Moore's Law and ICT Innovation in the Anthropocene

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Abstract In information and communication technologies (ICTs), innovation is intrinsically linked to empirical laws of exponential efficiency improvement such as Moore's law. By following these laws, the industry achieved an amazing relative decoupling between the improvement of key performance indicators (KPIs), such as the number of transistors, from physical resource usage such as silicon wafers. Concurrently, digital ICTs came from almost zero greenhouse gas emission (GHG) in the middle of the twentieth century to direct annual carbon footprint of approximately 1400 MT CO2e today. Given the fact that we have to strongly reduce global GHG emissions to limit global warming below 2°C, it is not clear if the simple follow-up of these trends can decrease the direct GHG emissions of the ICT sector on a trajectory compatible with Paris agreement.

In this paper, we analyze the recent evolution of energy and carbon footprints from three ICT activity subsectors: semiconductor manufacturing, wireless Internet access and datacenter usage. By adopting a Kaya-like decomposition in technology affluence and efficiency factors, we find out that the KPI increase failed to reach an absolute decoupling with respect to total energy consumption because the technology affluence increases more than the efficiency. The same conclusion holds for GHG emissions except for datacenters, where recent investment in renewable energy sources lead to an absolute GHG reduction over the last years, despite a moderate energy increase.

We formulate hypotheses for this absence of absolute decoupling from three scientific fields: ecological economics, economics of technology and sociology of technology. We argue that aligning direct GHG emissions of the ICT sector on a trajectory compatible with Paris agreement requires an ecological transition in innovation by adopting sobriety in addition to efficiency.

Keywords *Sustainability, Information and Communication Technologies, Climate Change, Carbon Footprint, Transition.*

1 Introduction

Over the last 200 years, technological innovation has massively contributed in developed countries to the economic growth, the rise in living standards and the increase of life expectancy. On the downside, it fueled the Great Acceleration in the ecological footprint of human activities that led us to the Anthropocene we are evolving in since 1950 [1]. Digital information and communication technologies (ICTs) are no exception to this as they came from almost zero greenhouse gas emission (GHG) in the middle of the twentieth century to annual electricity consumption and GHG emissions of approximately 1400 TWh and 1400 $MTCO_2e$ today, respectively (Table 1). This represents 6-7% and 3.5-4% of the world electricity and carbon footprints, respectively. If these values lead to a consensus across the scientific community, the evolution trends of the ICT energy and carbon footprint are less clear and still explicitly debated.

Table 1: Key studies of the global ICT footprint.

Source	**Reference year**	**Annual energy consumption**‡ **[final TWh]**	**Annual GHG emissions [MTCO$_2$e]**
Ericsson [2]	2010	1500	N/A
Ericsson [2]	2015	1390	1400
GreenIT.fr [3] †	2019	1300	1400
Huawei [4] †	2020	1600	N/A
GeSI [5] †	2020	N/A	1270
GeSI [6] †	2030	N/A	1250
Relative to world footprint (2018) [7]		*6-7%*	*3.5-4%*

† Source published without peer-review.
‡ Considering only operational electricity i.e. consumed by the use of ICT infrastructure and terminals.

In order to limit global average temperature increase close to 1.5°C according to the COP21 Paris agreement on climate change, we need to steadily reduce global GHG emissions by 7.6% a year to reach net zero emissions by 2050 [8, 9]. ICTs are responsible of GHG emissions resulting from the different life-cycle stages of the infrastructure and the terminals. In the infrastructure made up of datacenters and the network, use-phase electricity consumption usually dominates the carbon footprint [2]. For end-user terminals and particularly battery-powered ones such as smartphones, the carbon footprint is dominated by the device production [2, 10–12].

In ICT, a substantial portion of research and innovation efforts is focused on improving efficiency with respect to resource and energy usage. Moore's law related to semiconductor manufacturing is arguably the most iconic trend of exponential efficiency improvement but ICT innovation is full of similar empirical laws. The question we raise in this paper is thus whether the follow-up of these efficiency trends can lead to enough reduction in life-cycle GHG emissions to meet Paris agreement objective in the ICT sector. In this paper, we will refer to these life-cycle emissions as *direct*, in contrast to *indirect* emissions caused by ICT in other activity sectors through e.g induction and rebound effects, usually referred as negative enabling and structural impacts [13]. Let us mention that ICT can also help reducing emissions in other activity sectors through positive enabling and structural impacts such as substitution and optimization [13]. The dynamics behind these higher-order indirect effects is very complex to model and predictions are highly uncertain. In this paper, we thus focus on direct GHG emissions from the ICT sector as a prerequisite for potential studies of global ICT impacts including both direct and indirect emissions.

