environment thanks to a variety of sensors, with little or no human intervention. It can also be called a driverless car or an autonomous vehicle.

1 https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer (last retrieved: 13/04/2021)

Six levels of connected and automated vehicles

In the SAE J3016 standard, SAE International, previously known as the Society of Automotive Engineers, defines six levels of driving automation from level 0 (no automation) to level 5 (full autonomy: the vehicle can drive everywhere in all conditions with automated driving features).[2] This taxonomy is extensively used by the industry to define autonomous driving functionalities.

Within this taxonomy, driving automation starts at level 3, with conditional automation: the system executes steering and acceleration/deceleration, and monitoring of the driving environment, but the human driver can drive if necessary. Level 4 stands for high automation: the human in the driver's seat is not required to take over driving, but the automated vehicle can drive in limited conditions and will not operate unless these conditions are all met. Level 4 vehicles can be used for local driverless taxi uses, for example. At level 5, the driving automation system can drive the vehicle under all conditions.[3] McKinsey expects level 4 technology to be available between 2020 and 2022, and level 5 to arrive by 2030 at the earliest.[4] PwC Strategy& anticipates that level 4 will be available at low speed and in restricted areas from 2023 in the EU, while road-ready level 5 cars are not expected to be available before 2028. Around 25 per cent of new car registrations are expected to have level 4/5 autonomy by 2030.[5]

Main concepts

- **Ride-hailing company:** A ridesharing or ride-hailing company operates via a mobile application and a website to match passengers with drivers of vehicles for hire. Unlike taxicabs, ridesharing companies cannot legally be hailed from the street. The most well-known ridesharing companies in Europe are Uber and Bolt. Ridesharing is known to contribute to road congestion, reduce public transport use, and have no substantial impact on vehicle ownership.[6] Non-pooled ride-hailing is estimated to be more polluting than a private car ride due to emissions from 'deadhead' journeys, but electric and pooled ride-hailing can contribute to cutting emissions.[7]

- **Carpooling:** This mobility mode enables the full seating capacity of a car to be used: carpooling reduces each individual's travel costs (fuel costs, tolls), and is more environmentally sustainable.

- **VMT (vehicle-miles travelled) / VKT (vehicle-kilometres travelled):** A measurement of the distance travelled by vehicles. It can be used for comparison, to see if the distance travelled per vehicle increases or decreases depending on the scenarios and assumptions as to the variation of travel behaviours.

- **Platooning/flocking:** A method used to drive a group of vehicles together to increase the capacity of roads with an automated highway system. Platooning is made possible by autonomous driving, as it allows many vehicles to accelerate or brake simultaneously. It allows for closer headway between vehicles by eliminating the distance needed for human reaction. This transport method is still at the project stage. In the EU, the SARTRE Project began in 2009, funded by the European Commission. In 2011, SARTRE gave its first successful demonstration of platooning technology at the Volvo Proving Ground in Gothenburg, in Sweden. A second demonstration was given near Barcelona, in Spain, in 2012.[8] The potential benefits expected from platooning are a reduction of congestion and shorter commutes during peak periods, greater fuel economy due to reduced air resistance, and fewer traffic collisions. There are still security disadvan-

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2 https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic (last retrieved: 13/04/2021)
3 https://www.sae.org/standards/content/j3016_201401/ (last retrieved: 13/04/2021)
4 https://www.mckinsey.com/features/mckinsey-center-for-future-mobility/overview/autonomous-driving (last retrieved: 13/04/2021)
5 PwC Strategy&, *Digital Auto Report*, 2019, p.26
6 UCSUSA, *Ride-Hailing's Climate Risks Steering a Growing Industry toward a Clean Transportation Future*, 2020; Anne de Bortolli, *Environmental performance of shared micromobility and personal alternatives using integrated modal LCA*, 2021; Aggelos Soteropoulos, Martin Berger & Francesco Ciari, *Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies*, 2018
7 UCSUSA, *Ride-Hailing's Climate Risks Steering a Growing Industry toward a Clean Transportation Future*, 2020
8 https://cordis.europa.eu/project/id/233683/reporting (last retrieved: 15/04/2021)

tages to this system due to hacking issues that could create dangerous traffic situations, and to the problem of attention should the driver need to react in the event of software or hardware failure.

Environmental issues related to AV applications

By far the most keenly expected changes from autonomous vehicles are increased road safety without human error. Driving comfort and the increased possibilities for social inclusion are also highlighted to promote the benefits of the autonomous vehicles. Similarly, climate benefits are sometimes mentioned, mostly in vague terms. But what do we currently know about the potential environmental benefits and impacts of autonomous vehicles?

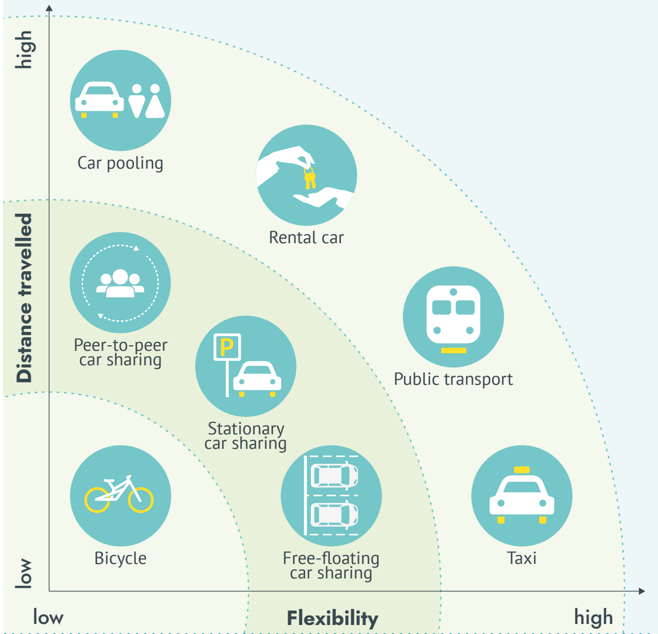
Autonomous vehicles: a lever to achieving the objectives of reducing environmental impacts?

The transport sector is in the throes of change: the development of the electric car market, the rise of ride-hailing platforms and carpooling are some of the major transformations the transport sector is undergoing. There would be no point in seeking to understand the environmental impacts linked to autonomous vehicles without considering these other, overlapping innovations, which are already influencing the sector's environmental footprint. Indeed, electric vehicles contribute to reducing atmospheric pollution in cities, and in some countries, depending on the GHG emissions of the energy mix, electric vehicles can help reduce the GHG emissions produced during the use phase of the vehicle. Moreover, carpooling helps reduce the number of cars in use and the overall vehicle kilometres travelled. On the other hand, ride-hailing platforms have an overall negative impact on transport sector, by shifting the use of public transport to ride-hailing.[9]

Pooling vehicles to divide the impacts

In the first place, the best known way of reducing the environmental impact of a car journey is to fill the vehicle as close as possible to capacity in terms of the number of passengers or goods, and to limit the number of vehicles and overall distance travelled. This is because when a vehicle is shared, the environmental impacts of that vehicle are also shared among the passengers. And it is not only the energy consumed by driving the vehicle that is shared, but also the impacts related to the vehicle's complete life cycle (including production), proportionally to the use of each beneficiary. If the consequence of carpooling is that passengers do not buy or renew their car, the environmental benefits of this substitution effect are even greater. On the other hand, this benefit can be reduced if it increases the use of the car at the expense of other mobility methods with less

Classification of car sharing among existing mobility concepts



Source: *Deloitte*.

9 UCSUSA, *Ride-Hailing's Climate Risks Steering a Growing Industry toward a Clean Transportation Future*, 2020

environmental impact (public transport, cycling, etc.).

With the optimisation methods enabled by ICT and their possible application in autonomous car systems, it may be possible to diminish traffic; yet the theoretical benefits are limited by other parameters such as the acceptability for the users of longer travel and waiting times, for example.[10]

"The best-known way of reducing the environmental impact of a car journey is to fill the vehicle as close as possible to capacity in terms of the number of passengers or goods and to limit the number of vehicles and overall distance travelled [...] When passengers share the same car, the environmental impacts are also shared proportionally."

The contribution of electric vehicles to limiting greenhouse gas emissions

Secondly, it is necessary to consider the efficiency gains from electrical vehicles to better understand how autonomous vehicles could be a lever for reducing environmental impacts. An autonomous car may be an internal combustion engine vehicle (sometimes shortened to ICEV or ICE) or an electric vehicle, but the trend is towards the development of electric vehicles to combat global warming and pollution peaks in cities – There are even electric trucks today.

A comparative life cycle assessment of the internal combustion engine and the electric car, published in 2018 by the Department of Industrial Engineering at the University of Florence[11], shows that the electric car allows a major reduction of impact in terms of climate change because of less gas emissions during operation: based on the energy mix of the electricity used to charge the battery, the greenhouse gas emissions of the use phase can vary. They note that this advantage grows significantly as more renewable sources are used in the mix for electricity production. On the other hand, this study also shows that the environmental loads of powertrain construction and manufacturing result in higher environmental impacts regarding acidification, human toxicity, particulate matter, photochemical ozone formation and ozone depletion.[12] These consistent findings show that even if the electric car does indeed have many advantages in terms of reducing GHG emissions from transport, there is still room for improvement, especially with regard firstly to the environmental impacts of the vehicle production process, which any policy must take into consideration to limit impact transfers, and secondly to the electricity grid mix. To attain sustainable mobility, these parameters must be taken into consideration. This will also be the case for autonomous vehicles, which can be either combustion or electric, and either designed to be autonomous or in some cases modified to become autonomous.

Could eco-driving, platooning and intersection connectivity contribute to reducing the environmental impacts of autonomous vehicles?

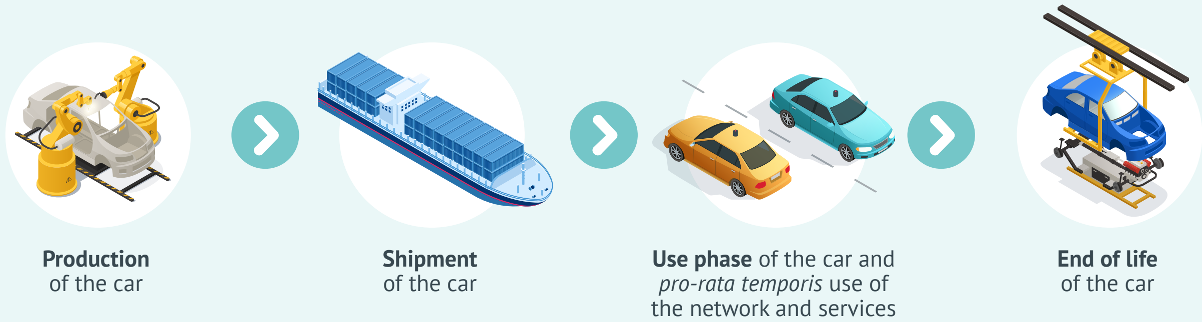
The next question we need to ask regards the efficiency gains autonomous vehicles themselves can achieve. Indeed, as autonomous vehicles carry more sensors and electronic components than human-driven vehicles, these ICT components are considered as a 'subsystem' in the life cycle of the vehicle. A life cycle assessment

10 User acceptability is questioned in the next section based on a study reviewing several travel behaviours and land-use studies.

11 Francesco Del Pero, Massimo Delogu, Marco Pierini, *Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car*, 2018

12 The study concludes: "*In the light of previous considerations it appears clear that the assessment of electric cars cannot be performed using a single indicator but it should be rather based on a more complex evaluation system. For this reason, market penetration of BEVs must be accompanied by a cautious policy which takes into consideration all the aspects of the LC management. To date electric mobility appears as an effective strategy for reducing GHG emissions in regions where electricity is produced from sources with limited contribution of fossil sources. However, production phase represents the main barrier for achieving the full maturity of this technology in the environmental perspective. Future clean electricity grid mixes and the development of more sustainable production processes could strongly contribute to the convenience of BEVs by minimising GHG emissions as well as countering potential setbacks in terms of other environmental impacts.*", in Francesco Del Pero, Massimo Delogu, Marco Pierini, *Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car*, 2018, p.8 and 14-15

Simple life-cycle of an autonomous car



copyrighted by the American Chemical Society[13] of the sensing and computing subsystem and vehicle level effects of level-4 autonomous vehicles (self-driving vehicles in specific conditions) emphasises that eco-driving, platooning and intersection connectivity could reduce energy and GHG emissions by up to 9 per cent in the base case, although the subsystems of the autonomous cars could increase vehicle primary energy use and GHG emissions by 3 to 20 per cent. The study assesses six different scenarios: three for electric vehicles (small subsystem, medium subsystem, and large subsystem) and three for internal combustion vehicles (small subsystem, medium subsystem, and large subsystem). The results of this study seem to show that eco-driving, platooning and intersection connectivity can counterbalance the energy and GHG emissions linked to CAV subsystems in four scenarios (both small and medium subsystems added to electric vehicles, and both small and medium subsystems added to internal combustion vehicle scenarios) but for none of the two scenarios where a large CAV subsystem is on board.

Unsurprisingly, the results show that the scenario with the least impact of the six scenarios, in terms of GHG emissions and energy consumption, is the electric vehicle with a small subsystem: indeed, the lighter subsystem needs fewer materials for the manufacturing phase and due to its lighter weight consumes less energy during driving. Yet although these results are interesting to scale the different scenarios, a 9-per cent saving in energy and GHG emissions is still little compared to the climate challenge and the environmental benefits that can be achieved by ridesharing.

"Digital innovations for transportation must be considered in the light of multiple and systemic parameters to limit side effects: what are the other mobility methods, and which have the most interesting ratio of distance/travel time/environmental impacts?"

However, the literature that explores complementary environmental indicators such as acidification, human toxicity, particulate matter, photochemical ozone formation, ozone depletion or raw material depletion in the life cycle of autonomous vehicles remains scarce. To provide a complete overview of the balance between the environmental benefits and costs of autonomous vehicles, more studies need to be done that also take into consideration both the means of direct reduction– such as platooning and intersection connectivity – and the pro rata use of the ICT infrastructure and ICT services needed to make pooling and intersection connectivity possible.

13 James H. Gawron, Gregory A. Keoleian, Robert D. De Kleine, et al, *Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects*, American Chemical Society, 2018 - Copyright © 2018, American Chemical Society

To sum up, to be a lever to achieving the objectives of reducing environmental impacts, digital innovations for transportation must be considered in the light of multiple, systemic parameters to limit side effects: what other mobility methods are there, and which have the most interesting ratio of distance/travel time/environmental impacts, while not being outweighed by a lack of user acceptability? If carpooling is definitely a lever, it is more complex in the case of electric vehicles, which have great benefits in terms of GHG emissions and energy consumption but significant impact transfers in terms of other environmental indicators such as acidification, human toxicity, particulate matter, photochemical ozone formation and ozone depletion. Regarding the ICT components of autonomous vehicles, the lighter the autonomous subsystem of the car, the lighter its impact, yet these components add environmental impacts to the overall impacts of the vehicle – and the overall infrastructure they rely on (5G, AI) also has to be considered.[14] Given this, the path by which autonomous vehicles can be a lever to limiting environmental impacts is a slippery one; it requires upstream regulation of user behaviour trends to maximise the environmental benefits and limit the risk of a lock-in[15] that would only add to existing issues. But what changes is the arrival of autonomous vehicles expected to have on mobility behaviours?

Autonomous vehicles: a hindrance to achieving the objectives of reducing environmental impacts?

In the previous section, we saw that carpooling can contribute to reducing the environmental impacts of road traffic, especially when it means that car passengers give up owning a personal car. Will the arrival of autonomous vehicles stimulate this behaviour or not? More broadly, with the arrival of self-driving cars, what behavioural changes can be expected that will diminish or raise environmental impacts?

“Autonomous vehicles are mostly found to increase vehicle distance travelled and reduce the share of public transport and slow modes of transport.”

An Austrian study[16] on the impacts of automated vehicles on travel behaviour and land use assesses an international review on existing modelling studies (mostly in Europe and the US) and compares results regarding the different scenarios and assumptions investigated.

One of the most important result of this study is that autonomous vehicles are mostly found to increase vehicle distance travelled and reduce the share of public transport and slow modes of transport.

The studies reviewed show an increase of VMT (vehicle-miles travelled) or VKT (vehicle-kilometres travelled) depending on the adoption rate: from 60 per cent if the adoption rate is high to 8 per cent if a small share of private vehicle trips, are replaced by shared autonomous vehicles and result in additional empty trips. These results indicate that **autonomous vehicles tend to increase the number of kilometres travelled in most**

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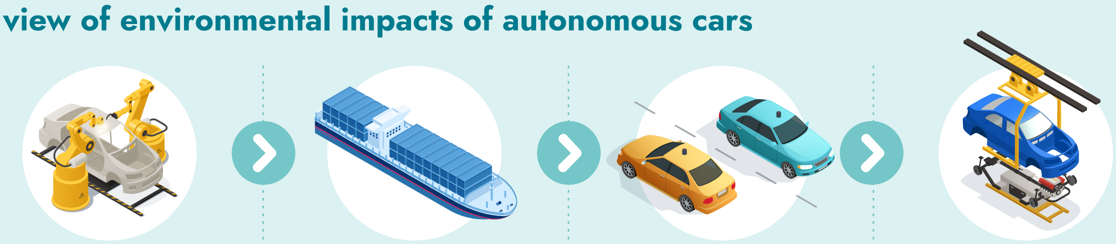
14 See our case studies on AI and on 5G
15 See our case study on rebound effects
16 Aggelos Soteropoulos, Martin Berger & Francesco Ciari, *Impacts of automated vehicles on travel behaviour and land use: an international review of modelling studies*, 2018

Simplified view of environmental impacts of autonomous cars



	Production of the car	**Shipment** of the car	**Use phase** of the car and *pro-rata temporis* use of the network and services	**End of life** of the car
ICT components	*Importance of impact depending on the size of the subsystem*		✖ Computing energy, contribution to the weight of the vehicle and pro rata use of network and services infrastructure adds to environmental impacts	✖ ICT components contribute to increasing the environmental impact of the vehicle
Internal combustion engine vehicle	✖ Less impact in the production phase than electric vehicle, high impact on resource depletion	*Depending on the shipment method and distance*	✖ Very high impact on most environmental indicators: **acidification, human toxicity, particulate matter, ozone depletion, photochemical ozone formation, etc.**	✖ Contributes to a slight decrease in the environmental impact of the vehicle
Electric vehicle	✖ Very high impact on **greenhouse gas emissions, particles emissions and energy use**		*Depending on the electric mix used to supply the vehicle and its weight, the use phase impacts can be completely different*	✖ Contributes to a very slight decrease in the environmental impact of the vehicle, electrical batteries cannot be fully recycled

✖ Potentially exponentially high environmental impact ✖ Potentially very high environmental impact ✖ Potentially high environmental impact
✖ Confirmed mitigated environmental impacts compatible with planetary boundaries ✖ Confirmed positive environmental impacts

cases, as car journeys are more accessible (for non-drivers, or in the case of drivers give them time to do other activities simultaneously). They also underline that autonomous vehicles "*lead to reductions of the public transport and slow modes share, especially when private AVs (Autonomous Vehicles) or SAVs (Shared Autonomous Vehicles) without ridesharing and a high reduction in the value of time are assumed*".

On the other hand, **VKT can decrease if a large share of the travellers are willing to rideshare and accept an increase in travel time of 30 to 50 per cent,** which would have the effect of a decrease of VKT by 11-24 per cent. Yet, this assumption is highly hypothetical: would people willingly accept such increased travel time for ridesharing when it is possible to use ride-hailing without sharing and complete the journey quicker alone?

"To ignore socially induced user behaviours in assessing measures to limit the environmental impacts of autonomous vehicles would, on the contrary, run the risk of triggering a potential rebound effect, made possible by the efficiency gains driven by technological and infrastructural innovations."

Indeed, it is highly possible that the travellers would be more sensitive to the timesaving and comfort of a first-come-first-served dispatching strategy. This means that without the frame of a binding environmental law and the consideration of possible rebound effects[17], autonomous cars could be more of a hindrance than a lever to achieving environmental objectives.

17 See our case study on rebound effects

Conclusion

Considering all the points mentioned above, it seems clear that without an appropriate policy, autonomous vehicles could exacerbate GHG emissions. Indeed, if infrastructure choices (regarding ICT infrastructure strategy but also mobility infrastructure strategy) are not supervised by political decision-makers, the arrival of autonomous vehicles is more likely to stimulate the use of the car as the main means of transport in urban areas at the expense of public transport and soft mobility. To avoid this predictable rebound effect, user behaviours must be considered in policy-making decisions. To ignore socially induced user behaviours in assessing measures to limit the environmental impacts of autonomous vehicles would, on the contrary, run the risk of triggering a potential rebound effect,[18] made possible by the efficiency gains driven by technological and infrastructural innovations.

18 See our case study on rebound effects

Recommendations for a digital evolution compatible with the Green Deal

In 2022, the imminent arrival of the autonomous car on the market was regulated upstream by ambitious and comprehensive policies that took into account the environmental impacts of both the vehicles and the overall infrastructure they rely on. The debates concerning preparations for the arrival of autonomous vehicles were an opportunity to question road safety not only as a vehicle issue, but also as a global infrastructure question inextricably bound up with environmental questions. This allowed for a complete, coordinated rethink of transport policy within the EU member states, with the clear and concrete objective of reducing the environmental impacts related to both transport (of people and goods) and ICT, based first and foremost on the objectives of the Paris Agreement and the aspirations of citizens of the whole of Europe, whatever the type of area they inhabited (not only metropolitan and urban areas but also rural areas).