We start in Section 2 by analyzing the recent evolution of the energy and carbon footprints from three ICT activity sub-sectors: semiconductor manufacturing related to Moore's law, mobile Internet access related to Cooper's law and datacenter usage related to Koomey's law. In Section 3, we then discuss in a more holistic way potential reasons for the observed trend of footprint increase. We finally conclude on the need for an ecological transition in ICT innovation in Section 4. Let us mention here that this work is rather prospective and that more statistical data analysis over longer time periods might be required to confirm the findings and hypotheses we make.

2 Energy/Carbon Footprint Evolution with Empirical Efficiency-Improvement Laws

Efficiency in ICT is usually defined as the ratio between a key performance indicator (KPI) metric, and a cost in terms of physical resource, as illustrated in Table 2. For many of the KPIs in ICT, innovation has led to exponential increase of the efficiency, thereby decoupling the KPI increase over time from the physical resource usage. Exponential efficiency improvement can be measured by its positive *compound annual growth rate* (CAGR) in %, or in an equivalent negative CAGR for the resource *intensity* (mathematical inverse of the efficiency). Historically, these trends have been empirically observed by influential engineers and laws were named after them by the community. These laws are emblematic of the technological progress in ICT and have shaped roadmaps for decades [14], enabled by the cleverness of engineers and the cooperation between companies, research institutes and academia.

Table 2: Empirical efficiency-improvement laws studied in this work

Law	**KPI metric**	**Physical resource**	**Efficiency CAGR**	**Intensity CAGR**
Moore	Transistors	Silicon wafer	+41%	-29%
Cooper	Datarate	RF spectrum	+32%	-24%
Koomey	Computations	Electrical energy	+59%	-37%

Energy gives us the ability to transform our environment and to turn physical resources into ICT KPI units such as transistors. Producing KPI units in ICT thus leads to GHG emissions due to energy consumption. Therefore, the achieved decoupling between the KPI unit increase and the physical resource usage leads to a *relative decoupling* from GHG emissions: thanks to efficiency improvement, the KPI units increase faster than the GHG emissions. However, it is not clear if the direct GHG emissions of the ICT sector, i.e. its carbon footprint, can be decreased while KPI units keep on increasing, which would result in an *absolute decoupling.* Let us examine the possibility of this absolute decoupling for the ICT activity sub-sectors associated to the laws from Table 2.

2.1 Methodology

In order to analyze the evolution of the ICT carbon footprint, we adopt a decomposition in several factors inspired by the Kaya identity. In the decomposition, we chose to disconnect from economic value factors to focus the analysis on physical resources [15]. The footprint measured in annual GHG emissions is expressed as a product between *population*, *technology affluence*, *energy intensity* and *carbon intensity* as shown in Figure 1(a). Population refers to the number of users of the technology, estimated by the number of people with Internet access [16]. Affluence reflects the degree of the technology adoption by the users measured in terms of KPI unit consumed per user on an annual basis. Energy intensity shows how much energy is needed for the production of one KPI unit. This is where efficiency laws have their direct impact. Finally, carbon intensity indicates the amount of GHG emitted for one kWh of energy consumed, for which we consider a global average by default. We combine historical data with exponential regression and scientific studies to obtain the annual evolution in terms of CAGR for each factor.

Let us mention here that Kaya identity has been discussed by the scientific community and by the IPCC itself for its limitations. Indeed, the individual terms can have inter-dependencies through e.g. rebound effects. Moreover, it hardly captures heterogeneous trends when large geographical regions are considered. However, it can help to understand the underlying factors that contribute to the evolution of GHG emissions.