Ambitious but realistic policies were developed by taking into account use behaviours, the knowledge and risks of socio-technical lock-ins, and digital innovations such as ride-hailing or connected and autonomous vehicles.

A focus on the modernisation of public transport rail infrastructures, intermodal transport and accessibility to railway stations and the funding of eco-design including the entire value-proposition of a vehicle made it possible to drastically cut emission factors at source and consequently reduce road congestion.

This has made it possible to drastically lower the greenhouse gas emissions and particle pollution linked to transport by stimulating virtuous behaviours and making them accessible. The indirect benefits of this ambitious policy are that it has enabled the EU to increase its sovereignty and resilience and has helped stimulate model innovations across all economic sectors within the EU, while strengthening regional networks thanks to a reliable rail and public transport network. Moreover, genuine consideration of people's needs throughout Europe has strengthened the cohesion and involvement of its citizens.

Research on user behaviours has continued and behaviour scenarios based on human sciences have been integrated to amplify the robustness of assumptions in the evaluation of environmental impacts. Life cycle assessments which take into account multiple emission factors and comparative scenarios based on various mobility modes, and which assess the complete functional units of these scenarios including the pro rata use of ICT infrastructure for every type of connected vehicle, have been encouraged.

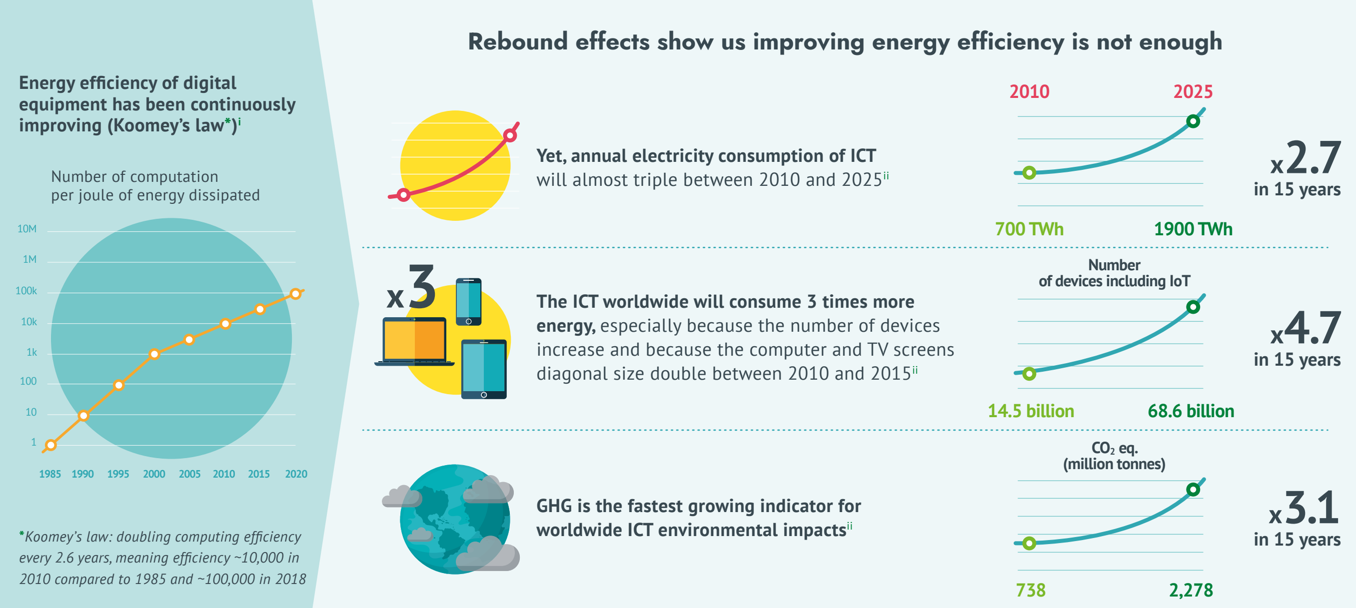
ENVIRONMENTAL EFFECTS CASE STUDIES:

- Rebound effects
- Raw materials in ICT
- E-waste & circular economy

Rebound effects due to ICT

Table of content

Key data for magnitude



[i] Koomey J., Naffziger S., *Efficiency's brief reprieve: Moore's Law slowdown hits performance more than energy efficiency*, in IEEE Spectrum. April, 2015
[ii] GreenIT.fr, *Environmental Footprint of the digital world*, 2019

Summary of the case study

This case study takes a look at rebound effects and more specifically explores the rebound effects of ICT. Rebound effect is a term used to describe the negative side-effects of efficiency strategies that end up cancelling out the targeted environmental gains. Rebound effects can be systemic, occurring at the economy-wide level, where they have the broadest impact; indirect, if, for example, savings are reinvested in activities or goods that have a bigger footprint; or direct, if improvement of a product or service results in greater consumption of that product or service. Quantifying rebound effects by computation is extremely difficult and uncertain, as the findings of this case study show, because of the variety of parameters that may be involved. This case study also found that without proper consideration of the established structures, habits and goals pursued by the stakeholders, efficiency measures increase the risk of missing their target, and may even be counterproductive.

Definitions

What is a rebound effect?

The notion of rebound effect is used to characterise "*the negative side-effects of efficiency policies and strategies that ended up taking back the environmental gains*" they targeted.[1]

> *"The more technological improvements increase the efficiency with which a resource is used at a micro level, the more the total consumption of that resource will tend to increase, rather than decrease, at a macro level.*

The rebound effect can be defined as follows: the more technological improvements increase the efficiency with which a resource is used, the more the total con-

1 Gossart, C., *Rebound Effects and ICT: A Review of the Literature*, 2014

sumption of that resource will tend to increase, rather than decrease.[2]

The rebound effect is often associated with an increase in consumption due to an increase in efficiency and a consequent price decrease. Nonetheless, rebound effects can also be identified regarding time, space, and technology[3]:

- **Time rebound:** When the improvement is more or less time consuming than the status quo, it leads to changes in consumption (**for example, see our case studies: 5G, autonomous cars**).

- **Space rebound:** When the improvement uses more or less space than the status quo, it leads to changes in consumption (e.g. it is easier to realise Bill Gate's dream of "a computer on every desk, and in every home" nowadays with desktops and laptops than with the first generations of computers such as ENIAC computers being as big as a room).

- **Technology rebound:** When the improvement changes the availability or affordability of certain resources or technologies, it leads to changes in consumption.

Identifying and considering rebound effects is crucial to ensure environmental gains from both environmental policies and technological improvements on a large scale.

Main concepts

Scientific literature consensually distinguishes between three levels of general rebound: direct, indirect, and economy-wide:[4]

- **Direct rebound effects:** When an improvement of a product or service lowers the cost (in money, time, space, etc.) of the consumption of the product, the result being more consumption of this product/service. **Example of a direct rebound: increased mobile data traffic outweighed efficiency gains from the 2G to the 3G network.**[5]

- **Indirect rebound effects:** When a resource is used more efficiently and cost savings are made, it causes more income to be spent on other products and services, potentially on other sectors. **Example of an indirect rebound effect: efficiency savings made by a consumer or an enterprise can be reinvested in other products or services, potentially environmentally impactful.**

- **Economy-wide rebound effects:** Greater efficiency drives greater overall economic growth and causes structural changes in production and consumption at a macro-economic level. These effects combine the results of both direct and indirect rebound effects and are rarely considered. One example: the arrival of the Internet.

"To address the rebound effects in an economy-wide perspective, an approach comparing efficiency gains and rebound effects within the planetary boundaries is more relevant, taking also econometrical and social parameters in account.

Another key notion is the one of **backfire**: When "*overall energy consumption actually increases after energy-saving measures*".[6]

How to measure rebound effects? Some of the scientists who measured rebound effects tried to summarise the different parameters into an equation that could be used as a model. In the case of rebound effects due to energy efficiency gains, the different levels of rebound

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2 *GreenIT.fr definition of the rebound effect*, 2014

3 Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., *Addressing the Rebound Effect, a report for the European Commission DG Environment*, 26 April 2011

4 Gossart, C., *Rebound Effects and ICT: A Review of the Literature*, 2014; Sorrell, S., Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. Energy Policy 37(4), 1456-1469 (2009); Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., *Addressing the Rebound Effect, a report for the European Commission DG Environment*, 26 April 2011

5 Faist et al. 2004, Girod et al. 2010, cited in Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., *Addressing the Rebound Effect, a report for the European Commission DG Environment*, 26 April 2011, p.14 and p.51; Faist Emmenegger, M., Frischknecht, R., Stutz, M. et al., *Life Cycle Assessment of the Mobile Communication System UMTS: Towards Eco-efficient Systems*, (12 pp). Int J Life Cycle Assessment 11, 265–276 (2006)

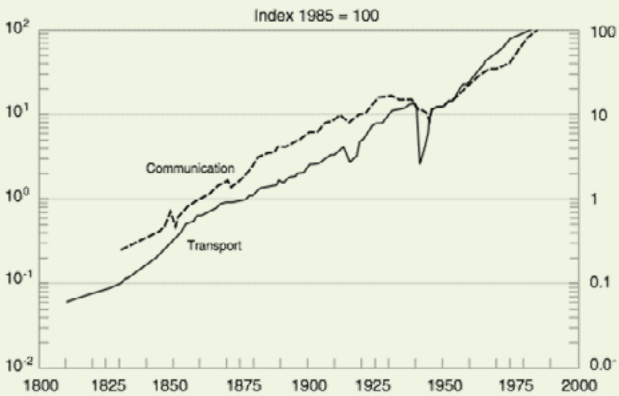
6 Gossart, C., *Rebound Effects and ICT: A Review of the Literature*, 2014

effect found from an energy improvement are then compared to the expected energy savings, and can be expressed as a percentage:

- If the percentage is below 100%, the energy savings are proportionally more important than the additional energy consumption.
- If the percentage attains 100% or more, "*the expected energy savings are entirely offset leading to zero net savings for the economy as a whole*"[7], meaning these savings "backfire".

However, this mathematical measurement of rebound

Compared evolution of information and transport flows since 1800



Source: Arnulf Grübler, *The Rise and Fall of Infrastructures*, 1990, cited by the IPCC, 2001

effects is limited to actually quantifiable measurements of direct or indirect rebounds and is often assessed on a micro-economic scale. To address the rebound effects with an economy-wide perspective, an approach comparing efficiency gains and rebound effects within the planetary boundaries is more relevant, also taking econometrical and social parameters in account (**see section "The expert's view"**). Moreover, "*a technology that leads to efficiency gains at the micro level might actually lead to efficiency losses at the macro level.*"[8] Indeed, even if a technology enables an improvement to be made, this is not always an improvement of our environmental footprint, and rebound effects can also come from improvements in terms of time, space or technology, as described above.

Environmental issues related to ICT rebound effects

Increases in energy efficiency lead to rebound effects. [9]However, the importance of these rebound effects depends on multiple parameters, and one single efficiency change can have multiple consequences in use behaviours, which makes rebound effects very difficult to assess. The main difficulties in understanding and estimating rebound effects due to ICT are related to the fact that ICT is pervasive, that is, it has a wide influence across many other sectors, and because ICT is a powerful tool for stimulating and generating innovation. Indeed, these characteristics show that ICT has a strong and complex interdependent relationship with many sectors of activity. As a result, the efficiency gains enabled by ICT have a knock-on effect with consequences across all sectors, as do their related rebound effects.

"Many studies and grey literature publications emphasise the energy-saving potential of ICT for specific use cases. As a result, there are fewer studies on the rebound effects at the macro level.

In many ways, ICT contributes to energy efficiency: ICT can reduce its own energy consumption (**see case studies on AI and on cloud**), contribute to energy savings in other sectors such as transportation, buildings, urban monitoring, etc. In a study published in 2012[10], Coroama et al. evaluate the abatement potential of greenhouse

7 Sorrell, S., Jevons' Paradox revisited: *The evidence for backfire from improved energy efficiency*. Energy Policy 37(4), 1456-1469 (2009), p. 1457
8 Gossart, C., *Rebound Effects and ICT: A Review of the Literature*, 2014, p.5
9 Lange S, Pohl J., Santarius T., *Digitalization and energy consumption. Does ICT reduce energy demand?*, 2020
10 Coroama, V.C.; Hilty, L.M.; Birtel, M., *Effects of Internet-based multiple-site conferences on greenhouse gas emissions.* Telemat. Inform. 2012, 29, 362–374.

gas related to the remote holding of international conference meetings via a video conferencing system rather than a worldwide, face-to-face conference on one site. The results show an abatement potential of 37% to 50% in travel-related GHG emissions compared to on-site conference scenarios, even accounting for the rebound effect of increased participation.

Many studies and grey literature publications emphasise the energy-saving potential of ICT for specific use cases. As a result, there are fewer studies on the rebound effects at the macro level. In an article published in 2020, Santarius et al. underline that "*literature abounds on energy-saving potentials from ICT-based efficiency improvements in various production and consumption processes. Yet, those studies focus on micro-level effects only and neglect any global effects at the macro-level. Additionally, they mostly describe potentials rather than actual developments. Theoretical arguments for incomplete substitution and potential rebound and induction (growth) effects are strong and are backed by anecdotal evidence, while empirical evidence on the causal link between digitalization and rebound effects has not yet been sufficiently researched on empirical grounds. These ambiguous facts suggest that ICT's overall effect on energy consumption via energy efficiency and rebound effects still remains unclear.*"[11] This shows that research on the rebound effects of digital technology is still incomplete.

Below, we will try to identify some areas within ICT where rebound effects are likely to be found, but more research needs to be done to make sure rebound effects are not overlooked.

ICT rebound effects: potential examples

As seen in the main concept section, rebound effects can be divided into direct, indirect and economy-wide rebound effect categories.

Direct rebound effects:

Of the direct rebound effects of ICT, the best-known is related to Moore's law: the observation that the number of transistors in an integrated circuit almost doubles every two years. Since this allows lighter and more powerful computers to be manufactured, it generates rebound effects regarding time (computing is quicker, so more and more complex computing tasks are possible), regarding raw materials (each successive processor generation being smaller it requires less material to be manufactured than the previous one, but demand soars). New models quickly supersede previous, slower ones, thereby contributing to the market obsolescence of computers or smartphones, even though many users would have been satisfied with older processors.[12]

Another example of rebound effect can be found in the case of datacentres (**see our case study on cloud**). Major progress has been made in energy efficiency for datacentres: a server delivers 4 times more calculations for identical power consumption than 8 years ago: the PUE (Power Usage Effectiveness) of recent datacentres has halved in 20 years.[13] Yet instead of observing a proportional fall in datacentre consumption, a slight increase has been observed, with a 6 per cent rise in power consumption between 2010 and 2018. Why is that so? At the same time the improvements cited above occurred, service demands rose. Indeed, computing needs grew six-fold between 2010 and 2018 and network traffic ten-fold, while storage capacity was multiplied by 25 during the same period.[14] Although datacentre effi-

11 Santarius T., Pohl J. and Lange S., *Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing?*, 2020

12 Gossart, C., *Rebound Effects and ICT: A Review of the Literature*, 2014, p.6; Hilty, L.M.: Information technology and sustainability: Essays on the relationships between information technology and sustainable development. Books on Demand, Norderstedt (2008)

13 Eric Masanet, Arman Shehabi, Nuoa Lei, Sarah Smith, and Jonathan Koomey, *Recalibrating global data center energy-use estimates*, 2020; *https://www.greenit.fr/2020/03/04/data-center-seulement-6-de-hausse-en-8-ans/* (last retrieved: 25/10/2021)

14 Eric Masanet, Arman Shehabi, Nuoa Lei, Sarah Smith, and Jonathan Koomey, *Recalibrating global data center energy-use estimates*, 2020;

ciency gains are offset by increased demand, the impact of increased demand on equipment and networks is much larger, which is an indirect rebound effect.

In our LCA study, we found that equipment constitutes the greatest area of impact within ICT, representing between 62 and 89 per cent of ICT environmental impact for Europe in 2019 depending on the indicators, with more than 65 per regarding climate change and around 89 per cent regarding resources, minerals and metals.[15]

In the case of smartphone uses, some rebound effects are easy to see even though the boundary between direct and indirect rebound effects may vary. Between 2011 and 2019, the time spent on the Internet via mobile phones worldwide increased from 32 minutes to 132 minutes per day, while in the meantime desktop time spent on the Internet has slowly decreased from 43 to 39 minutes per day, which means an overall augmentation of 228% of time spent on the Internet (a 9% decrease for desktops and 413% increase for smartphones).[16]

The reasons for a such an increase in the amount of time spent on the Internet are numerous and intertwined: more powerful smartphones[17], a fall in mobile data prices[18], increasingly rapid broadband access (each mobile network generation being quicker than its predecessors)[19], more applications to access social networks, media, games, everyday-life services[20], etc., often designed to increase time spent on them[21], more and more intuitive to use and with an increasingly smoother user experience[22], etc. Ultimately, when more time is spent on the Internet via mobile networks, smartphone renewal rates rise (for more powerful smartphones, or to replace with a phone with a more powerful battery), as do the environmental impacts of ICT.

The case of socio-technical lock-ins in ICT

Socio-technical lock-ins are positive social and technical feedbacks or increasing returns on the adoption of a selected technology.* This means that the use of the technology is having social or socio-economical positive impacts which supports the use of this technology.

Socio-technical lock-ins happen when there is a co-evolution of a technology and the adoption of social behaviours related to this technology.

In the case of ICT, users are familiar with socio-technical lock-ins when, for example, the adoption rate of a piece of software (Microsoft Office), a social network (Facebook, WhatsApp, etc.) or a technology (smartphone, mobile broadband, computer) makes it difficult to interact with fluidity without adopting it, and even more difficult to stop using it.

Socio-technical lock-ins create path dependencies at the macro scale which can be barriers for more sustainable habits. These path dependencies include institutions and infrastructures in the "rule-set" they involve.*

Since it is very difficult to escape a socio-technical lock-in once established, policies have to address how to prevent new lock-ins happening. Limiting socio-technical lock-ins in ICT is also a means of creating greater inclusion to bridge the digital divide. Moreover, it enables more disruptive innovation in ICT by enabling the introduction of radically new technological trajectories.

* Geels FW, *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study*, 2002; Gregory C Unruh, *Understanding carbon lock-in*, 2000; Rip A, Kemp RPM, *Technological change*, 1998;

Similarly, the increasing availability of unlimited subscriptions (unlimited video-on-demand subscriptions,

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15 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

16 Zenith Media, Media Consumption Forecasts, 2019

17 https://www.androidauthority.com/smartphone-performance-improvements-timeline-626109/ (last retrieved: 25/05/2021)

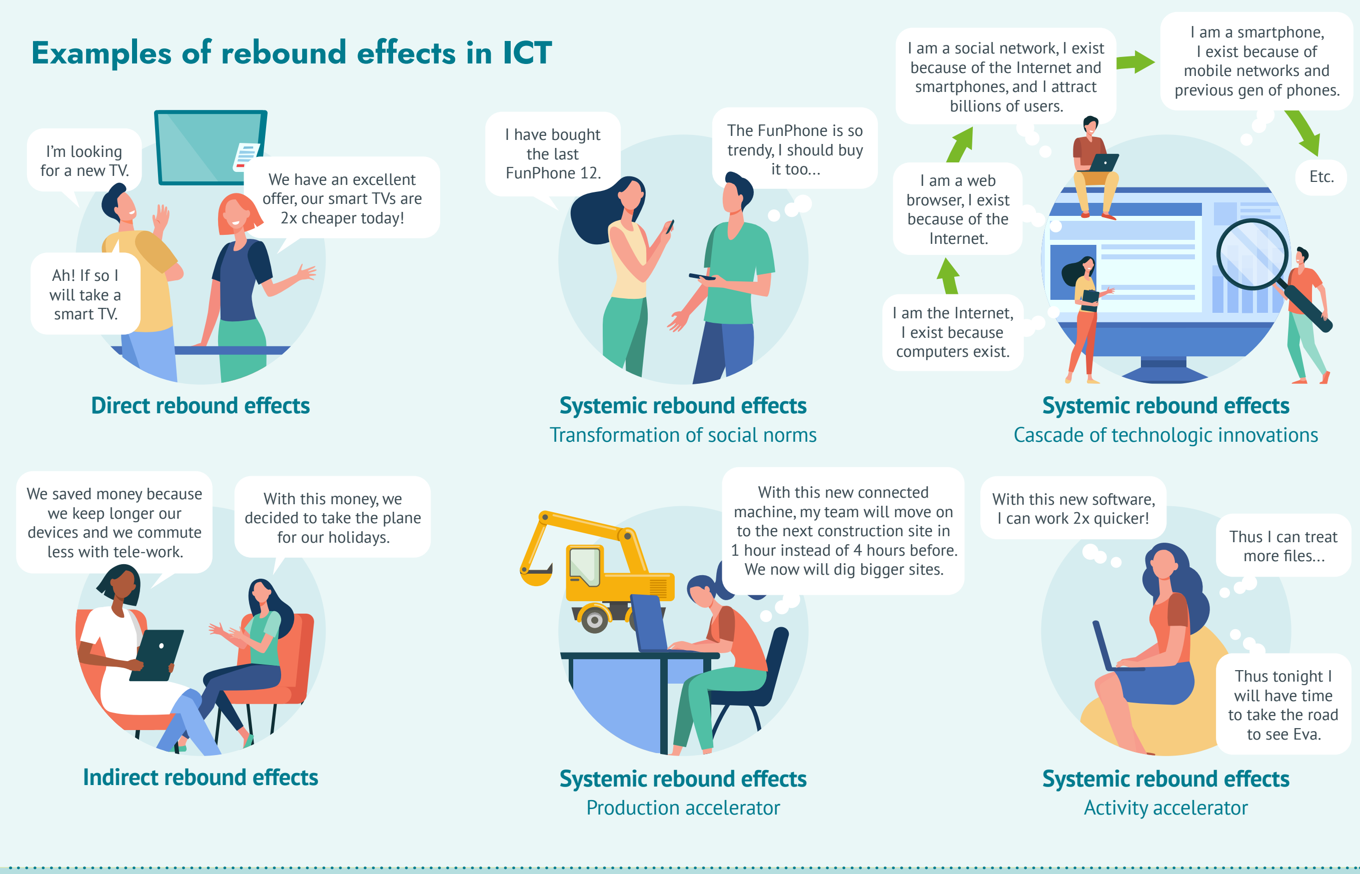
18 Empirica and TÜV Rheinland for the European Commission DG Communications Networks, Content & Technology, Mobile broadband prices in Europe 2019, Digital Single Market, 2019

19 Vora L. J., Evolution of mobile generation technology: 1g to 5g and review of upcoming wireless technology 5G, IJMTER, 2015

20 https://techcrunch.com/2021/01/13/app-stores-saw-record-218-billion-downloads-in-2020-consumer-spend-of-143-billion/ (last retrieved: 25/05/2021)

21 A 2020 documentary called The Social Dilemma, explores the addictive effects of social networking, while tech experts sounding the alarm on their own creations.

22 https://www.textrequest.com/blog/history-evolution-smartphone/ (last retrieved: 25/05/2021)



Inspired from: https://ligue-enseignement.be/rapport/projet-europeen-conscience-numerique-durable/

unlimited streaming music subscriptions, on-demand video games, subscription with unlimited access to press or channel archives) will potentially boost ICT equipment (bigger TV screens[23], connected objects such as connected speakers, etc.) and, complementary to this, cloud demand, meaning the construction of more data centres.[24]

Also, as more electronic components are used to produce new cars, including autonomous cars, combined with the anticipated rise of autonomous car sales in the next decades[25], it is possible that rebound effects will be observed depending both on policy frameworks and on adoption and use behaviours.

The same is likely to happen with the increased production of connected objects and the growing hype around the IoT[26], meaning a dramatic increase in demand for ICT equipment and the related environmental impacts of production (greenhouse gas emissions, critical raw material depletion[27], water pollution, etc.) and its rapid obsolescence (e-waste[28]).

Moreover, massive new technology adoptions have important rebound effects by stimulating equipment renewal. This is what happened with the evolution from 2G to 3G[29], for example, and a few years later from 3G to 4G[30], the effect being widespread smartphone replacement to access new-generation mobile networks.

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23 IFA, *IFA Global Press Conference 2019*, April 2019, page 13
24 See our case study on the cloud
25 See our case study on autonomous vehicles
26 See our case study on the IoT
27 See our case study on raw material depletion
28 See our case study on e-wastes
29 Faist et al. 2004, Girod et al. 2010, cited in Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., *Addressing the Rebound Effect, a report for the European Commission DG Environment*, 26 April 2011, p.14 and p.51; Faist Emmenegger, M., Frischknecht, R., Stutz, M. et al. *Life Cycle Assessment of the Mobile Communication System UMTS: Towards Eco-efficient Systems*, int J Life Cycle Assessment 11, 265–276, 2006
30 GSMA, *The Mobile Economy Europe 2018*, 2018

These various potential current and future ICT rebound effects should be anticipated, and if they occur, measured and monitored. Although the literature does not always agree on the magnitude of a rebound effect,[31] there is a consensus that preventing rebound effects is necessary and that it requires the establishment of **"an emission-constraining framework"**[32] suggesting that energy efficiency technologies alone are not enough to foster energy savings.

Apart from the energy efficiency gains made possible by ICT, these technologies also allow numerous gains in terms of comfort and time, which profoundly modify the uses and the level of expectation of consumers and businesses, as we witnessed during the Covid crisis (e-learning, telework, e-commerce, etc.). These behavioural effects are likely to contribute to the ICT rebound effects.

Indirect rebound effects:

Indirect rebound effects happen when a resource is used more efficiently and savings are made (in terms of cost, time, etc) and it causes more income, time, etc. to be spent on other products and services, potentially in other sectors. The first two main possibilities we can think of regarding indirect rebound effects are:

1. Visible rebound effects at the individual level: when one use is replaced by another with a greater environmental footprint. A concrete example might be celebrating small efforts to reduce one's carbon footprint by taking a plane trip, which would cancel out the small efforts and result in an enormous backfire effect.

2. Visible rebound effects at the collective level: developing new uses focused on socio-technical efficiency gains with a wide range of impacts on multiple sectors, many of them having a large carbon footprint (transport, construction, goods production…)

As we saw spectacularly during the recent Covid crisis between 2020 and 2021, many sectors of activity are now inextricably tied to ICT and deeply reliant on the Internet to function. This relationship between business activities and ICT have been exacerbated during the Covid crisis, and even if it is too soon to know what the long-term behavioural changes and rebound effects related to the role of ICT during the crisis will be, it is clear that ICT played a preeminent role in maintaining business activities, schooling and relationships.

> *"As soon as we force ourselves to quantify absolutely, we miss out on many non-quantifiable mechanisms.*
>
> **Jacques Combaz, CNRS research engineer**

Beside positive socio-economic impacts which are not the subject of this study, positive environmental impacts can be shown in that ICT enabled people to learn and work entirely remotely. This is the case of e-learning[33] or teleworking[34]. However, in both cases, the distances travelled by car that are not cut[35] by e-learning or teleworking (class group meetings, picking up the kids from school by car, shopping by car, …) can have rebound effects, as new daily trip patterns can consume more. Other rebound effects of e-learning and teleworking concerns the duplication of the workplace in the home, cancelling out the benefits of a shared workspace: more equipment, more home-heating, more paper consumption. Regarding teleworking, studies assessing its environmental impacts tend to show that although teleworking appears to lower CO_2, NOx, SO_2 and CO emissions (due to less car transport), this is largely based on assumptions and "*rebound effects can significantly affect not only the transportation but also the*

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31 Gossart, *Rebound Effects and ICT: A Review of the Literature*, 2014, p.5

32 GeSI, *Smart 2020: Enabling the low carbon economy in the information age*, 2008; Lorenz M. Hilty, *Information Technology and Sustainability. Essays on the Relationship between ICT and Sustainable Development*, 2008, p. 41; Tilman Santarius, Johanna Pohl and Steffen Lange, *Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing?*, 2020 p. 6

33 Herring, H., Roy, R.: *Sustainable services, electronic education and the rebound effect. Environmental Impact Assessment Review* 22(5), 525-542, 2002

34 Kitou E., Horvath A., *Energy-related emissions from Telework*, 2003; ADEME, *Étude sur la caractérisation des effets rebond induits par le télétravail*, 2020

35 In some rare cases, telework and e-learning can even allow very impactful way of life such as remote working around the globe (plane-travels).

company and home office-related effects. The success of a telework program appears to depend mainly on commuting patterns, induced energy usage, and characteristics of office and home space use."[36]

Indeed, if a worker usually commuting by public transport or soft mobility modes works from home rather from the office, and consequently heats their home more and buys more ICT equipment, the overall environmental impact of teleworking for that worker is very likely to result in severe rebound effects, causing the environmental benefits of teleworking to backfire. On the contrary, if workers who usually commutes by car works from home rather than from the office and by consequence substantially diminishes the distances they travel by car, does not heat their home more and uses the same ICT equipment as at the office, the benefits of teleworking are likely to be much greater.

"The difficulty lies in the regulatory framework, in the social project that we want to have, the point of arrival, "where do we want to go?". I have the impression that today all of this is overshadowed by technical debates.

Jacques Combaz

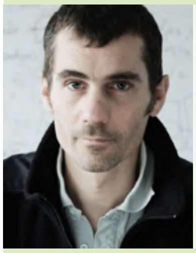
E-commerce and home delivery

E-commerce is causing significant and rapid growth in the global economy: the share of e-commerce in global retail trade is estimated to have risen from 10.4 per cent in 2017 to 17 per cent in 2020.[37] In the case of e-commerce, ICT has clearly created a profound shift in the shopping habits of many. In the EU, 72 per cent of internet users bought or ordered goods or services online in 2020, mainly clothes, shoes and accessories (64 per cent of e-buyers).[38] Some studies tend to show that an e-commerce purchase is more environmentally friendly than an in-store purchase because of the lower infrastructure energy and material consumption (e.g. less building due to increased rates of logistics and less energy per square meter in a warehouse than in physical retail stores). [39]However, some rebound effects are noted due to increases in consumption patterns. Moreover, in the case of home delivery, the last kilometre generates potentially more environmental impacts than in-store retailing when online buying with home delivery replaces walking, public transport or "soft mobility" solutions. This effect is amplified by instant delivery, which results in greater traffic congestion.[40] Similarly, the boom in deliveries of food and small goods due to online delivery and the use of food delivery platforms dramatically increases plastic waste and carbon footprint, which is a major rebound effect of ICT, but peculiar to the food and delivery business. A review published in 2020 states that consequently, "*the most serious environmental impact in this new industry is solid waste pollution, followed by water pollution, resource consumption and air pollution.*"[41] Consequently, this new industry enabled by digital platforms has a very tangible effect, which is highly dependent on social acceptability and future policy regulations.

36 Kitou E., Horvath A., *Energy-related emissions from Telework*, 2003
37 United Nations, *COVID-19 and e-commerce, A global review*, 2021
38 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=E-commerce_statistics_for_individuals#Most_popular_online_purchases (last retrieved: 20/05/2021)
39 Khurana A., Pal R., *Impact of e-commerce on environment*, 2013
40 https://www.cnbc.com/2020/01/14/last-mile-delivery-push-will-worsen-commutes-hurt-the-environment-world-economic-forum-says.html (last retrieved: 20/05/2021)
41 Charlene Li, Miranda Mirosa and Phil Bremer, *Review of Online Food Delivery Platforms and their Impacts on Sustainability*, 2020

The expert's view

Fabrice FLIPO is a philosopher of politics, science and technology, a teacher at the Mines-Télécom BS Institute and a researcher at the Laboratory for Social and Political Change at the University of Paris who has been working on ecological transition for twenty years. In 2020, he published a book on the "digital sobriety imperative"[i] *as well as a memorandum on the "dark side of digital".*[ii]



Jacques COMBAZ, a CNRS research engineer, works in a research laboratory called Verimag. He joined the EcoInfo service group of the CNRS in 2018 and in this capacity has participated in the work on rebound effects since that date.

What is a rebound effect?

Jacques COMBAZ: I see it this way: we address a problem with several dimensions, and we try to play on one of the dimensions. Obviously, since the system is complicated, when we touch one dimension we indirectly touch the other dimensions. If the desired effect was to touch just one of the variables without touching the others, the rebound problem becomes evident.

Fabrice FLIPO: When we look sociologically at the structure of choices (how people consume), we observe that there are consumption norms. These sociological regularities, which are necessary for the regularity of the technical system, are perfectly predictable. For me, what we call the rebound effect are engineering or micro-economic-type analyses that inadequately take these social structures into account and are then surprised that their diagnosis and measures do not achieve the goals they hoped to achieve.

What are the main lessons that you draw from your different works on the environmental impacts of digital technology and rebound effects?

Fabrice FLIPO: We have shown[iii] that many studies, such as those by GeSI, put forward technical solutions or use cases from which they conclude wonderful promises of reducing ecological impact – and thus the potentially widespread use of teleworking or autonomous cars.[iv] But they do not take into account the established use structures (habits, goals usually pursued by the actors, etc.). At the same time, studies taking this into consideration have shown that without a change in norms, the expected promises were likely to materialise only partially, solely for heating and lighting. Not entirely unaware of this weakness, the GeSI made its promises conditional on the establishment of a binding framework on greenhouse gas emissions, such as taxes or permits, "to avoid the rebound effect". The problem lies not only in the fact that this condition is socio-politically unrealistic, but also that the solutions proposed by the GeSI overlap at least in part with those that its member industries are pushing for reasons which have the opposite effect to that desired. Thus, the real goal of teleworking is to reduce labour costs or increase flexibility, and that of the autonomous car is to make passengers spend as much time as possible watching "infotainment". Ecological ambitions are constrained by inappropriate "solutions", grossly flawed policy, and therefore fail to achieve their goals, whereas the economic or industrial goals are attained. And then those who promote them fob off their responsibility onto society, as if society had consciously turned its back on ecology. •••

i Fabrice Flipo, *L'impératif de la sobriété numérique*, L'enjeu des modes de vies, 2020
ii *http://www.fondationecolo.org/blog/Note-de-la-FEP-23-La-face-cachee-du-numerique* (last retrieved: 12/05/2021)
iii Fabrice Flipo, François Deltour, Michelle Dobré, Marion Michot, *Peut-on croire aux TIC vertes ?*, 2012
iv Maxwell, D., Owen, P., McAndrew. L, Muehmel, K., Neubauer, A., *Addressing the Rebound Effect, a report for the European Commission DG Environment*, 26 April 2011

••• Any analysis that ignores this game of pretence and sticks to micro-sociological approaches is bound to fail to anticipate in any informed manner. Any analysis that ignores this game of pretence and sticks to micro-sociological approaches will inevitably fail to anticipate future developments. It misses the crucial point that the solutions it is taking seriously constitute greenwashing in the strictest sense of the term – ecological action that remains incidental in a game of pretence that, fundamentally, remains unchanged.

Jacques COMBAZ: In most cases the rebound effect is not a surprise, it is voluntary. If I take the example of Moore's Law, for processors the goal is to put twice as many transistors in new processors in each generation, not to make processors smaller. Moreover, the consumer does not really have a choice.

As soon as we force ourselves to quantify absolutely, we miss many non-quantifiable mechanisms. These are deep social mechanisms, so ultimately we omit a very large part of the story. Quantification can be potentially interesting for very short-term consumer responses, because we will be basing our calculations on phenomena that we know. For profound transformations at the level of society, this does not work at all. In the context of the ecological transition I think that we should, in particular, not study the rebound effect solely from a quantitative perspective, because it is misleading.

The difficulty with ecological transition today is not so much one of technological efficiency, since that is something that we know how to do and that we do anyway. The difficulty lies in the regulatory framework, in the social project that we want to have, the point of arrival, "where do we want to go?". I have the impression that today all of this is overshadowed by technical debates.

Conclusion

We have seen above that rebound effects can take various forms and have very tangible environmental impacts. To identify rebound effects, it is necessary to include them in environmental assessments from a behavioural perspective, including an evaluation of habits, social constraints and the goals pursued by various actors in the system, as far as possible each time an improvement in energy efficiency, time, space or technology is proposed.

It is also crucial to put into perspective the environmental impacts of ICT as a whole and define environmental objectives to respect the Paris Agreements and limit the environmental footprint of ICT to planetary boundaries (**see our LCA study results**).[42] When framing such objectives, it is necessary to include effectiveness measurement to assess whether the policy measures are meeting their goals and plan a readjustment in the light of observed future developments. Just as rebound effects include changes and adaptions in user behaviour to efficiency gains, future framework policies should consider stimulating "debound" effects, that is, the reverse. ■

42 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E. GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*

Recommendations for a digital evolution compatible with the Green Deal

Rebound effects (direct, indirect, and systemic) are countered by ensuring that each time an efficiency measure is enabled, it goes hand in hand with proportionate frugality measures.

To do so, the public funding of innovation is submitted to a mandatory peer-reviewed life cycle assessment of the environmental impacts of the innovation, whether it is a product or a service, regarding the complete use scenarios of the innovation. European Green Deal Innovation funding is open to products and services based on innovations of models and eco-designed services from manufacturing to end-of-life, including user journey. This funding stimulates the circular economy and the economic resilience of the Member States and the European Union as a whole; it stimulates employment, as was anticipated by the International Labour Organisation*.

The eco-design of products and services also contributes to greater social inclusion and to bridging the digital divide, with an often smoother user journey – as, for example, when costly web or app services are replaced by a simple SMS or an email, which consume far less than a web service. As the user journey is focused on the most important user needs, it is less subject to both rebound effects and infobesity.

At the same time, consumers have become more aware that buying energy-efficient equipment in itself is not enough, but that an overall reduction of both resources and energy dependency needs to be attained, with a target within planetary boundaries. For example, buying less ICT equipment including smaller screens, keeping devices longer and repairing them.

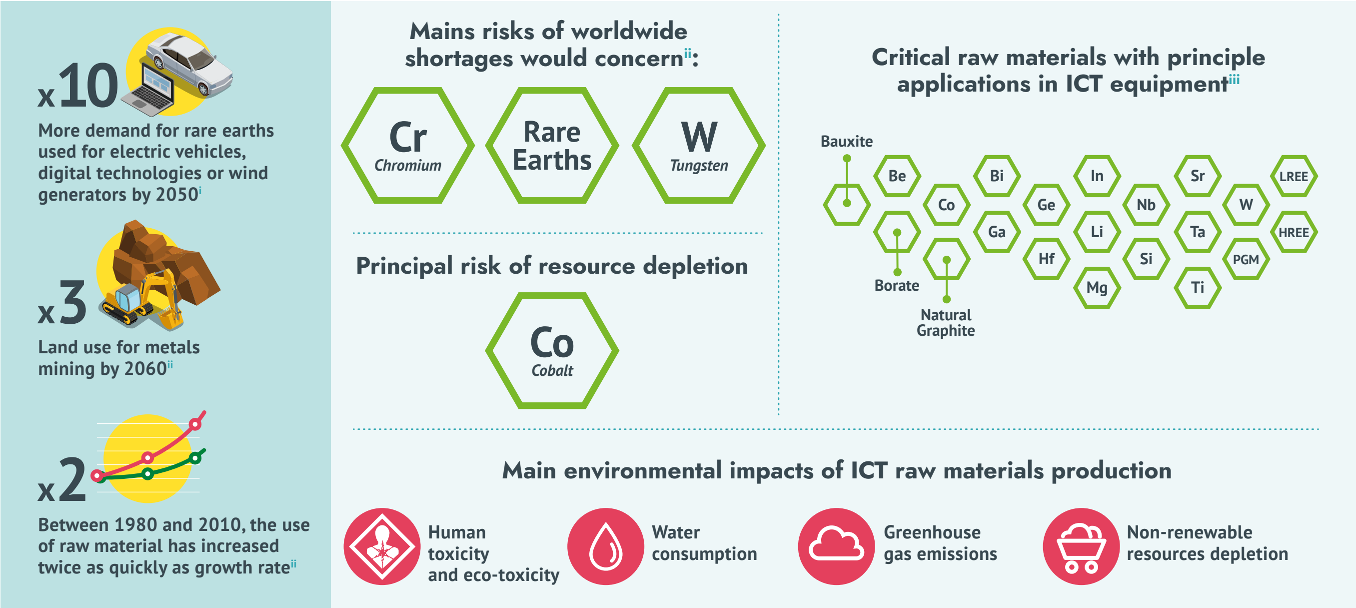
Hyper-connection, the limits of which are recognised both at work and in people's personal life, especially regarding health risks, has helped to ensure the right to disconnect, at the initiative of Member States. Taking rebound effects in ICT into account has also enabled ethical questions to be asked about the way we use and depend on technology, and socio-technical lock-ins. Finally, finding solutions for limiting the rebound effects related to ICT has at the same time helped us improve our resilience to climate, economic and social crisis, and encouraged us to take a step back from a rapidly changing world.

* International Labour Organisation – Geneva: ILO, *World Employment and Social Outlook 2018: Greening with jobs*, 2018

Raw Materials in ICT

Table of content

Key data for magnitude



[i] For permanent magnets: Dysprosium, Neodymium, Praseodymium, Samarium; The remaining rare earths are: Yttrium, Lanthanum, Cerium, Promethium, Europium, Gadolinium, Terbium, Holmium, Erbium, Thulium, Ytterbium, Lutetium ; European Commission, *Communication from the commission to the European Parliament, the council, the European economic and the committee of the regions, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, 2020.

[ii] OECD, *Global Material Resources Outlook to 2060: Economic Drivers And Environmental Consequences*, 2019.

[iii] European Commission, *Study on the EU's list of Critical Raw Materials, Final Report*, 2020.

Summary of the case study

Paradoxical as it may appear at first glance, the very same green techs which are at the basis of the energy and digital transition are themselves causing major environmental impacts, mainly during the manufacturing phase. Although the ICT sector accounts for only a small share of the increasing demand for rare metals and rare earths, ICT is highly dependent on these non-renewable raw materials. A communication from the European Commission in September 2020 underlines that "*demand for rare earths used in permanent magnets, e.g., for electric vehicles, digital technologies or wind generators, could increase tenfold by 2050*".[1] The issue of metals and rare earth dependency is therefore twofold for the EU, affecting both its environmental responsibility and its geopolitical strategy. This case study sets out to explain which are the metals and rare earths on which ICT depends and the environmental impacts of the raw materials used in ICT equipment, and draw up some recommendations to help the EU become more resilient in coping with possible future shortage crises, reduce its dependency and ensure a sustainable digital transformation.

1 European Commission, *Communication from the commission to the European Parliament, the council, the European economic and the committee of the regions, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*, 2020

Definitions

Main concepts

Raw materials used in ICT: The most sophisticated supply chain system in human history is that which serves to manufacture hardware components[2]. The raw materials used in ICT are all non-renewable materials. Some of them, such as aluminium, carbon and iron, are present in very high quantities on earth, but to manufacture the core components of ICT devices, rare metals and rare earth elements are also essential.

Scarce metals: Unlike metals such as iron, copper, zinc, aluminium, and lead, scarce metals are less abundant in the earth's crust. For example, on average there is 2,650 times less gallium than iron in the soil[3]. From the most to the least abundant, the scarce metals are: gallium, beryllium, germanium, mercury, silver, indium, palladium, bismuth, platinum, gold, osmium, rhodium, iridium, ruthenium, tellurium, rhenium.

Rare earth elements: They are identified as rare because it is unusual to find them in large concentrations in the earth's crust. Rare earths carry very similar properties. "*In rare cases they are found in deposits together. Unlike an element such as gold, natural rare earth deposits never occur as pure metals, but are bonded in low-value minerals, making extraction challenging.*" [4] They are a set of 17 nearly indistinguishable, lustrous, silvery-white, soft heavy metals: cerium, neodymium, lanthanum, yttrium, scandium, praseodymium, samarium, gadolinium, dysprosium, erbium, ytterbium, europium, holmium, terbium, lutetium, thulium, promethium.

Characteristics of those scarce metals that differentiate them from other metals:

- Approximately 240,000 tonnes of rare earths were produced in 2020 while 2,228,000,000 tonnes of iron were produced in the same year (approx. 9,300 times less than rare earths).
- Rare metals can often be found in the same places as abundant metals in the earth's crust, but in very tiny portions (for example, there is 1,200 times less neodymium and as much as 2,650 times less gallium than iron)[5].
- They have exceptional properties, ideally suited to the performance of modern IT equipment and energy transition equipment, the first of which is their magnetic capacity.

Non-ferrous metals: Most metals contained in a laptop computer are non-ferrous metals, such as aluminium, copper, tin, nickel, gold, silver, lithium, palladium, or platinum.

Copper: Used in printed circuits but also in many electronic components for its excellent electrical conductivity and very good thermal conductivity.

Cobalt: A major component of lithium-ion or lithium-ion-polymer batteries. Lithium-ion cobalt batteries are currently those with the greatest capacity to store energy per unit mass. A report from the JRC published in 2018 predicts that, "*under average conditions, demand will outgrow supply by 64,000 tonnes in 2030.*" Even if the substitution of cobalt with other metals (such as nickel) is possible, the same report states that "*substitution will not be enough to resolve imbalance in the mid-to-long term*". [6]

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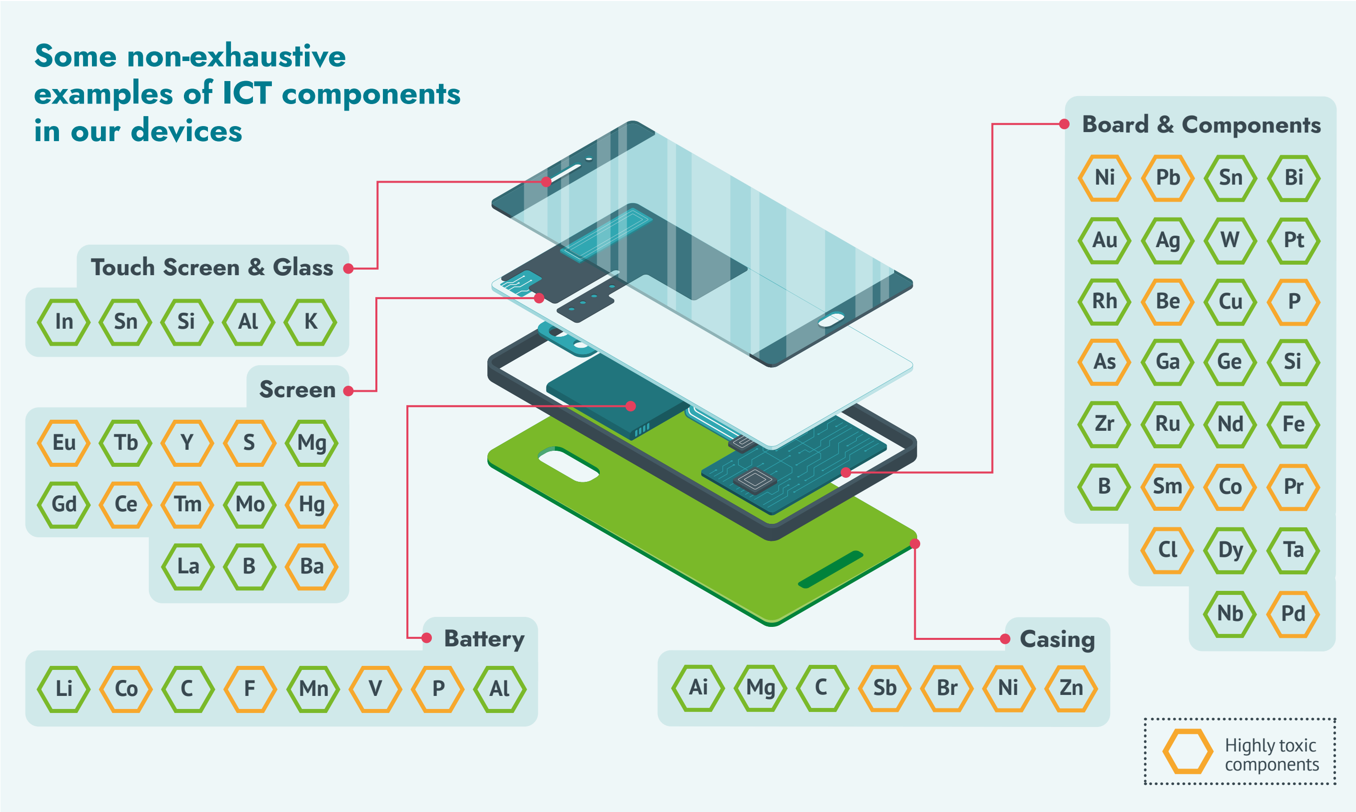
2 https://www.engineering.com/story/what-raw-materials-are-used-to-make-hardware-in-computing-devices (last retrieved: 14/06/2021)
3 Guillaume Pitron (trans. Bianca Jacobsohn), The rare metals war: the dark side of clean energy and digital technologies, 2021, chapter 1
4 https://idealmagnetsolutions.com/knowledge-base/extract-rare-earth-elements-from-acid-mine-drainage/ (last retrieved: 03/06/2021)
5 Guillaume Pitron (trans. Bianca Jacobsohn), The rare metals war: the dark side of clean energy and digital technologies, 2021, chapter 1
6 JRC report, Cobalt, demand-supply balances in the transition to electric mobility, 2018

- **Nickel:** Nickel is used mainly for electrical vehicles batteries but can also be found in many other nickel metal hydride batteries (NiMH), such as payment terminals, aircraft electronics, access controls and a host of digital equipment. Nickel is one of the main alloy elements in stainless steel as well. JRC forecasts "*global demand for nickel to increase by 2.6 Mt to 2040 up from only 92 kt in 2020*" for automotive electrification alone, which means global demand would be multiplied by 28 in 20 years. Within the EU27, the same report forecasts "*nickel demand from the automotive sector to increase by 543 kt from 17 kt in 2020*", which means EU27 demand would be multiplied by 32 in 20 years.[7]

- **Gold:** Used in electrical contacts and as an anti-corrosion and anti-oxidation layer on printed circuits for its stability and good electrical and thermal conductivity.

- **Lithium:** By 2020, the predominant use for lithium was the production of lithium-ion batteries both for electric vehicles (EVs) and portable electronics (smartphones, tablet, laptops, connected objects, etc.), which represented 65 percent of its use in 2019.[8]



Source: Ingénieurs sans frontières, composition of a smartphone: https://www.systext.org/sites/all/animationreveal/mtxsmp/#/7 (last retrieved: 08/06/2021)

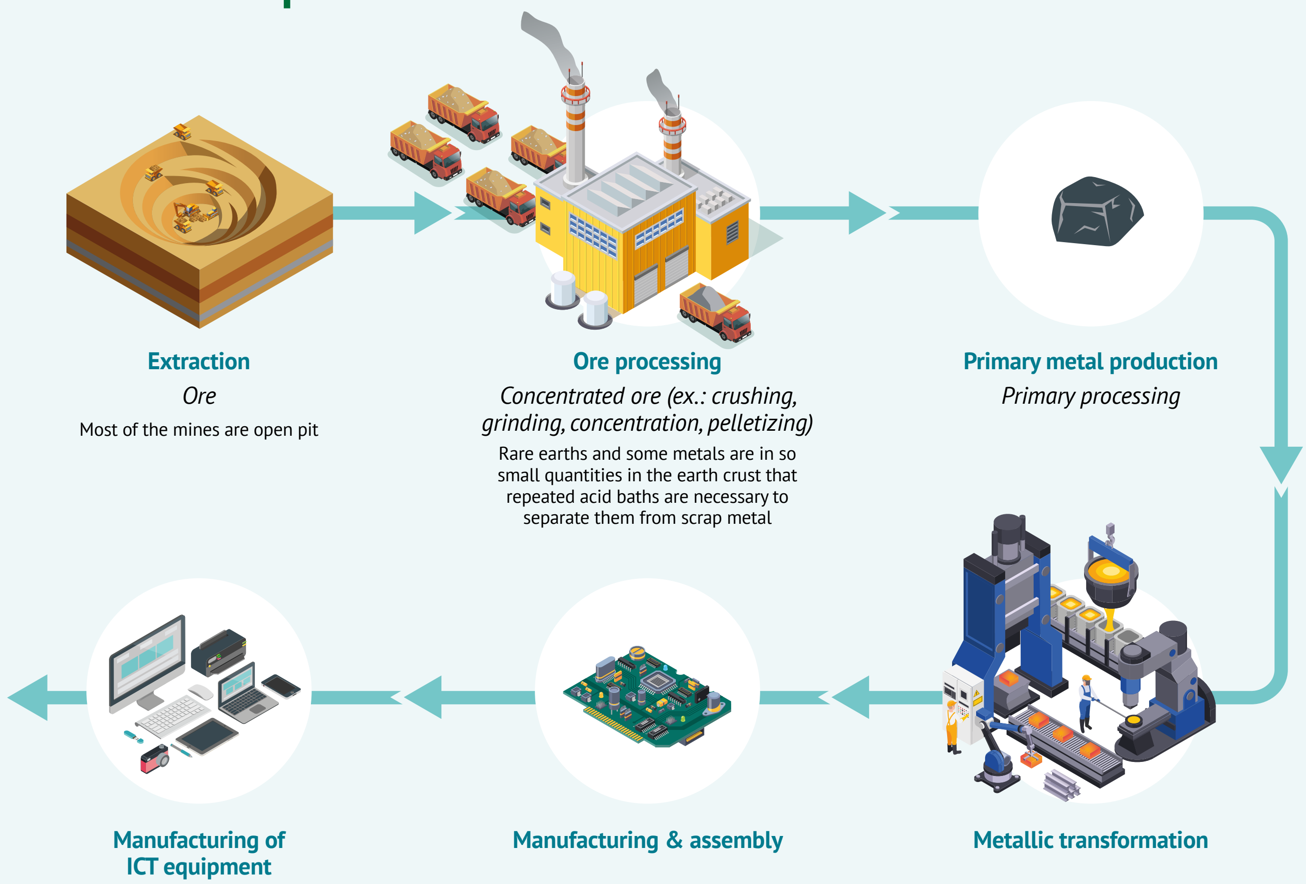
7 Fraser, Jake; Anderson, Jack; Lazuen, Jose; Lu, Ying; Heathman, Oliver; Brewster, Neal; Bedder, Jack; Masson, Oliver, *Study on future demand and supply security of nickel for electric vehicle batteries*, Publications Office of the European Union, Luxembourg, 2021

8 U.S. Geological Survey, *Mineral Commodity Summaries*, January 2020

Environmental impacts related to raw material extraction and refining to produce ICT components

The equipment for storing, transmitting, and processing data is commonly called hardware. Currently, ICT is increasingly based on a multitude of hardware devices more and more complex and miscellaneous. To understand the environmental impacts of raw material extraction and refining for ICT, is it necessary to remember that the raw materials used for ICT are non-renewable and consequently, availability functions like stocks and shares. It is also important to keep in mind the production process of extraction and refining metals, which is far from neutral from an environmental point of view.

1. Production process



2. Minerals, beside the environmental impacts, have social and geopolitical impacts

In many cases, the extraction of minerals is done without proper worker protection. In some cases, such as that of cobalt in the Democratic Republic of Congo, some 200,000 workers excavate without any protection equipment and suffer from pulmonary and skin diseases. [9]

Moreover, children also work in the mines, which is regularly denounced by human rights NGOs. In December 2019, the association International Rights Advocates (IRA) announced the filing of a complaint against several transnational companies such as Alphabet (the parent company of Google), Apple, Dell, Microsoft, and Tesla, accused of complicity in the deaths of fourteen children in the Congolese cobalt mines. [10]

Metals such as tin, tungsten, tantalum, and gold, are often the result of conflicts, corruption, illegal exploitation and child labour. [11] In a report published in 2016, the UN group of experts on Congo declares that gold "provides the most significant financial benefit to armed groups" [12] and states that in 2010, "in the Kivu provinces in Congo, almost every mining deposit [was] controlled by a military group" [13]. This was illustrated in the Danish documentary "Blood in the Mobile", produced in 2010 by Franck Piasecki Poulsen.[14]

3. Environmental impacts

The extraction and refining of metals and rare earths to produce the components used for ICT is contributing to serious environmental damage. In 2016, industrial mining and ore-processing ranked second in the list of the world's worst pollution problems, just after used lead-acid battery recycling and before lead smelting.[15] The extent of the threats of mining to biodiversity are still under-documented: indeed, most of the literature focuses on the direct and on-site impacts of mineral extraction activities[16], while the impacts on the biodiversity and at the regional[17] and even the global scale[18] are more scarcely documented.

> *"Today, the data shows a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realising those ambitions."*
>
> **Dr Fatih Birol**
> IEA Executive Director

a. Human toxicity

The first of these impacts are toxicity and, more specifically, human toxicity. [19] Indeed, people who work in the extraction and refining of ores are directly exposed to the metal dusts that they breathe and ingest daily in very high concentrations. Yet, not only those who

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9 https://www.monde-diplomatique.fr/2020/07/BELKAID/61982
10 http://www.iradvocates.org/press-release/iradvocates-files-forced-child-labor-case-against-tech-giants-apple-alphabet-dell
11 https://www.numerama.com/tech/307318-minerais-et-conflits-au-congo-quelles-sont-les-entreprises-de-la-tech-les-plus-responsables.html
12 UN Security Council, "Final report of the Group of Experts (2016)," S/2016/166, p. 2, May 23, 2016, available at http://www.un.org/ga/search/view_doc.asp?symbol=S/2016/466
13 UN Security Council, "Interim report of the Group of Experts on the DRC," S/2010/252, para. 77, p.17, May 24, 2010, available at http://www.un.org/ga/search/view_doc.asp?symbol=S/2010/252
14 https://www.youtube.com/watch?v=Tv-hE4Yx0LU "Blood in the Mobile" is a 2010 documentary film by Danish film director Frank Piasecki Poulsen. The film addresses the issue of conflict minerals by examining illegal cassiterite mining in the North-Kivu province in eastern DR Congo. In particular, it focuses on the cassiterite mine in Bisie.
15 Green Cross & Pure Earth Blacksmith Institute, *World's Worst Pollution Problems*, 2016
16 Habitat loss and rehabilitation, see figure 1 in: Laura J. Sonter, Saleem H. Aliand James E. M. Watson, *Mining and biodiversity: key issues and research needs in conservation science*, 2018
17 Biodiversity offsets, waste discharge and pollution, habitat fragmentation, see figure 1 in: Laura J. Sonter, Saleem H. Aliand James E. M. Watson, *Mining and biodiversity: key issues and research needs in conservation science*, 2018
18 Climate change, invasive species, see figure 1 in: Laura J. Sonter, Saleem H. Aliand James E. M. Watson, *Mining and biodiversity: key issues and research needs in conservation science*, 2018
19 **See our LCA results: human toxicity impacts of ICT.**

work directly with minerals in the mining industry are affected: the entire population for miles around a mine are exposed to an increased risk of cancer mortality. This was shown by a study published in 2012 and carried out in Europe, where the mining industries are regulated by the Integrated Pollution Prevention and Control Directive and the European Pollutant Release and Transfer Register Regulation.[20] In the case of rare earths, these elements have the particularity of being found in the earth's crust associated with radioactive ores (thorium and uranium), which makes them even more hazardous to treat. Exposure to radioactive waste can lead to dental loss, respiratory issues, cancer and even death. In many mining areas, the number of cancers and the mortality rate have exploded.[21 22]

b. Air, soil, and river pollution

Most of the mines use surface excavation[23], which has the consequence of leaving the metal particles in the open air, blown by the wind and washed away by the rain, depending on regional hydrology.[24] The metals can therefore be dispersed both locally and over long distances, exacerbating the pollution in cities and the risk of mortality of the populations, and also having significant impacts on the pollution of waterways and crops near the mines,[25 26] with increased hazards when refining.

The issue of metal ore is more complex than that of stone, sand, or gravel mining, because to be used, these metals require processing with chemical reagents. Consequently, metal mining may produce much more severe pollution than the extraction of construction materials, releasing mercury, arsenic, or cyanide.[27]

The term "ecological rucksack" is sometimes used in the literature to describe the volume of waste that is extracted from the earth to segregate the small amounts of valuable material present in it. The amount of waste depends on the mineral extracted, but for metals, waste greatly exceeds net production. For example, for 1 tonne of copper 450 tonnes of waste are generated, for nickel 597 tonnes, and for gold 1,069,000 tonnes.[28] In many cases, there is no market for this waste. While the volume of waste is one of the issues encountered by public authorities, producers and residents, another issue is that waste streams are often chemically reactive: chemical pollution occurs because reagents are released into the environment during processing or by oxidation as a result of exposure to air. The leaching process, which consists in converting valuable metals into soluble salts while the impurities remain insoluble, is often used for rare earths [29] or metals such as gold because it requires less energy and causes no gaseous pollution; however, it has significant drawbacks such as the production of large quantities of toxic waste effluent, either highly acidic or alkali.[30]

20 Pablo Fernandez-Navarro, et al., *Proximity to mining industry and cancer mortality*, 2012
21 https://www.malaysianow.com/opinion/2020/12/08/the-toxic-risks-of-mining-rare-earths/ (last retrieved: 03/06/2021)
22 Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021, chapter 1
23 https://pubs.usgs.gov/circ/2007/1294/paper1.html#table2 (last retrieved: 04/06/2021)
24 Laura J. Sonter, Saleem H. Aliand James E. M. Watson, *Mining and biodiversity: key issues and research needs in conservation science*, 2018
25 Albert K. Mensah, Ishmail O. Mahiri, Obed Owusu, Okoree D. Mireku, Ishmael Wireko, Evans A. Kissi, *Environmental Impacts of Mining: A Study of Mining Communities in Ghana*, 2015
26 Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021, chapter 1
27 Bridge G., *Contested terrain: mining and the environment*, 2004
28 *Ibid.*
29 Peelman, S., Kooijman, D., Sietsma, J. et al., *Hydrometallurgical Recovery of Rare Earth Elements from Mine Tailings and WEEE*. J. Sustain. Metall.4, 367–377 (2018)
30 X. Jin Yang, Aijun Lin, Xiao-Liang Li, Yiding Wu, Wenbin Zhou, Zhanheng Chen, *China's ion-adsorption rare earth resources, mining consequences and preservation*, 2013

The expert's view

*Guillaume Pitron is a journalist (***Le Monde Diplomatique, National Geographic***, etc.), and documentary maker. In 2018, he published his first book,* **The Rare Metals War: The Dark Side of the Energy Transition and Digitalisation**[i], *and in September 2021 another on digital pollution. He focuses his work on commodities and on the economic, political, and environmental issues related to their use. He has authored around 100 reports, investigations, and documentaries across more than 40 countries and has been awarded 14 French and international journalism awards. He received the Izraelezewicz Prize for best investigative report of the year, awarded by the leading daily newspaper* **Le Monde**, *and the 2018 BMTV award for Economic Book of the Year for* **The Rare Metals War.**

"Metals are used in a very wide variety of industries: aeronautics, real estate, automotive, and of course digital. Today, more new materials which are mixtures of metals are used. Because they are used in the form of alloys, these new materials increase the properties of materials and allow new types of use.

Digital technology is no exception to this consumption of metals. To quote some precise recent figures: 12.5 percent of world copper production is used specifically for ICT, 7 percent of that of aluminium, 15 percent of palladium, 23 percent of silver, 63 percent of dysprosium, 70 percent of gallium and 87 percent of germanium, all specifically used for the different uses in the ICT – screens, magnets, lighting, capacitors, etc.

For one specific metal, cobalt, which is used in ICT and for batteries for electric vehicles, production could in the future be insufficient in relation to demand due to a lack of sufficient geological resources.

For other metals, there is no clearly identified geological scarcity problem. For metals considered critical, it is rather a risk of shortage of supply because world production is concentrated in certain countries. Since production is concentrated in the hands of a few state actors, the failure of one of these nations could result in a shortage of supply. It is an industrial and geopolitical risk. This is the case for rare earths, lithium, antimony, tantalum, etc.[ii]

One of the issues with ICT is its rebound effects[iii]: a technology is not made to make people consume less; it is made to make people consume more. The energy gain and material gain for one unit of a technology can be quite clear, but because this technology allows energy savings and material savings, we tend to consume more of it. Applied to the metals sector, this means that we will consume more metals in the future instead of less.

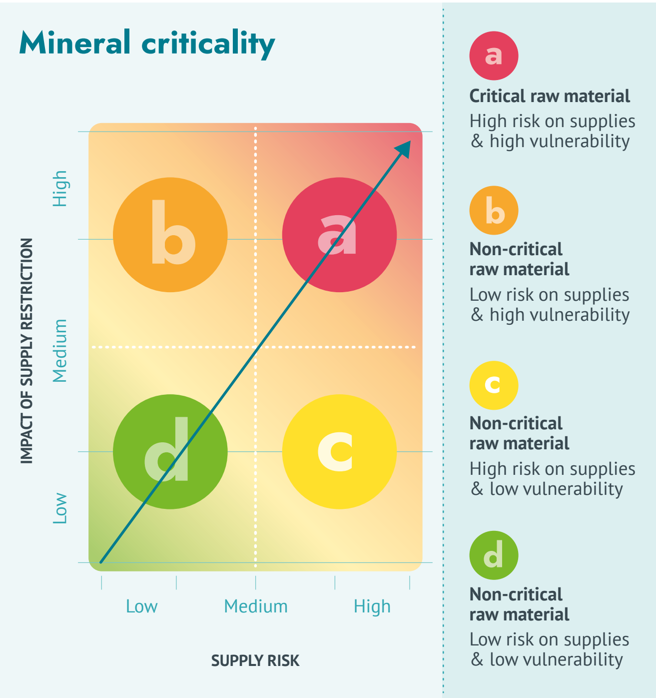
Despite technological progress, it is to be feared that our new uses and our growing consumption cannot be offset. This applies to the metals used in ICT, which are the same as those of green technologies, demand for which is set to explode and be multiplied 10 to 40-fold over the next 20 to 30 years.

Political decision-makers are starting to address these subjects, as shown by the index of repairability of electronic tools and household appliances now mandatory in France. One of the best ways to act is through the circular economy.

We have all the means to act. We are responsible for the pollution linked to digital technology. Just giving in to our dependence on GAFAM is too easy; we must all assume our responsibilities.

[i] Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021.
[ii] See the list of the 30 critical metals established by the European Commission: *European Commission, Study on the EU's list of Critical Raw Materials, Final Report*, 2020
[iii] **See our case study on rebound effects due to ICT.**
[iv] *https://www.vie-publique.fr/loi/268681-loi-lutte-contre-le-gaspillage-et-economie-circulaire* (last retrieved: 05/07/2021).

In Ghana, formerly known as the Gold Coast, mining of gold, bauxite and manganese, which are used for ICT components, "*results in adverse environmental impacts on rivers and streams through a release of effluents such as mercury, arsenic and solid suspensions.*"[31] It has been found that mercury discharges into water bodies also lead to de-oxygenation and the death of aquatic organisms and their habitat, thus ultimately decreasing their population (mercury is used to refine gold amalgam).[32] Mining also impacts ecosystems and leads to a loss of vegetation, often resulting in mass deforestation, loss of land fertility and productivity, and massive erosion. In China, which is the world's largest producer of 28 mineral resources, around 80 percent of the water from underground wells is unfit for consumption and 10 percent of Chinese arable land is contaminated with heavy metals,[33] which is equivalent to the surface area of a country the size of Greece.[34] [35]



c. Hydric stress[36]

One of the most significant effects of the production of metals for ICT is hydric stress. This is because mining uses large quantities of water, primarily for mineral processing, dust suppression, slurry transport and employees' needs. For example, around 84,210 litres of water are used to obtain 1 tonne of copper.[37] In most mining operations, water is sought from groundwater, streams, rivers, and lakes, or through commercial water service suppliers. However, mine sites are often located in areas where water is already scarce, which exacerbates hydric stress in these areas.[38] But water procurement is not the only issue: mainly in the case of underground mining, water needs to be pumped out of the mine site. This can lead to a depletion of surface water as well as polluting local rivers. Due to a lack of published data on water by companies, it is still difficult to find reliable information to get a full idea of the water consumption of mining commodities. However, the water data from company sustainability reports shows that withdrawals vary widely depending on the metal mined and ore quality.[39]

Acid mine drainage impacts surrounding water resources, as the sulphide minerals in the waste rock react with the water and oxygen in the surface environment leading to the creation of sulphuric acid, which in turns dissolves salts and heavy metals, which are toxic to aquatic ecosystems. As future production will come from increasingly lower grade ores, the water consumption per unit of metal produced will be a challenge, as will GHG emissions, solid wastes and other pollutants.

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31 Albert K. Mensah, Ishmail O. Mahiri, Obed Owusu, Okoree D. Mireku, Ishmael Wireko, Evans A. Kissi, *Environmental Impacts of Mining: A Study of Mining Communities in Ghana*, 2015
32 *Ibid.*
33 Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021, chapter 1
34 Estimation based on Chinese's arable land (in hectares) / 10. Chinese's arable land data: *https://data.worldbank.org/indicator/AG.LND.ARBL.HA?end=2018&locations=CN&start=1961&view=chart* (last retrieved: 03/06/2021)
35 *https://www.bbc.com/future/article/20150402-the-worst-place-on-earth* (last retrieved: 04/06/2021)
36 Stephanie Yang, *The Chip Shortage Is Bad. Taiwan's Drought Threatens to Make It Worse*, The Wall Street Journal,16 April 2021, (last retrieved: 03/06/2021)
37 *https://www.csiro.au/en/work-with-us/industries/mining-resources/Processing/Water-footprint* (last retrieved: 15/06/2021)
38 *https://www.mining-technology.com/features/feature-managing-water-consumption-mining-global-shortage/* (last retrieved: 15/06/2021)
39 Michael Tost, Benjamin Bayer, Michael Hitch, Stephan Lutter, Peter Moser, and Susanne Feiel, *Metal Mining's Environmental Pressures: A Review and Updated Estimates on CO_2 Emissions, Water Use, and Land Requirements*, 2018

d. Greenhouse gas emissions

Mining, processing, and transportation are also major emitters of greenhouse gases: from the excavation of minerals to transport and processing, large amounts of embodied energy[40] (fuel and electricity) are needed to produce metals pure enough for high-technology uses. When the carbonate minerals are broken down, carbon dioxide is also released. Overall, **estimates show that the greenhouse gas emissions related to primary mineral and metal production were equivalent to approximately 10 percent of total global energy-related greenhouse gas emissions in 2018**.[41] Moreover, the scarcer resources become, the more energy they require to be excavated. One example of this is copper mining in Chile: from 2001 to 2017, fuel consumption increased by 130 percent and electricity consumption by 32 percent per unit of mined copper, largely due to decreasing ore grade.[42] As the demand for metals is expected to skyrocket in the years ahead, this trend of growing energy demand to produce the same quantity of certain metals is being confirmed, just as greenhouse gas emissions from mining, processing and transportation are expected to dramatically increase instead of decreasing.[43]

e. Depletion of resources[44]

Resource depletion is the consumption of natural resources faster than they can be replaced. Natural resource depletion can be divided into the depletion of renewable resources and the depletion of non-renewable resources. **Resources used to manufacture ICT equipment are by nature limited, as they are non-renewable**. A frequently asked question about the metals used for technologies such as ICT is: "*Will we have enough metals to keep producing equipment?*". However, the answer is more subtle than "yes" or "no", and depends on numerous factors such as geological availability, the availability of metals pure enough for high-tech purposes, fluctuations of market demand for metals, the just-in-time supply rationale, geopolitical strategies and environmental considerations.

> *"For one specific metal which is cobalt, used in ICT and for batteries for electric vehicles, production will be insufficient in the future in relation to demand due to lack of sufficient geological resources. For other metals, there is no clearly identified geological scarcity problem. It is an industrial and geopolitical risk."*
>
> **Guillaume Pitron**

From a geological perspective, the metals used for ICT are numerous and unequally distributed across the earth's crust, with China being the world's number one producer, supplying 66 percent of the critical raw materials on the European Commission 2020 list.[45] A recent OECD report expects global uses of metallic ores to grow from 9 Gt in 2017 to 20 Gt in 2060 in the absence of new policies, in a business-as-usual scenario.[46]

As we rely more and more on them for our technologies in our economies, extracting them to satisfy demand represents an increasing challenge. A very complete study debating the sustainability of mining in Australia underlines the strong evidence that for most mineral commodities, average ore grades have declined over time. The study concludes that for commodities present in Australia, extraction of some could be maintained for "some decades", while for gold, zinc and lead, "present

40 Embodied energy is the sum of all the energy required to produce any goods or services, considered as if that energy was incorporated or 'embodied' in the product itself" Wikipedia: https://en.wikipedia.org/wiki/Embodied_energy (last retrieved: 08/06/2021)
41 Azadi, M., Northey, S.A., Ali, S.H. et al., *Transparency on greenhouse gas emissions from mining to enable climate change mitigation*. Nat. Geosci. 13, 100–104 (2020)
42 *Ibid.*
43 OECD, *Global Material Resources Outlook to 2060: Economic Drivers And Environmental Consequences*, 2019
44 https://www.greenit.fr/2021/03/30/nickel-des-tensions-des-2027/ (last retrieved:07/06/2021)
45 European Commission, *Study on the EU's list of Critical Raw Materials, Final Report*, 2020
46 OECD, *Global Material Resources Outlook to 2060: Economic Drivers And Environmental Consequences*, 2019

The environmental implications of the growing scarcity of rare metals and earths: a trap to be avoided at all costs

"Can we substitute a non-critical metal for a critical metal?"

Currently, much research is under way to find substitutes for the most critical metals in ICT equipment. However, in many cases, the substitutes are alloys composed of other critical metals. This is the case of antimony, for example, which over the past decade has consistently been considered a critical raw material by both the EU and the US. Current antimony world reserves are estimated to cover about 12 years of the global annual consumption of 2019. Today, antimony is still used in ICT for TV screens and in semi-conductors, and has many other applications outside ICT from flame retardant (major use) to pharmaceutical medicines. Many substitutes for antimony have been developed, however, most of them being regarded as less effective than antimony[i] and most based on other rare metals that can also be critical, such as titanium (critical), chromium and tin (both near-critical).[ii] The substitutes therefore open the door to other issues, such as how to ensure that increasingly complex alloys will not obstruct future recycling of the metals used? Substitution may provide a partial solution, but will not prevent the threat of shortages, is impossible for most of the metals, will not solve pollution issues related to the production of components, and may cause further difficulties for component valuation in e-waste. Indeed, most of the critical metals are still extremely difficult to recycle (see figure below), and as more and more complex alloys are used, the more limited the possibility of recycling will be.[iii]

"What about new mines opening in the EU?"

From an environmental perspective, the opening of new mines is associated with all the environmental impacts described above. Even with strict regulations and mitigation measures, mining projects have both important environmental impacts on local and regional biodiversity and global impacts on GHG emissions, as well as toxic impacts on human health. New mines, even if they are regulated more strictly to limit their environmental impacts, will never be sustainable, because mineral resources are "finite"; also they will not be a long-term solution to the EU dependency on ICT nor, ultimately, to imports from China. From an economic perspective, for example in the case of rare earths[iv], the dominance of China enables the country to nurture regional producers in Africa and Asia at moderate profitability so outside producers are prevented from climbing the metal production value chain[v]. In the absence of any metal production outside China, rare earth producers can be no more than low-value suppliers to the Chinese manufacturing industry, fuelling China's monopoly, say market analysts.[vi]

Recycling's contribution to meeting demand for materials (Recycling Input Rate)*

Recycling Input Rate	Materials
0%	Niobium, Indium, Lithium, Tantalum, Bauxite, Berylium, Bismuth, Coking Coal, Dysprosium, Gallium, Hafnium, Phosphorus, Scandium, Silicon metal, Strontium
1-5%	Neodymium, Fluorspar, Baryte, Cerium, Erbium, Gadolinium, Holmium, Thulmium, Lutecium, Ytterbium, Rubber, Samarium, Borate, Germanium, Vanadium, Natural graphite
6-10%	Terbium, Praseodymium
11-20%	Ruthenium, Magnesium, Iridium, Phosphate rock, Titanium
21-30%	Cobalt, Platinium, Antimony, Palladium, Rhodium
31-45%	Yttirum, Europium, Tungsten

*The Recycling Input Rate (RIR) is the percentage of overall demand that can be satisfied through secondary raw materials. Figure from: European Commission, *Study on the EU's list of Critical Raw Materials, Final Report*, 2020.

[i] CRM_InnoNet, *Critical Raw Materials Substitution Profiles*, 2015
[ii] U.S. Geological Survey, *Mineral Commodity Summaries*, January 2018; European Commission, *Study on the EU's list of Critical Raw Materials, Final Report*, 2020
[iii] Xiuyan Li, K. Lu, *Improving sustainability with simpler alloys*, 2019
[iv] In the case of rare earths, which are used in ICT devices for example for very powerful and miniature magnets, and to set the different colour scales in the screen, most of the mining extraction and refining is currently done by China.
[v] Stuart Burns, *Rare earths are the next geopolitical chess game*, MetalMiner, February 2021
[vi] Resource World, *Rare Earths sector a challenge: can anyone stand up to the Chinese?*, 2020

economic resources will last for approximately three decades or less" at the time of the study.[47]

The US Geological Survey (USGS) department publishes a yearly survey[48] that monitors as closely as possible the quantity produced each year, mineral by mineral, as well as the estimated reserves for each mineral, and estimated global resources. The quantity of a mineral produced corresponds to the quantity extracted and processed (mining), the estimated reserves correspond to the mineral resources accessible in current mining projects, and the global resources take into account the earth's overall resources, both on land and in the ocean. For many metals, estimates of world resources and reserves are partial, which makes it difficult to evaluate precisely to what extent resources are depleting, even though it is clear, since these are non-renewable resources, that there is a depletion phenomenon and that this phenomenon is important enough to address the issue.[49] **It is important to understand that the large majority of the theoretical global resources of scarce metals are often present in exceedingly small concentrations in the earth's crust, which means only a small portion of those minerals is economically, energetically, and technologically feasible to exploit. This is called the mineralogical barrier.**[50] **At the current rate of production, the profitable reserves of some fifteen base metals and rare metals will be exhausted in less than 50 years**.[51] The metals concerned are antimony, tin, lead, gold, zinc, strontium, silver, nickel, tungsten, bismuth, copper, boron, fluorite, manganese, and selenium.[52] As technology evolves, the mineralogical barrier may vary on a small scale,[53] but with tremendous adverse effects regarding local, regional, and global environmental impacts, as mining will require more energy and increasingly deeper and wider operations. Eventually, the economic cost of e-waste recycling is expected to become increasingly competitive compared to the economic cost of mining for the metals[54] most in demand (see our case study on e-waste & the circular economy).

Even if not directly related to resource depletion, short-term shortages and highly volatile prices are expected to occur increasingly as demand grows greater and faster than supplies, which provides a first insight into our current and growing dependency on metals. This has been the case since the beginning of 2021 with the semi-conductor shortage. This shortage is affecting vehicle production on a broad scale, due to a significant growth in the personal computer market during the 2020 Covid-19 crisis, concomitant rising interest in electric automobiles (high demand for integrated circuits) and the resulting shortage of raw materials for printed circuit boards.[55]

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47 Mudd, G M, *The Sustainability of Mining in Australia: Key production trends and Environmental Implications*, Research Report No RR5,Department of Civil Engineering, Monash University and Mineral Policy Institute, 2009

48 *https://www.usgs.gov/centers/nmic/mineral-commodity-summaries* (last retrieved: 14/06/2021)

49 van der Voet, E.; Salminen, R.; Eckelman, M.; Mudd, G.; Norgate, T.; Hischier, R for the UNEP, *Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles, A Report of the Working Group on the Global Metal Flows to the International Resource Panel*, 2013

50 Bihouix P., de Guillebon B., *Quel futur pour les métaux ? Raréfaction des métaux: un nouveau défi pour la société*, 2010

51 Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021, chapter 8

52 Myrtille Delamarche, *De surprenantes matières critiques*, L'usine nouvelle, 10 July 2017; Myrtille Delamarche, *Les nouvelles matières critiques*, L'usine nouvelle, 2018

53 Sometimes, the opening of new mines and the exploration and discovery of new reserves can change the geological criticality of a metal, but this is only exceptionally the case and does not fundamentally change the criticality and depletion issues of a metal. In recent years, this has been particularly true for lithium, for which world reserves were estimated by the USGS to 14,000,000 metric tons both in 2016 and 2017, with a jump to 17,000,000 metric tons in 2018 and 21,000,000 metric tons in 2018 because further extensive explorations resulted in new mines opening, especially in South America in a region known as the Lithium Triangle, which is estimated to hold about 54% of the world's lithium reserves. Those further explorations were motivated by the growing demand, regular and sustained, of lithium for batteries, for smartphones and smart devices and even far more for electric vehicles batteries.; Ellsworth Dickson, *South America's prospective - The Lithium Triangle*, Resource World, 2017

54 OECD, *Global Material Resources Outlook to 2060: Economic Drivers And Environmental Consequences*, 2019

55 Mario Mckellop, *Raw Material Shortage Marks Latest Setback for Components Industry*, 24 May 2021

Conclusion

We have to remember that humanity has not always been so dependent on these metals and in such quantities: from Antiquity to the Renaissance, humanity used only seven metals, only 10 during the 20th century and around 20 during the 1970s. Currently, almost the entire periodic table of Mendeleyev is used (about 80 elements out of 90).[56]

> *"Despite technological progress, it is to be feared that our new uses and our growing consumption cannot be compensated for."*
>
> **Guillaume Pitron**

This dependency threatens the economically available reserves for future generations and economical and geopolitical stability, as well as representing a phenomenal setback to the ambition of ecological transition, since it has irreversible, toxic effects on ecosystems, biodiversity and human lives, and contributes to more greenhouse gas emissions and hydric stress at a time when human activities need to drastically reduce greenhouse gas emissions and preserve fresh water for primary needs.

If the ICT sector accounts for only a small share of global demand for metals, several resources of importance to ICT are becoming scarce, and the anticipated escalation of ICT components for the IoT[57] runs contrary to a sustainable use of digital technologies. To develop a more sustainable use of digital technologies, it is crucial to understand that ICT will always rely on hardware, and hardware will always rely on metals, which are non-renewable resources. This means we must view the daily economic and social benefits ICT offers us as a limited stock which it is our duty to preserve, and to prioritise our needs in the digital and environmental transition to pinpoint exactly where we can be the most efficient. In this, sobriety, and lower-tech solutions[58] can be tremendously beneficial, addressing on a broad scale the multiple environmental issues described in this case study, as well as social and economic issues, such as bridging the digital divide, limiting screen addiction and associated pathologies, limiting the EU's dependency on imports and helping forge Europe's resilience.

Recommendations for a digital evolution compatible with the Green Deal

In an ideal digital evolution perspective, high-tech effectiveness has been ingeniously coupled with low-tech innovations to propose the best of both, boosting EU competitivity and strengthening its position as a precursor and active leader of disruptive innovation for climate and the environment.

The reuse industry is a strong provider of employment in many regions and ICT equipment is collected on a large enough scale to sustain the massification of reuse.

Devices such as smartphones, feature phones, laptops, TVs and monitors frequently have a second, third or fourth life with other users. The rush on the most powerful devices has given way to a balanced use of long-lifespan devices suited to daily needs. Eco-design of devices, robustness and high reparability are promoted. Most ICT equipment such as Wi-Fi boxes are shared.

People keep their equipment longer and have been massively empowered in their choices so they can choose the kind of device that offers the best compromise between sustainability and their needs.

Screen addiction, which was an increasing issue in the 2020s, is now very low: indeed, ICT devices are used as tools, and entertainment has made impressive progress with a return to shared live emotions and away from isolation.

56 Guillaume Pitron (trans. Bianca Jacobsohn), *The rare metals war: the dark side of clean energy and digital technologies*, 2021

57 Tilman Santarius, Johanna Pohl and Steffen Lange, *Digitalization and the Decoupling Debate: Can ICT Help to Reduce Environmental Impacts While the Economy Keeps Growing?*, 2020; see our case study on IoT

58 For example, the current global semi-conductor shortage has driven market interest in older chip-making equipment that shows that lower-tech solutions are a quick resilience solution in the event of massive and immediate shortage. This also underlines that this solution is too often left aside but is a valuable solution to address and it should be considered and planned to be as efficient as possible. (Sourceengine team, *Global Semiconductor Shortage Drives Interest in Older Chip-making Equipment*, 9 March 2021)

E-Waste and Circular Economy

Table of content

Key data for magnitude

x5,307
Eiffel towers each year. This is the amount of e-waste generated globally in 2019[i ii]

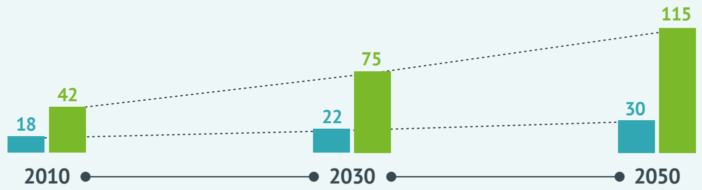
x53.6Mt
global e-waste generated in 2019 (7.3kg per capita)[ii]

~82.6%
of global e-waste are still not documented

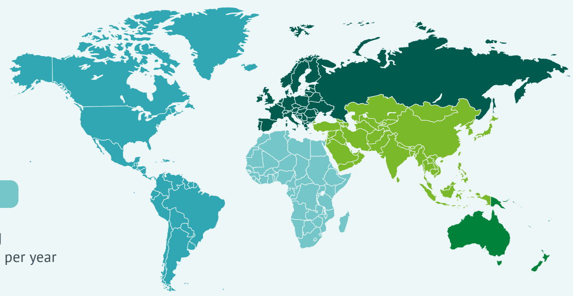
Forecasts of e-waste quantities shows the quantity of e-waste will inevitably increase

In million tonnes/year

- Global e-waste quantities
- OECD 90 and EU member states and candidates e-waste



In 2019, Europe is the continent where the most e-waste per capita is generated



Americas
13.3kg
per capita per year

Africa
2.5kg
per capita per year

Europe
16.2kg
per capita per year

Oceania
16.1kg
per capita per year

Asia
5.6kg
per capita per year

[i] Parajuly, K.; Kuehr, R.; Awasthi, A. K.; Fitzpatrick, C.; Lepawsky, J.; Smith E.; Widmer, R.; Zeng, X., *Future E-waste Scenarios*, StEP (Bonn), UNU ViE-SCYCLE (Bonn) & UNEP IETC (Osaka), 2019

[ii] Forti V., Baldé C.P., Kuehr R., Bel G., *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*, UNU/ UNITAR – co-hosted SCYCLE Programme, ITU & ISWA

Summary of the case study

Electric and electronic waste (e-waste) is recognised as one of the most urgent issues to tackle, as e-waste may have either positive or negative impacts on the environment. Why positive? Because e-waste contains critical raw materials – some of them hazardous, others not – that can be depolluted, recycled and reused and can therefore reduce environmental pollution, health hazards and raw material depletion (**see our case study on raw materials**). Yet before it becomes e-waste, the lifespan of equipment can be extended to reduce the production of more equipment that will ultimately become e-waste. This is the principle of a circular economy system, which is only in its infancy.

This case study looks at the actual state of e-waste management in the EU and explains the key notions related to the the emerging circular economy as applied to digital devices. We also explain the environmental and health impacts related to e-waste when improperly collected and treated, which on the one hand can have damaging effects on biodiversity, greenhouse gas emissions, water and land pollution, and on the other hazardous effects on health, especially children's.

As forecasts of e-waste predict an inevitable increase due to population growth and increasing purchasing power, it is crucial to understand the contribution of ICT to e-waste and the levers to tackle the roots of this global issue.

Definitions

What is the circular economy?

Circular economy: the circular economy is an economic system aimed at preventing waste and the continual depletion of resources. It aims to create a closed-loop system to minimise the use of resource inputs and pollution from waste generation and greenhouse gas emissions. Sharing, reuse, repair, refurbishment, remanufacturing and recycling are the key principles of the circular economy. Currently, the circular economy is promoted by the EU Circular Economy Action Plan,[1] but we have found no example of circular economy projects supported by the EU concerning digital devices to reduce e-waste.[2]

What is e-waste?

E-waste: E-waste is an abbreviation for waste electrical and electronic equipment (WEEE). A product enters the category of "waste" when it has been "discarded by the owner without the intention of reuse".[3] Electrical and electronical equipment can be "any household or business item with circuitry or electrical components with power or battery supply". In the EU, the WEEE Directive requires the separate collection and proper treatment of e-waste and establishes quotas for minimum e-waste to be collected by EU member states, as well as for its recovery and recycling. The Directive also makes it harder for exporters to disguise illegal shipments of e-waste.[4] As described below, the WEEE Directive distinguishes between 6 different categories of equipment:

1. Temperature exchange equipment (TEE)	4. Large equipment
2. Screens and monitors	5. Small equipment
3. Lamps	6. Small IT

In this case study, as far as possible we will consider specifically the 2nd and 6th categories (2. Screens and monitors, 6. Small IT), as they include the majority of ICT equipment.[5] However, it is often difficult to find detailed data per category, so in those cases we will consider all categories of e-waste.

Main concepts

The 5Rs applied to ICT equipment

Reduce: Each piece of equipmentthat is not produced is one that will not pollute. This is the first principle of the 5R approach.

Reuse: Each piece of equipment that is reused helps reduce our dependency on the latest equipment. On an economy-wide scale, it contributes to promoting the circular economy, bridging the digital divide and reducing inequalities. This is the second principle of the 5R approach.

Repair & Refurbishment: Each piece of equipment that is repaired is one that will have a longer lifespan. Each piece of equipment that is repaired or refurbished from second-hand components reduces resources depletion and entropy. On an economy-wide scale, it also contributes to promoting the circular economy and creating skilled employment.

Recycle: A piece of equipment that is recycled will have two main benefits: it will emit less pollution at the end of its life and, once disassembled, its components can be valorised for secondary uses. Overall, recycling e-waste has broad, long-term benefits for the environment and contributes to safeguarding the future use of metals. This is the final principle in the 5R approach.

1 https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf (last retrieved: 22/06/2021)
2 Based on researches made in June 2021 on the open data platform: https://data.europa.eu/
3 Step Initiative, *Solving the E-Waste Problem (Step) White Paper: One Global Definition of E-waste*, 2014
4 https://ec.europa.eu/environment/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en (last retrieved: 21/06/2021)
5 Some equipment, such as small consumer electronics (headphones, remote controls), or speakers, cameras, and video players and projectors, can be found in the 5th category (Small equipment), but many other non-ICT electronic equipment such as household tools, household monitoring and control equipment or household medical equipment can be found in the same small equipment category, so we do not focus on this 5th category.

What happens to e-waste when someone discards a piece of equipment?

The different e-waste circuits

Store and Collection point

E-waste is brought back to the store or is brought by its owner to a collection point.

It will be collected & reported. Then it will be treated in line with EU standards.

Mix with other waste

E-waste is mixed with other waste and hazardous substances contaminate the remainder of the waste.

E-waste will be either burned (greenhouse gaz emissions) or landfilled (land and water pollutions).

Mix with metal scrap

E-waste is mixed with metal scrap without proper treatment of hazardous components.

Workers risk being exposed to hazardous substances, pollution can occur.

Reuse

E-waste is sent aboard for "reuse". Workers risk being exposed to hazardous substances, pollution can occur.

Scavenging

E-waste is collected by scavengers interested in their components.

Scavengers risk being exposed to hazardous substances, pollution can occur.

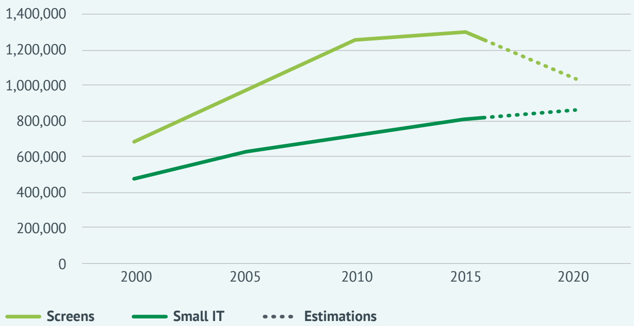
Recycling

E-waste can be collected for complementary recycling to repair or upgrade other e-products. This activity is just starting to be developed. Sometimes, e-waste collected in official e-waste circuits is sent to the repair sector.

Currently, although there are regulatory directives and incentives to collect and report generated e-waste, a very large volume of e-waste still either ends up in the waste bin or is treated together with other metal scrap. Other possible situations that exist but are exceedingly difficult to estimate are, for example, the exportation of ICT equipment for reuse, component scavenging, and complementary recycling as products.

E-waste is often collected and mixed with metal scrap and is therefore recorded as metal scrap in waste statistics instead of e-waste. In this case, there are various possible treatments, from illegal and rudimentary scrapyards and metal merchants to large-scale, authorised, end-of-life vehicle shredders. Some e-waste mixed in metal scrap is also exported to other countries for processing.

E-waste generation in tonnes per year in the EU28



The weight of screens is expected to diminish because of the smaller size of screens and monitors. However, the number of e-waste products generated for the screen category is still expected to increase from about 1,800,000,000 pieces of equipment per year to 240,000,000 pieces of equipment per year in the EU28 + Norway + Switzerland.
http://www.urbanmineplatform.eu/urbanmine/eee/weightpercolcat
http://www.urbanmineplatform.eu/urbanmine/eee/quantity
(last retrieved: 22/06/2021)

E-waste categories for ICT

Small IT

Routers, mice, keyboards, external drives, accessories, desktops (excl. monitors), printers (scanners, multifunctional, faxes), telecommunication equipment, mobile phones, game consoles

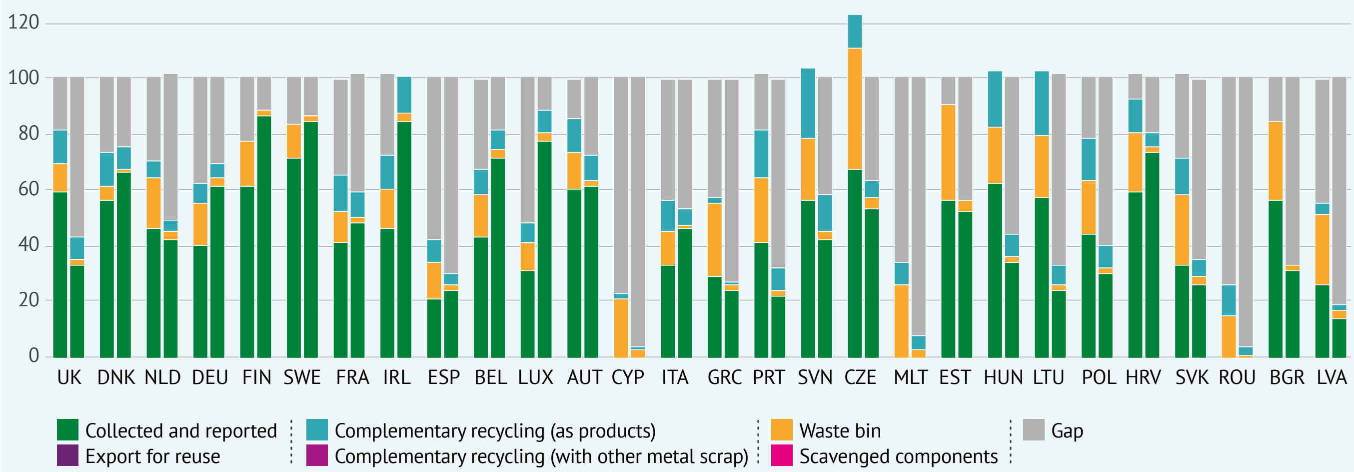
Screens

Laptops, tablets, cathode ray tube monitors and TVs, flat display panel monitors and TVs (LCD, LED, plasma)

The Urban Mine Platform project estimates that depending on the EU country and with an extremely high degree of uncertainty (we lack data for about a third of small IT equipment), between 0 per cent to 25 per cent of small IT equipment (including desktops) was recycled with other metal scrap in 2015, while 5 per cent to 43 per cent of small IT equipment ended up in the waste bin and only 12 countries in the EU exceeded 55 per cent of small IT equipment collected and correctly reported as e-waste.[6] For screens and monitors (including laptops and tablets), it is even more difficult to get reliable data as we lose track of about half of the screens at the end of their life. The disparity between countries is even larger in this category, with only 9 countries in the EU exceeding 55 per cent of screens collected and correctly reported as e-waste and 13 countries with missing data exceeding 55 per cent (see table below).

6 Some equipment, such as small consumer electronics (headphones, remote controls), or speakers, cameras, and video players and projectors, can be found in the 5th category (Small equipment), but many other non-ICT electronic equipment such as household tools, household monitoring and control equipment or household medical equipment can be found in the same small equipment category, so we do not focus on this 5th category.

Share of equipment collected compared to other flows treating WEEE produced in 2015 in the EU-28 (for small IT / screens categories)



Source: *the Urban Mine Platform*. *"The lack of harmonisation across the member states in the reporting of volumes of collected WEEE in particular also for the split of total WEEE volume to individual collection categories can lead to discrepancies between the quantity of waste generated and the quantity collected. In addition, due to lacking harmonisation in quantifying Waste Bin, Export for Reuse, Complementary Recycling and Scavenging, the uncertainties displayed here are high."*

What happens to e-waste when properly collected for recycling in the EU?

"Even if recycling has environmental benefits, it is still imperfect and improving. It is therefore important to focus on limiting renewal and increasing lifespan, as well as reusing our equipment for as long as possible before discarding it."

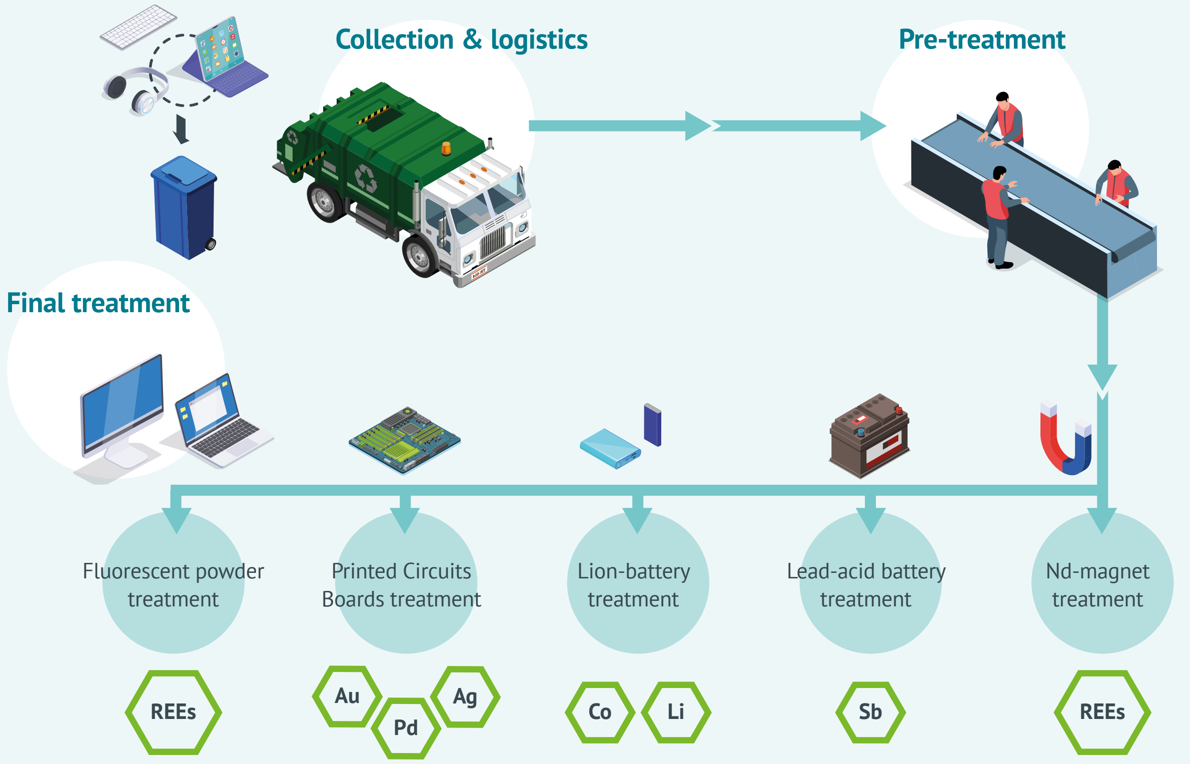
From collection to pre-treatment facility

When a piece of equipment is discarded by a consumer and accepted at a collection point or collection facility, it is shipped to a pre-treatment facility where it is evaluated to see if it can be reused and whether it contains any key critical raw materials. If the equipment can be reused, it is prepared for reuse; if it cannot be reused, external batteries are removed for appropriate treatment (lead-acid and li-ion batteries are very difficult to treat and are processed separately) and the different disassembled parts sent to final treatment facilities.

From pre-treatment to final treatment

If the equipment contains hazardous substances – which is the case of every piece of digital equipment – it goes through a de-pollution process which enables the hazardous fractions to be separated from the key critical raw materials that can be valorised after final treatment in a proper facility. The hazardous fractions are treated or disposed of, and the e-waste fractions that are neither hazardous nor key critical raw materials are treated.

E-waste recycling process



Final treatment facilities can treat and valorise different kind of key critical raw materials such as the rare earth elements present in monitors, the gold, silver and palladium present in printed circuit boards, the copper, and lithium present in Li-ion batteries, etc.[7]

Environmental benefits of recycling

Recycling reduces the risk of e-waste being disseminated, burned or landfilled, with all its metals and chemicals degrading with time, rain or fire and improper handling. Depending on how much is invested in optimising the collection and recycling of e-waste, recycling can have environmental benefits on various environmental aspects such as:

- Limiting freshwater eutrophication (which happens when water is over-enriched by nutrients and minerals, the ecological effects being a decrease in biodiversity, invasion by new species and toxicity),
- Limiting terrestrial acidification (which damages the plants and soil organisms and endangers species),
- Limiting the negative effects on ecosystem quality,
- Limiting the negative effects on human health,
- Limiting the formation of fine particulate matter,
- Limiting the scarcity of fossil resources,
- Limiting global warming,
- Limiting the scarcity of mineral resources,
- Limiting non-carcinogenic human toxicity.

A 2019 study on the economic and environmental benefits of recovery networks for e-waste in Europe[8] shows that the more e-waste is collected and recycled in optimal conditions, the greater the potential benefits for environmental preservation, including economic opportunities in some cases, with compromise scenarios possible between satisfying multicriteria environment goals and economic goals.

However, all the environmental goals do not always perfectly converge and from a certain level of requirement demand very substantial investment[9] or further research to achieve progress, especially since the equipment to be recycled is more and more diverse and the alloys in the equipment are more and more complex (see our case studies on the IoT and raw materials).

> *"The weight-based collection and recycling targets for e-waste in the EU are insufficient to address the problem of small quantities of critical metals disseminated in various equipment"*

Some of the main obstacles to sound recycling of e-waste in the EU currently identified are[10]:

1. Insufficient collection rates of e-waste which prevents formal e-waste management systems from treating e-waste to full potential.

2. A lack of financing that prevents the recycling of critical raw materials even where it is technically feasible with acceptable additional effort at a reasonable cost-benefit balance.

3. The absence of clear requirements to recycle critical raw materials, since weight-based collection and the recycling targets for e-waste in the EU are insufficient to address the problem of small quantities of critical metals disseminated across various pieces of equipment.

4. The difficulty of accessing components containing critical raw materials, which could be improved by eco-designing products, and the lack of detailed and quantitative information and marking of critical raw material components and chemical compositions.

7 EWASTE, *A contribution to future Critical Raw Materials Recycling: CEWASTE Project final report*, 2021
8 Lukas Messmann, Christoph Helbig, Andrea Thorenz, Axel Tuma, *Economic and environmental benefits of recovery networks for WEEE in Europe*, 2019
9 *Ibid.*
10 CEWASTE, *A contribution to future Critical Raw Materials Recycling: CEWASTE Project final report*, 2021, p.19

A 2017 LCA study of a leading Austrian pre-treatment facility showed that in terms of secondary material gain a recycling rate of 80.5per cent enables just over 50 per cent of the input material to be recovered, while for recycling close to the minimum legal target of 62.5 per cent, the amount of recovered material is around 45 per cent.[11]

Even if recycling has environmental benefits, it is still imperfect and improving. It is therefore important to focus on limiting renewal and increasing lifespan, as well as reusing our equipment for as long as possible before discarding it to allow more time for recycling sector to improve.

What happens to e-waste that is not properly collected for recycling?

E-waste in the waste bin

Some e-waste that is not properly collected for recycling is simply discarded. The consequence is that e-waste may be compressed in waste collection vehicles, running the risk of breakageand releasing hazardous components which will contaminate the rest of the waste. Depending on the country's waste management infrastructure, this waste is most likely to be incinerated or landfilled without material recycling. The principal environmental effects are toxic pollution, with dangerous impact on health and biodiversity, and critical resource losses. The chemicals released from e-waste are not biodegradable: they persist in the environment for long periods of time, increasing exposure risk.

Incineration of e-waste results in toxic particulate emissions with disastrous environmental effects. Depending on incineration facility quality, it can release particulates , dioxins and furans from plastic burning, and toxic heavy metals such as cadmium, mercury, lead, zinc, chromium, and nickel in the air, having disastrous effects on human health (cancer and other diseases)

E-waste & the Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal is an international treaty adopted by 188 countries. The treaty aims to prevent the transfer of hazardous waste from developed to less developed countries and minimise the rate and toxicity of generated waste and ensure that hazardous waste is managed in an environmentally sound manner as close as possible to the source of generation. The convention states that illegal hazardous traffic is criminal.

The Basel Convention exempts from regulation cases of electronic and electrical equipment exports intended for reuse. In absolute terms, reuse is an environmentally sound practice since it makes it possible to extend the life of the equipment and limit the use of new equipment. However, the quality level necessary for reuse of the equipment thus exported is sometimes questionable, and the purpose of reuse is sometimes misused as a way of getting rid of e-waste.

To limit this misuse, the Global E-Waste Monitor 2020 report highlights "*two sound policy decisions that can be made unilaterally with regard to ensuring better and more effective enforcement*"*:

- Provide more resources to customs and harbour officials to help them combat the illegal trade of e-waste
- Increase penalties for trying to export e-waste illegally.

* Forti V., Baldé C.P., Kuehr R., Bel G., The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, UNU/ UNITAR – co-hosted SCYCLE Program, ITU & ISWA, p.54

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11 N. Unger, P. Beigl, G. Höggerl, S. Salhofer, 'The greenhouse gas benefit of recycling waste electrical and electronic equipment above the legal minimum requirement: An Austrian LCA case study' (2017), Journal of Cleaner Production, Volume 164, (p. 1635-1644)

and contributing to the greenhouse gases emissions.[12]

Landfilling with e-waste also has disastrous environmental effects, such as water and land pollution.[13]

E-waste collected outside formal e-waste collection systems, such as metal scrap

When e-waste is collected through the metal recycling and plastic recycling system but not sent back to formal e-waste collection and treatment flows, the hazardous components will most probably not be depolluted. The e-waste will not be treated in a specialised recycling facility for e-waste management, which means that recycling the metals (such as copper) and plastics from e-waste will in all probability involve polluted substances.[14] In this case, e-waste might sometimes be exported to developing countries with less advanced or no appropriate recycling facilities for e-waste.

E-waste collected outside formal e-waste collection systems in countries with no developed e-waste management infrastructure

In most developing countries, there are no proper facilities for e-waste recycling, which results in "backyard recycling" in hazardous working conditions with severe damage to human health as well as to the environment.

Informal recycling from e-waste leads to environmental contamination due to the dumping of acid (used to remove gold) into rivers, the leaching of substances from landfills or stored e-waste, particulate matter, dioxins and furans from the improper dismantling of electronics, and contaminants entering the water systems and food chain (fish, crops, livestock). Inhabitants are exposed to e-waste pollution through air, water, and food contamination, and from workshops, by inhaling fumes from burning wires and circuit board heating.

Emerging solutions for ICT in the circular economy

To limit the impacts of smartphone production and e-waste, a social enterprise company named Fairphone* was founded in 2013 in the Netherlands to produce a new smartphone, the Fairphone. The Fairphone is eco-designed to be as easy as possible to repair and to last much longer than usual smartphones. The Fairphone contains no conflict minerals such as gold, tin, tantalum and tungsten and ensures as far as possible fair labour conditions for the workforce along the production supply chain. The company is also committed to helping people use their phone longer before replacement. Fairphone aims to open a recycling service soon.

Another initiative is the Commown cooperative**, which rents responsible desktops, laptops, smartphones (fairphones), and headphones. Commown retains responsibility for the pool of equipment based on the idea of a "commonly owned good" (hence the name of Commown). The cooperative is currently accessible in France and Belgium.

* https://www.fairphone.com/
** https://commown.coop/

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12 Charu Gangwar, Ranjana Choudhari, Anju Chauhan, Atul Kumar, Aprajita Singh, Anamika Tripathi, *Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk*, (2019) Environment International, Volume 125; *https://orlandorecycles.com/2021/01/5-effects-of-e-waste-on-the-environment/* (last retrieved: 22/06/2021); Forti V., Baldé C.P., Kuehr R., Bel G., *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*, UNU/ UNITAR – co-hosted SCYCLE Programme, ITU & ISWA

13 Lee, G. F., and Jones-Lee, A., *Electronic Wastes and MSW Landfill Pollution of Groundwater*, Report of G. Fred Lee & Associates, El Macero, CA, September (2009)

14 Forti V., Baldé C.P., Kuehr R., Bel G., *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*, (2020) UNU/ UNITAR – co-hosted SCYCLE Programme, ITU & ISWA

The expert's view

Claire Downey is Executive of the Community Resources Network Ireland (CRNI). She holds a Bachelor of Engineering and has over 15 years of experience in the waste and resources sector. She sits on national and EU policy committees, is vice-president and board member of the REUSE network Europe and a fellow of the Chartered Institute of Waste Management. Through CRNI Claire participated in the Q2Reuse project, a major two-year project funded by Ireland's Environment and Protection Agency (EPA). This project, led by the Clean Technology Centre (CTC), is undertaken in collaboration with the Rediscovery Centre, Community Reuse Network Ireland (CRNI), and the Eastern Midlands Waste Region. The aim of the project is to gather information on the scale and size of the reuse sector, compare it with other Member States and inform policy makers on potential targets.[i]

"In 2018, 50 million tonnes of e-waste were generated globally. It is evident from this level of generated e-waste that the electrical and electronic equipment (EEE) placed on the market is not properly valued or used to its full potential. By extending the lifespan of our electronic and electrical devices, millions of tonnes of CO2 could be saved.[ii]

Targets can help to address market failures like this by providing a strong policy focus and requiring policy measures to be put in place. Reuse targets could drive growth in the reuse of equipment that exchanges hands but becomes waste much later - for example, ICT equipment donated for reuse. Preparation for reuse targets could drive growth in the checking, cleaning and repairing of equipment that has become waste - for example, equipment collected through take-back schemes.

One major barrier to setting reuse targets in particular has been the difficulty in measuring reuse. As reuse does not involve any waste materials, it is unregulated and can take place through a variety of channels such as informal family-to-family exchanges, flea markets, online or centralised reuse centres. For this reason, Ireland's Environment and Protection Agency (EPA) has funded a major two-year research project called Q2Reuse to develop a qualitative and quantitative method for measuring reuse in Ireland.

Through the project, now near completion, the research team led by the Clean Technology Centre together with the Rediscovery Centre and Community Resources Network Ireland has identified over 1,200 reuse outlets. Initial estimates indicate that reuse activity accounts for less than 1 per cent of all waste generated in Ireland, which leaves much scope for progress. Importantly, it has facilitated the Irish Government in committing to introducing and providing a statutory framework for reuse targets in the recent General Scheme of the Circular Economy Bill.

Methodologies are now available to measure reuse. We cannot continue to waste vast quantities of resource and energy-intensive equipment, or indeed other consumer goods. The development of targets for reuse across Europe is currently too slow when taking into consideration the urgency of our climate crisis. This project has demonstrated that it is possible to refine a methodology and set targets in a short timeframe. Other Member States should be encouraged to look to these examples to ensure that prevention and reuse are properly prioritised for the transition to a more circular economy.

i The results of the project can be found on the following website: http://www.rediscoverycentre.ie/research/q2reuse/

ii Ina Rüdenauer, Siddharth Prakash, Ökonomische und ökologische Auswirkungen einer Verlängerung der Nutzungsdauer von elektrischen und elektronischen Geräten, Öko-Institut und VZBV, 2020

Currently, an increasing number of studies show the dangers to human health of unregulated e-waste recycling: adverse birth outcomes[15], DNA damage[16], cardiovascular effects[17], respiratory effects[18], skin diseases[19], hearing loss, cancer[20], disruption to the immune system, neuro-developmental disorders[21], etc.[22]

Why are children especially sensitive to e-waste exposure?

Compared to adult e-waste recycling workers, the potential health risk to children was found to be eight times higher. Children's bodies are especially sensitive to e-waste hazards for many reasons. They have a higher metabolism rate, a smaller size, and a larger surface area in relation to their weight. Moreover, children frequently put their hands, objects or soil to their mouths, which increases the risk of exposure through ingestion. Some chemicals can also be passed from mothers to children during pregnancy and breast-feeding.

A 2017 report by the International Labour Organisation estimates that some 73 million children aged 5-17 are working in hazardous labour, with unknown numbers in the informal e-waste recycling sector.[23] Children and adolescents working in collection, dismantling and recycling, are especially exposed.

A recent report of the World Health Organisation on exposure to e-waste and child health shows evidence of health and developmental impacts from children's exposure to e-waste, ranging from injuries and short-term effects to growth, neuro-developmental, learning and behavioural impacts, adverse effects on immune system function, thyroid function and lung function, respiratory symptoms and asthma, cardiovascular health, DNA damage etc. The report underlines the potential co-benefits of tackling the e-waste problem in the context of both climate and health agendas[24].

Conclusion

Although collection and recycling in the EU has generally progressed in terms of technique and volume in recent years, recycling is currently limited by the sheer volume of e-waste that is not properly collected and treated (waste bins, scrap metal, illegal shipping to other countries with less efficient or no proper treatment facilities, etc.). With regard to e-waste flows, there is room for improvement and for ensuring, by means of further regulation, more in-depth tracking and monitoring of e-waste. For the EU, it is not only a question of tracking and recycling e-waste as efficiently as possible, but also of ensuring that the reuse and recycle targets contribute to reinforcing the EU's position on the raw material market. Developing e-waste recycling into an efficient, mature sector is not only an environmental but also a geostrategic issue (**see our case study on raw materials**).

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15 Kim SS, Xu X, Zhang Y, et al., *Birth outcomes associated with maternal exposure to metals from informal electronic waste recycling in Guiyu, China*, (2020) Environ Int, *https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7257595/*

16 Alabi, O.A., Adeoluwa, Y.M. & Bakare, A.A., *Elevated Serum Pb, Ni, Cd, and Cr Levels and DNA Damage in Exfoliated Buccal Cells of Teenage Scavengers at a Major Electronic Waste Dumpsite in Lagos, Nigeria*, (2020) Biol Trace Elem Res 194, 24–33

17 Cong X, Xu X, Xu L, Li M, Xu C, Qin Q, Huo X, *Elevated biomarkers of sympatho-adrenomedullary activity linked to e-waste air pollutant exposure in preschool children*, (2018) Environ Int 115:117–126,

18 AmoabengNti AA, Arko-Mensah J, Botwe PK, Dwomoh D, Kwarteng L, Takyi SA, Acquah AA, Tettey P, Basu N, Batterman S, Robins TG, Fobil JN., *Effect of Particulate Matter Exposure on Respiratory Health of e-Waste Workers at Agbogbloshie, Accra, Ghana*, International Journal of Environmental Research and Public Health, 2020

19 Decharat, S., & Kiddee, P., *Health Problems Among Workers Who Recycle Electronic Waste in Southern Thailand*, Osong Public Health and Research Perspectives, 11, 34 – 43, 2020; Seith R, Arain AL, Nambunmee K, Adar SD, Neitzel RL., *Self-Reported Health and Metal Body Burden in an Electronic Waste Recycling Community in Northeastern Thailand*, J Occup Environ Med, 2019

20 Davis JM, Garb Y, *A strong spatial association between e-waste burn sites and childhood lymphoma in the West Bank, Palestine*, Int J Cancer, 2019

21 Haoxing Cai, Xijin Xu, Yu Zhang, Xiaowei Cong, Xueling Lu, Xia Huo., *Elevated lead levels from e-waste exposure are linked to sensory integration difficulties in preschool children*, NeuroToxicology, Volume 71,2019

22 Forti V., Baldé C.P., Kuehr R., Bel G., *The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential*, UNU/ UNITAR – co-hosted SCYCLE Programme, ITU & ISWA, 2020; Nithya, R., Sivasankari, C. &Thirunavukkarasu, A., *Electronic waste generation, regulation and metal recovery: a review*, Environ Chem Lett 19, 1347–1368, 2021

23 International Labour Organisation, *Global estimates of child labour: results and trends, 2012–2016*, 2017

24 *Children and digital dumpsites: e-waste exposure and child health*. Geneva: World Health Organization; 2021. Licence: CC BY-NC-SA 3.0 IGO.

“As the legacy of digital equipment is expected to expand in the coming years, there is an urgent need to become more efficient in collecting e-waste, as well as to boost confidence in repaired and second-hand devices by structuring and supporting the development of an appropriate skilled industry”

While e-waste recycling within the EU is a key element in limiting resource depletion as well as e-waste pollution and health hazards, e-waste recycling is necessary at the very end of the equipment’s life. In this respect the circular economic system, which enables equipment to be shared, reused, repaired or refurbished, is still very young and not yet sufficiently explored and supported to respond to current and future challenges regarding climate, environment, health, and sovereignty over critical raw materials. In this respect, repairability indicators are a first step, as is the indexation of the eco-tax to ease of recycling.

As the legacy of digital equipment is expected to expand in the coming years with the rapid renewal of devices and the diversification of equipment, there is an urgent need to become more efficient in collecting, sorting, removing and tracking e-waste, as well as to boost confidence in repaired and second-hand devices by structuring and supporting the development of an appropriate skilled industry. ■

Recommendations for a digital evolution compatible with the Green Deal

In an ideal digital evolution compatible with the Green Deal, the lifespan of ICT equipment is extended by both the eco-design of hardware and software. Eco-design aids repairing and upgrading, thereby postponing their end-of-life. It also aids recycling, as equipment is designed by taking end-of-life into account.

Anyone who is aware of the 5R approach and regulatory system, the eco-design solutions and the circular stream in place can easily and efficiently apply the 5Rs to their personal or professional usage.

Transparency as to the repairability of a piece of equipment and the traceability of its components and chemicals is guaranteed by a trustworthy product “passport”, a kind of product registration card that helps consumers choose and repairers and recyclers to better understand the product components.

Treatment of e-waste flows ensures with high certainty rates that the vast majority of e-waste is efficiently collected, sorted and disassembled and processed in the soundest possible manner. Financial mechanisms ensure continuous improvement to maximise the recovery of critical raw material and valuable material as well as limiting the environmental impacts of e-waste as far as possible.

The EU circular economy and e-waste management systems enable interesting complementary facilities to be deployed within the EU which stimulate employment and pave the way for the recruitment of sought-after professional skills that strengthen local employment areas.

This circular economy and waste management system gives the EU advantages in international cooperation, enhances its resilience to crises and enables it to position itself as a pioneer and leader with major commercial advantages thanks to the quality of the refurbished or repaired reusable equipment.

European legislation clearly sets out waste (recycling) and equipment (reuse) flows. The regulations force Member States to favour reuse over recycling while addressing both. Eco-organisations have the obligation to reroute equipment that works or can be repaired to the reuse sector. Each device is sold with an indicator of repairability, and the eco-tax is evaluated on the basis of the ease with which the product can be recycled.

RECOMMENDATIONS

Introduction

In the second chapter of its special report (SR15) explaining the impacts of global warming of 1.5°C above pre-industrial levels, the IPCC presents the remaining carbon budget in $GtCO_2$eq.: to limit global warming to 1.5°C with a two-third level of certainty, the remaining carbon budget for humanity is estimated at around 420 $GtCO_2$eq. as from 01/01/2018.[1]

The EU-28 was directly responsible for 9% of greenhouse gas emissions in 2019[2] and even more if we also take into account imported emissions, that is, the emissions of products manufactured outside the EU but consumed within its borders.[3]

In 2019, ICT contributed to 185 Mt CO_2 eq. emissions for the EU-28 alone, as our LCA shows[4], which represents 4.2% of EU-28 emissions in 2019[5], but as much as 40.7% of EU-28 GHG emission budget to stay below 1.5°C of global warming. Moreover, for the same period, ICT used 5,760 tonnes of antimony- equivalent resources, which means that 116 Mt of waste were produced for ICT needs in the EU-28, equivalent to the weight of 3.6 humans for an average European ICT consumption. This shows how important it is to consider not only climate change indicators, but to embrace a multicriteria approach to understand the overall environmental impacts of ICT and take appropriate policy measures to reduce its contribution to climate change without pollution transfers.

In this chapter, we report our principal recommendations for a digital roadmap that reduces environmental impacts and is compatible with the Paris Agreement and the Green New Deal, although they would require further measurement to estimate to what degree a combination of them could effectively contribute to mitigating ICT's role in climate change, which is outside the scope of this study.

Our recommendations are aimed at reducing the contribution of ICT not only to climate change, but also to other concomitant environmental impacts, such as resource depletion, e-waste pollution and health hazards.

In 2018, the ILO published a study showing that "*a just transition to a more sustainable economy offers much potential for job creation and the promotion of decent work*"[6]. The digital roadmap we recommend also has economic and social benefits for the EU that are listed in the table below. Our recommendations are aimed at tackling the environmental issues of ICT at a systemic level, which is necessary to empower citizens in their choices as consumers and to ensure economic and strategic benefits at the European level, as well as stimulating regional economies and employment. To do so, our recommendations do not set high tech against low tech, but are aimed at bridging the divide by taking the best of both, in a disruptive and lower-tech combination of efficiency and sobriety.

1 Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférian, and M.V. Vilariño, 2018: *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

2 https://www.climatewatchdata.org/ghg-emissions?breakBy=regions-ABSOLUTE_VALUE&end_year=2018&regions=EUU%2CGBR%2CWORLD&source=PIK&start_year=1850 (last retrieved: 27/08/2021); Daniel Moran, KGM & Associates, Ali Hasanbeigi and Cecilia Springer, Global Efficiency Intelligence, *THE CARBON LOOPHOLE IN CLIMATE POLICY Quantifying the Embodied Carbon in Traded Products*, August 2018

3 https://www.carbonbrief.org/mapped-worlds-largest-co2-importers-exporters (last retrieved: 14/06/2021)

4 Bordage, F., de Montenay, L., Benqassem, S., Delmas-Orgelet, J., Domon, F., Prunel, D., Vateau, C. and Lees Perasso, E., GreenIT.fr. 2021. *Digital technologies in Europe: an environmental life cycle approach*.

5 Note: The EU-28 scale comparisons are aimed at providing a scale of related impacts and should not be understood as absolute results. The scopes are different: some emissions related to digital services in the EU-28 occur outside the EU-28 and are considered within the scope of the study (manufacturing of the devices); while the total emissions considered for the EU by the IEA are only emissions occurring within EU borders. To learn more about imported emissions: https://www.idhsustainabletrade.com/news/hidden-co2-emissions-europes-imported-responsibility/

6 International Labour Organisation – Geneva: ILO, *World Employment and Social Outlook 2018: Greening with jobs*, 2018

Priority	#	Environmental objectives	Principal stakeholders	Economic benefits	Social benefits
1	1	**Reduce environmental impacts by reducing the number of devices** • Reduce the number of devices needed • Pool • Eco-design	Policy-makers + Experts + Economic stakeholders*	Stimulate innovation, attract, and retain talents, less dependency on imports, reduce maintenance costs and reduce e-waste costs	Bridge the digital divide (eco-design/pooling)
1	2	**Fight against all forms of obsolescence: increase lifespan**	Policy-makers + Experts + Citizens + Economic stakeholders	Reduce dependency on imports, reduce e-waste costs	Increase equal opportunities, bridge digital divide
1	3	**Massify reuse**	Policy-makers + Experts + Economic stakeholders	Stimulate regional economies, stimulate the circular economy	Stimulate employment in emerging sectors, bridge the digital divide
1	4	**Provide European citizens with reliable data on digital responsibility**	Experts + Policy-makers + Citizens	Create vocations and disruptive innovation opportunities	Bring out social cohesion, stimulate citizen empowerment
1	5	**Generalise environmental diagnosis:** a product can be green only if it has been demonstrated to be so	Experts + Economic stakeholders + Policy-makers + Citizens	Stimulate European position as a precursor and leader on environmental expertise	Stimulate citizen empowerment
1	6	**Support mixed low- and high-tech innovation for climate**	Policy-makers + Economic stakeholders	Stimulate innovations that can accurately divide GHG emissions, stimulate regional economies	Stimulate employment, bridge the digital divide, increase equal opportunities, bring out social cohesion
2	7	**Green procurement for public institutions**	Policy-makers + Experts	Stimulate the circular economy and reuse industry, reduce costs	Bridge the digital divide, increase equal opportunities, bring out social cohesion
2	8	**Regulate the IoT**	Policy-makers + Experts + Economic stakeholders	Stimulate the emergence of competing APIs originating in the EU	Stimulate citizen empowerment
2	9	**Move towards complementary networks instead of overlaying networks**	Policy-makers + Experts + Economic stakeholders + Citizens	Cost-saving benefits, less maintenance	Reduce exposure to electromagnetic waves, increase equal opportunities, bridge digital divide
2	10	**Bring the cloud to sustainable management maturity**	Policy-makers + Experts + Economic stakeholders	Cost-saving benefits, less maintenance, cloud security improvements	Empower users in their choices
3	11	**AI: engage in frugal and sovereign data opportunities**	Policy-makers + Experts + Economic stakeholders	Ensure data sovereignty of Europe, stimulate Europe's position as a precursor and leader on frugal data	Address Europeans preoccupations on data confidentiality issues
3	12	**Set mandatory environmental conditions of access to the European market for autonomous vehicles**	Decision-makers + Mobility experts + Citizens + Economic stakeholders	Stimulate economic exchanges inside the EU with a shared and planned eco-mobility strategy	Prevent the widening of regional mobility inequalities

* Economic stakeholders can include, for example, manufacturers in the digital sector, suppliers of digital services or products. This category encompasses both large multinational players and smaller local players.

Attempt to define two key concepts: digital sobriety & low tech

Digital sobriety consists of voluntarily designing digital services and products that have lower environmental impacts (resources, GHG emissions, consumption, waste production, ecotoxicity, etc.) and moderating one's daily use of digital technology.

Low tech refers to technologies and a rationale aimed at sobriety in the use of energy and materials, high sustainability and collective resilience. It is an approach that encourages techno-discernment. The objective is to set an optimal logistics level (the lowest level to ensure essential functionalities). The low-tech approach is based on three principles:

1. Thinking about the need to reduce as far as possible at source the extraction of resources and the pollution this generates.

2. Thinking about what is produced to increase the lifespan of the products.

3. Thinking about production methods to make our lifestyles more resilient.*

* This definition of low-techs is based the following note from a work group of La Fabrique Écologique: Philippe Bihouix, Emiline Baume de Brosses, Geneviève Besse, Fabrice Bonnifet, Marc Darras, Thomas Désaunay, Jean-Marc Gancille, Amandine Garnier, Thierry Groussin, Thomas Guillermou, Arthur Keller, Catherine Lapierre, Dominique Py, Sandrine Roudaut, Agnès Sinaï, Mathilde Soyer, Bruno Tassin, Arnaud Vanhove, Dominique Viel, *Vers des technologies sobres et résilientes – Pourquoi et comment développer l'innovation « low-tech » ?*, April 2019

Our priority #1 recommendations

Reduce environmental impacts by reducing the number of devices

Reduce the number of devices needed

Our most important recommendation is to reduce the number of devices at consumer, professional and corporate levels. Each potential acquisition or change of device has to be evaluated in terms of the balance between gain (for example – energy efficiency) and cost (for example – equipment renewal).

Most of the resource-related environmental impacts in the life cycle of a user device occurs during the manufacturing phase. Changing an ICT device in the interests of greater energy efficiency has adverse effects on non-renewable resources, which are limited (see the results of our study regarding resources, mineral and metal, the normalised and weighted results, and our case study on raw materials). Each time we replace a device by another, we draw on limited capital, since the resources used to manufacture ICT equipment are non-renewable.

To reduce the number of devices needed on an economy-wide scale, it is also crucial to consider the impact of deploying any new technology in terms of obsolescence and the risk of a massive renewal of current user equipment. We also must be careful about efficiency gains, which often go hand in hand with an increase in consumption (see our case study on rebound effects).

When we consider renewing an item of hardware such as a screen, it is important to remember how greedy a TV is in terms of energy and resources, and therefore to opt rather not to replace it, or to replace it by a smaller screen. Rather than buying a larger, new television, go for a second-hand purchase and smaller diagonal size.

Pool

› At the economy-wide level

Whenever possible, go for pooled solutions rather than individual ones to lower environmental impacts. For example, equip a building with a single Internet box rather than one per household.

Other cases of pooling at the economy-wide level need to be evaluated by life cycle assessments. Companies and non-profit initiatives which offer users the benefits of a pool of ICT equipment that can be shared or reused should be promoted and incentivised, as they will stimulate a European circular economy and resilience.

In the EU-28, there are about 202,030,000 DSL or fibre boxes installed in households[7]. For households living in buildings in dense areas, boxes could be pooled, as is already the case for hotels, companies, hospitals and some student residences. Pooling would also result in less intensive exposure to electromagnetic waves. Peak consumption in the evening would have to be taken into consideration, however, as this can detract from the benefit of pooling boxes.

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7 90% households equipped in 2019, source: https://ec.europa.eu/eurostat/product?code=isoc_ci_in_h&mode=view&language=EN ; 224,478,700 households in EU28 in 2019, source: https://ec.europa.eu/eurostat/databrowser/view/lfst_hhnhtych/default/table?lang=en

Equipment

Pooling functionalities can bring increased benefits. For example having one multifunctional device – such as a smartphone – instead of multiple connected devices that would offer identical or similar functionalities: pedometer, GPS, connected watch, standalone mobile broadband modems.

Similarly, using a smaller monitor for multiple uses instead of having different types of monitor for different uses, including a large TV, will lower one's environmental footprint.

Producing and using one multifunctional device has a lower environmental impact than producing and using multiple devices of various types (see the results of our study regarding the environmental impacts of end-user equipment, especially the environmental impacts per type of device).

Base technological development on existing equipment

Encourage the upgrading of existing equipment to lower environmental impact.

Encourage modularity through standardisation.

The feasibility of developing new technology based on existing equipment should be investigated and therefore incentivised to lower environmental impact.

In the short term, this would help to bridge the digital divide by ensuring equal treatment of users. In the medium term, this will allow e-waste to be refurbished and recycled more easily. In the long term, it will contribute to European resilience and sovereignty on critical raw materials.

Eco-design

Eco-design is a lever for resilience, independence and geopolitical autonomy. Three factors will enable Europe to be autonomous in ICT: firstly, the pool of equipment currently in stock[8]; secondly, e-waste from previous equipment; thirdly, skilled human resources. The EU has the of differentiating itself from China and the USA **by relying on immaterial capital**, which is more resilient and depends less on external markets. As the EU does not have the resources to be independent by extracting its own precious and critical metals[9], eco-design coupled with a circular economy is an economic solution that pollutes less[10], may require less investment and may be quicker to put in place.[11]

Eco-design of equipment

Make it mandatory to eco-design equipment using multicriteria, ISO 14040-44-compliant LCA before and after eco-design, and complying with ISO 14062 for the eco-design.

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8 Regarding resources, minerals and metals, existing equipment has already caused most of its environmental impact during the manufacturing phase (**see our multicriteria LCA results for end-user equipment**).

9 **See our case study on raw materials**

10 **See our case study on e-waste and circular economy**

11 See Greenconcept feedbacks on *http://www.greenconcept-innovation.fr/temoignages/* such as for ELA INNOVATION : *http://www.greenconcept-innovation.fr/wp-content/uploads/2020/02/ELA_INNOVATION_fiche_Ademe_GreenConcept2409.pdf*, PriceComparator: *http://www.greenconcept-innovation.fr/wp-content/uploads/2020/02/PriceComparator_fiche_Ademe_GreenConcept2108.pdf*

Eco-design of digital services

As innovation under constraint is recognised as being an efficient stimulus for disruptive innovation, we recommend:

> Making it mandatory to eco-design digital services with a focus on the principal functionalities and key user needs, constrained by planetary boundaries and using multicriteria, ISO 14040-44-compliant LCA before and after eco-design, and complying with ISO 14062 for the eco-design.
>
> Incentivise full exploitation of the potential of existing and generalised technologies before shifting to another, for example by rewarding innovative services that use existing and generalised technologies in an eco-designed approach to the value chain of the service.

Focusing on the principal functionalities means making websites, applications, and software that contribute to infrastructure congestion and slow down response times leaner. The immediate benefits are swifter services that work on a larger number of devices, including older ones, and less infobesity, which also makes it easier for users to find the key information they are looking for.

Eco-designing digital services is one means of developing frugal and resilient infrastructures and optimising data transmission and computing. Eco-design is a global approach that includes "lighter" code, but not only. It can be a lever to reduce data traffic and, eventually, the number of servers needed. Optimising the technological solution helps increase the lifespan of equipment and to a lesser extent also reduces energy requirements.

Fight against all forms of obsolescence: increase lifespan

Reduce fonctional obsolescence

> Reinforce legislation against programmed obsolescence:
>
> Encourage high recyclability and reuse rates, ensure compatibility between generations (of network technologies, hardware, software), accessories, encourage availability of spare parts. Involve recycling stakeholders in defining recyclability criteria and targets based on multicriteria life cycle assessments.
>
> Encourage the development of activities in favour of the second-hand market: set targets and a calendar for the development of a repair industry for ICT equipment, with initial key steps such as a product passport.

The product passport would be an initial key step towards making product repairs more reliable and raising confidence in second-hand devices. It would help structure the repair industry in Europe to ensure reliability and maturity.

Reduce indirect obsolescence: psychological and incompatibility obsolescence

Beyond the mechanical and resource problems of a device that can be solved by repairing it, public knowledge of the environmental impacts of ICT as well as the eco-design of digital services also have a role to play.

General public communication

Make all generations aware of the environmental impacts of digital technology by communicating publicly on the environmental impacts of end-user equipment and ICT in general.

Forbid advertising in favour of equipment renewal.

At the eco-design level

A distinction can be made between two types of incompatibility obsolescence: one is between new software and older equipment and operating systems, and another is between new versions of an operating system and older software.

Make software compatibility with older equipment and older operating systems (OS) mandatory.

Make operating system (OS) compatibility with older software mandatory.

In the first case, for example, the principal functionalities of smartphone apps or computer software should still be supported and accessible on previous operating systems (OS). In the second case, when a new version of the OS is installed on the device, the principal functionalities of the older software should still be accessible.

Backward incompatibility is the result of a failure to eco-design (due to a lack of motivation). Backward incompatibility can be incentivised at first. The developers in the industry need to work together to ensure common backward compatibility efforts. Applying best eco-design practices for operating systems, software and applications will ensure that backward compatibility is possible, with complementary advantages in terms of the rapidity and responsiveness of the services, and lower memory use and data consumption (**see our recommendation on eco-designing digital services**). Eco-designing digital services can also extend the lifespan of a device: since the design is lighter and deliberately compatible with older equipment, older devices can continue to be used.

Massify reuse

We recommend three tools to massify reuse:

Introduce a European reuse directive. This directive should be aimed at measuring reuse flows, increasing the links between e-waste producer responsibility organisations (PROs) and the reuse sector, and limiting e-waste leaks out of Europe. It should also help promote reuse in the circular economy and set targets.

Europe has a pool of active and dormant equipment that is a sunk cost. This reuse directive will encourage postponing the moment when devices inevitably become waste. The European reuse directive should be consistent with the existing e-waste directive to ensure that there is no contradiction between encouraging the collection of e-waste and encouraging the collection of equipment that is reusable, and to set consistent targets for both.

Introduce a product passport similar to vehicle registration cards to ensure traceability of products and their components and, above all, to provide a stricter framework for refurbishing.

This product passport is a first step towards defining the term refurbishing and developing a regulatory framework for the refurbishing sector.

Establish strict specifications for refurbishers and establish compulsory, standardised technical testing for electronic devices, with a product guarantee which should be between 100% and 50% of a new product time guarantee.

As with roadworthiness tests for vehicles, technical testing for electronic devices would help build customers' confidence in second-hand devices. The absence of any such test damages the credibility of the entire sector: people mistrust repaired devices. Testing would help build an active, reliable and prosperous circular economy and repair industry in Europe.

Provide European citizens with reliable data on digital responsibility

Create and run an information platform with reliable, consensual and multicriteria data on ICT environmental impacts to stop greenwashing.

At the European level, have a set of independent experts who guarantee the quality of the content and validate the information posted on the platform by peer review to ensure the reliability and exhaustivity of the data to which decision-makers, as well as teachers from across the EU and abroad, will have access.

Incentivise the industry both to use the tools available on this platform and feed the platform with the latest data with a view to data transparency and openness.

The environmental impact data on this platform could, for example, be drawn from LCAs on frequent digital uses by Europeans and the key measures to be implemented (for example, promoting the reuse of smartphones) to demonstrate their effectiveness. The platform could also help debunk false good ideas.

Generalise environmental diagnostics: a product can be green only if it has been demonstrated to be so

Regarding environmental communication, or when funding an innovative product or service for climate or resource preservation, rely systematically on a multicriteria, ISO 14040/44-compliant life cycle assessments (LCAs), taking into account and distinguishing between 1) positive and negative impacts, and 2) direct and indirect impacts.

The analysis should also distinguish between the effects on the market and the effects on the eco-system of the product or service, such as the type and number of accessories related to the product or service.

As multicriteria, ISO 14040/44-compliant life cycle assessments are the most reliable means of measuring the environmental impact of a product or service, a product can only be considered "green" if it has been demonstrated to be so, and its development should be financed by European climate funding only if the preliminary studies prove it.

Support mixed low- and high-tech innovation for climate

Most breakthrough innovations are not always high-tech: innovation can be an innovative model. The innovations we recommend for achieving a more sustainable future are innovations geared toward progress. Low tech is an enabler for new, progressive organisational models and business models that must be considered at the same level as high tech.[12]

Consider funding a mix of low and high-tech innovations as priority breakthrough technologies, in the innovation funding named "climate and resources frontrunners".

There is a semantic distinction between innovation and progress: innovation is a means; progress is a target. We recommend seeking the goal of progress and then choosing the appropriate tools in line with that objective. The means for achieving this goal can be innovation, as well as through low tech as through high tech, and the two can be combined, to get the best of both.[13]

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12 See definition of low-tech.

13 A few examples:

1. Weather Force is the publisher of the digital rainfall forecasting service for farmers, Last Mile Agriculture. The Last Mile Agriculture 4G smartphone application allows you to view detailed rain forecasts for the same day and the next day. It therefore allows farmers to optimise crop yields. The functional unit chosen is: "Consult the rain forecast indicator for today and tomorrow". In an operation financed by the ADEME, and conducted by GreenIT.fr, LCIE CODDE Bureau Veritas, Neutreo by APL, environmental impacts (PED, GWP, WD, ADP) were divided by a factor of 2 to 5 via an eco-design approach combining low and high tech. Source: Greenconcept v3, 2019

2. The company Makina Corpus publishes the digital service Geotrek which allows the creation of hiking routes which are then available as online (web) and PDF documents. The functional unit retained is: "Build and use an itinerary". In an operation financed by the ADEME, and conducted by GreenIT.fr, LCIE CODDE Bureau Veritas, Neutreo by APL, environmental impacts (PED, GWP, WD, ADP) were reduced from -23% to -65% via an eco-design approach combining low and high tech. Source: Greenconcept v3, 2019

3. The company BS We operates the digital Price Comparator service, which monitors the price of products sold online. The functional unit retained is: "Monitor the price of 200 products from 5 competitors once a week for 1 year". In an operation financed by the ADEME, and conducted by GreenIT.fr, LCIE CODDE Bureau Veritas, Neutreo by APL environmental impacts (PED, GWP, WD, ADP) were divided by four via an eco-design approach (replacement of the application interface by an email alert). Source: Greenconcept v1, 2017

See more examples of feedback on innovations mixing both high and low-tech combinations on http://www.greenconcept-innovation.fr/temoignages/

Our priority #2 recommendations

Green procurement for public institutions

Anticipate the end-of-life and reuse of all new devices procured for public institutions. To do so, the second life of the device must be provided for in calls to tender.

This will help increase the supply of second-hand devices and help build the reuse market.

Regulate the IoT

The growth of the IoT must be questioned given that digital technology is subject to constraints and limited in resources, non-renewable and non-biodegradable. Regulating the IoT will also give Europe scope to plan and anticipate its resilience strategy in a world where pressure on metals and therefore on digital technology is increasing.

› Design

Make the opening of the communication interface of connected objects (API) mandatory to allow users to continue using their connected objects even if the service is no longer supported by the original manufacturer. Give competency to public regulators on this issue.

Today, we are forced to buy proprietary devices, as if it were impossible to sell a device with multiple channels, as is the case with TVs. This limitation has huge consequences in terms of obsolescence: if a consumer is not satisfied with the service, or if the API is no longer maintained, the whole device is discarded and, in most cases, not reused.

As no regulator would conceive of having a TV set for one sole channel, making it mandatory to open the communication interface (API) of connected objects would allow users to continue using their connected objects.

› Use and reuse

Promote a business model for the IoT based on functionality, including the temporary installation and monitoring of sensors that can be pooled and reinstalled elsewhere after each monitoring sequence.

In many cases, IoT sensors can be installed and monitored for a certain period and then reinstalled elsewhere, as there is no need to keep them once good practices and reflexes are in place. This limits both the energy consumption of IoT devices – since they are pooled and used for a limited time – and the resource consumption and waste generation resulting from device production.

On the other hand, buying IoT-disabled devices instead of the same device designed without IoT on-board components makes no sense.

End-of-life

Limit the number of device and promote e-waste collection in cities to limit pollution at the end-of-life.

In absolute value, the amounts of raw – and in many cases, critical – material resources disseminated around the world are huge, but the amount in each electronic device is tiny[14]. As resources are spread across more and more billions of small devices as a result of the IoT, the challenge of collecting and recycling these components is increasing. But recycling these components is still exceedingly difficult, all the more so when components are alloyed together. Propositions therefore have to be made to regulate and limit the number of devices and, ultimately, the phenomenon of entropy from the most concentrated to numerous smaller components, such as RFID tags (in textiles, books and many other goods).[15]

Move towards complementary networks instead of overlaying networks

Our networks are at a stage of development where over 97% of households in the EU have fixed broadband coverage and average 4G coverage is over 96%[16]. From an environmental point of view, the issue of the superposition of very high-speed networks should be addressed. There is a triple environmental cost in superimposing 5G on fibre and satellite broadband.

The public policy issue is how to complement these networks rather than overlaying them, for example by imagining public Wi-Fi zones in the cities to which smartphones preferentially connect instead of to the mobile network. This is to avoid unnecessarily incurring the costs of three different networks stacked on top of one other with three times as much environmental impact, plus the rebound effect of massive replacement of the terminals to access them when there is a change of generation (which also reduces the lifespan of Internet access boxes and smartphones).

In the meantime, it is necessary to ensure that lower-tech networks, such as 2G, are maintained to guarantee affordable minimum access to everyone, including people using a feature phone, and thus to avoid increasing the digital divide as regards usage.

The benefits of complementing networks instead of overlaying them are manifold: remember that manufacturing equipment accounts for about 40% of the environmental impacts of digital technology in the EU-28.[17] Reducing the number of devices needed for the networks helps lower the overall environmental cost of manufacturing those devices and overall consumption by the network, and to ensure that users are less exposed to electromagnetic waves. It also reduces maintenance and renewal costs.

Bring the cloud to sustainable management maturity

Data centre servers

Identify and reduce zombie servers to below 8%.

At present, the cloud generates a rebound effect because it removes old frictions: it allows easier access to the IT resource. IT managers can extend their IT capacities in a few clicks, while at the other end, hardware is still needed. As IT resources are easily accessible, we forget what our virtual machine (VM) is for, and we let it run for nothing: currently, about 30% of servers are unused[18]. It has been proven that these zombie servers can be efficiently reduced from 30% to 8% within a

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14 See our case studies on the IoT & connected objects, on Raw materials, and on E-waste & circular economy.
15 See our case study on the IoT & connected objects
16 https://digital-strategy.ec.europa.eu/en/library/broadband-coverage-europe-2019 (last retrieved: 10/06/2021)
17 See our LCA study results
18 Jonathan Koomey and Jon Taylor, Zombie/Comatose Servers Redux, 2017; https://www.koomey.com/post/159279936533 (last retrieved: 10/06/2021)

year if an enterprise takes action when presented with evidence of the magnitude of the problem. Eliminating zombie servers can result in considerable capital and operational savings (power, hardware, licenses maintenance, staffing and floor space). It can also improve data centre security since zombie servers are much less likely to have security updates.

Edge computing

Question the need to rely on edge computing and regulate it to ensure it does not contribute to increasing the environmental impacts of ICT.

Today, edge computing is highlighted more and more often to gain few milliseconds of ping. However, although it makes a difference in specific sectors (medicine, finance, autonomous cars), does edge computing generate greater or fewer environmental impacts? Since edge computing runs contrary to the principle of pooling – the same principle which currently allows the largest data centres to be more energy efficient than the smallest – further investigation is required as to its environmental impacts.

When should data centres, which share computing capacity, be preferred to edge computing, and when the other way round? What are the environmental impacts of manufacturing, installing and maintaining numerous countrywide or continent-wide edge computing units? What are the environmental costs and potential rebound effects of overlaying existing data centre capacity, and for what benefits? As this subject was just emerging at the time this report was written, we suggest investigating this matter further in future life cycle assessments.

Marketing-induced uses

Similarly to the GDPR, set up a mandatory "eco" mode on platforms (websites and applications). The aim is to promote freedom of choice for users on their consumption patterns.

This "eco" mode must be accessible to every user without purchase, both on website versions and app versions of the platforms. "Eco" mode must include: prevention of automatic launching of videos, turning off infinite scrolling, turning off data tracking, and on video and audio streaming platforms the ability to play music and videos offline with a local loading option.

The aim of "eco" mode is to limit the rebound effects associated with Internet consumption. Indeed, automatic launching of videos, infinite scrolling, data trackers and online music and video **are used to increase the time users spend on the service**. This is at the expense of user health (mental and physical) and plays on addictive stimulus. As a result, TV and screen use is increasing, leading to more energy consumption. Plus, growing data consumption results in steady or greater energy consumption by data centres (even when taking into account energy efficiency gains, huge as they are)[19], whereas consumption needs to be reduced to comply with the Paris Agreement and the 1.5°C limitation target. Moreover, it incites people to renew their devices more frequently to have the most recent and most powerful iterations, which goes against our first recommendation.

19 See our case study on rebound effects

Our priority #3 recommendations

AI: engage in frugal and sovereign data opportunities

Currently, AI is used mainly to increase digital usage (cross-selling recommendations, item and product proposals). The environmental effects of AI applications are far from carbon-neutral: AI is often coupled with Big Data for machine learning, and deep learning consumes huge amounts of data.[20]

However, as for statistics, when data quality is high, less data is needed to train the AI (machine learning). To attain very high AI accuracy, huge amounts of data are needed for training, which the scientists at Google call "the unreasonable effectiveness of data"[21].

We therefore have to address the question of whether to regulate AI usage with a view to limiting resource consumptions and future shortages of critical resources needed to manufacture hardware.

> Prioritise frugal data and sovereign data investments to ensure the long-term resilience of Europe.
>
> Restrict AI deployment to projects where the overall environmental gain is proven to be greater than the environmental cost by an independent, ISO 14040-44-compliant, multicriteria life cycle assessment.

Low tech[22] should therefore be considered a priority, not in the sense of low tech versus high tech, but to combine them to get the best of both[23] for the benefit of society and within planetary boundaries, in an approach that harnesses both sobriety and efficiency.

Set mandatory environmental conditions of access to the European market for autonomous vehicles

> As part of a broad mobility plan to be assessed at the European scale, including a comparison of all modes of transportation currently possible, lay down mandatory environmental conditions of access to the European market for autonomous vehicles that ensures to avoid rebound effects and promote the most environmentally friendly transportation modes.

The autonomous car is not yet ready to be generalised, and so now is a unique opportunity to ask ourselves how we can ensure that it is not developed at the expense of the climate, planetary resources and, consequently, future generations. The main concern with autonomous cars at this point is that ICT should help fill vehicles to optimise the environmental cost of transport, rather than having vehicles running empty, and to limit potential rebound effects by making this issue part of a large-scale debate to regulate the transition to the mobility of the future. This issue is at the crossroads of digital technology and mobility. In the light of current knowledge,

20 See our case study on artificial intelligence
21 Alon Halevy and Peter Norvig and Fernando Pereira, *The Unreasonable Effectiveness of Data*, 2009
22 See definition of low-tech
23 See the example of use of AI and non-AI detections of cancers in our case study on artificial intelligence

for every environmental benefit autonomous cars might achieve, trains or public transport achieve more[24].

This area is at the border of our expertise and raises questions of mobility policy, public transport incentives and social behaviours. We recommend considering autonomous cars not as a replacement for current cars, but as part of a wider reflection on the mobility of tomorrow on the European scale, and ensuring that the most resilient, efficient and widely accessible transport modes are always promoted and prioritised.

24 See our case study on autonomous vehicles

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