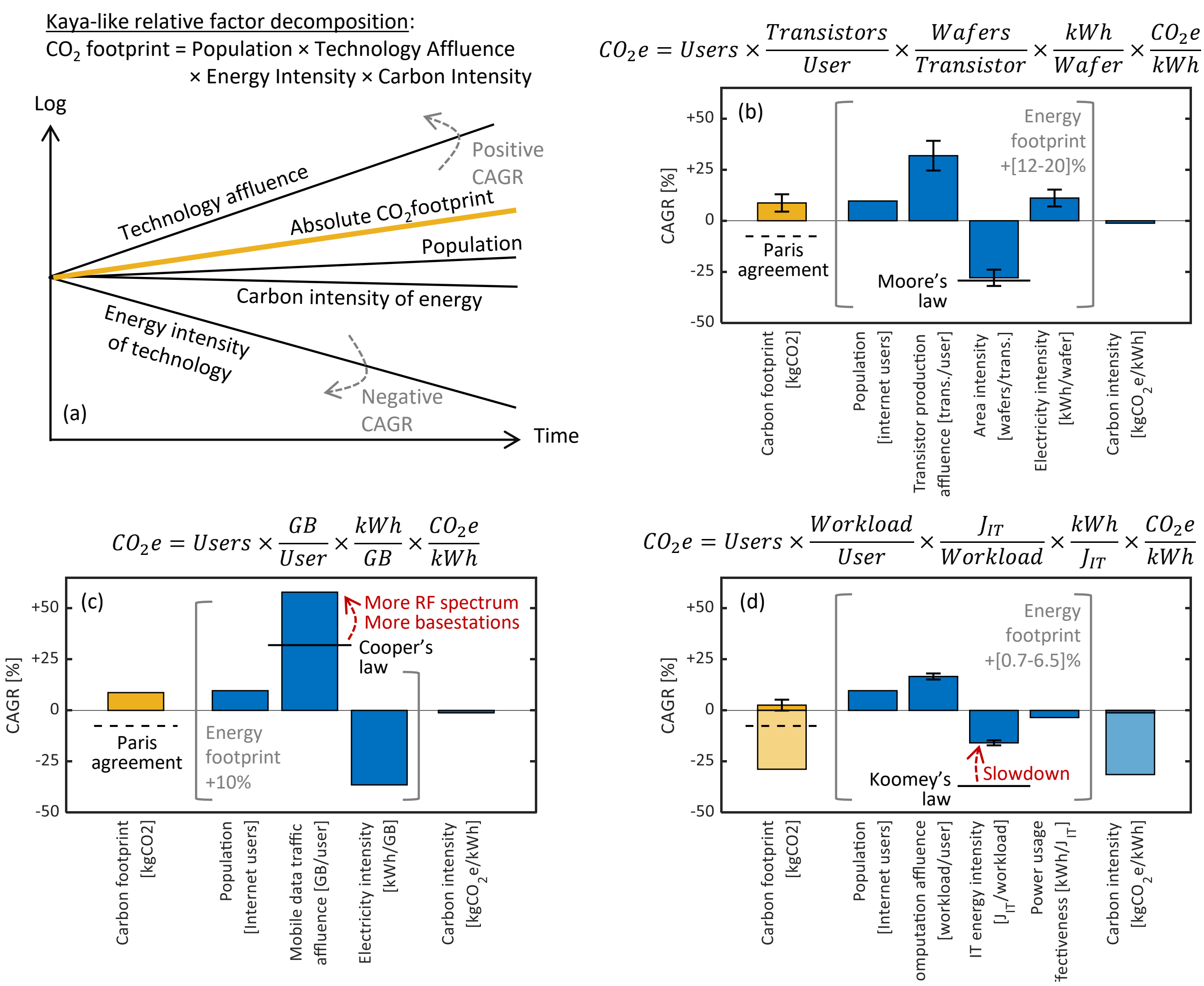

Figure 1: Annual evolution of direct GHG emissions of ICT sub-sectors: (a) Principle of Kaya-like decomposition in intensity factors (b) Semiconductor manufacturing (2004-2019), (c) Mobile Internet access (2010-2015) and (d) Datacenter usage (2010-2018). Light-color bars illustrate the low-carbon intensity for specific providers with strong commitment to net carbon-free objectives. Energy footprint brackets indicate the CAGR related to total energy in kWh, which is positive for all sub-sectors. Paris agreement dashed line indicates the CAGR (-7.6%) that should be achieved to be in-line with GHG reduction targets to limit global warming close to 1.5°C. Data sources are provided in the text.

2.2 Moore's law in semiconductor manufacturing

In life-cycle assessment studies of ICT terminals, the production of integrated circuits (ICs) is usually reported as the dominant source of the *embodied* energy consumption and GHG emissions (i.e. related to the production phase of the life cycle) [2, 11, 12]. Originally, Moore's law extrapolated the constant doubling of the number of transistors per wafer every 18-24 months enabled by CMOS technology downscaling. This results in a cost reduction per transistor, which is the driving force behind Moore's law and arguably the main reason for the increase in IC complexity and functionality. In the recent years however, concerns about a slowdown of Moore's law have been widely discussed due to the fact that transistor dimensions are getting closer to the theoretical physical bound i.e. the size of the atom size.

Over the 2004-2019 period, shipment statistics by major stakeholders of the semiconductor manufacturing industry show a steady CAGR around 4% for the total area of silicon wafers produced annually [17]. The electrical energy consumption of wafer production has been evaluated by Boyd on logic CMOS technology nodes from 90nm to 32nm [18] and by Garcia from 28nm to 5nm [19], with an estimated CAGR between 7 and 15.2% (equipment and facility considered). Finally, the area intensity varies slighly between foundries with respect to the exact CAGR.

As shown in Fig. 1(b), the affluence increase, measured by the number of transistors per user, has been primarily enabled by Moore's law. However, the growth of wafer production indicates an additional affluence increase from a growing global ICT device production (more terminals). This production also appears to rise faster than the number of users, resulting in an increased consumption of physical resources per person. On top of that, the higher complexity of manufacturing processes due to smaller transistors explains the reported increase of production energy per wafer. Indeed, the higher CAGR for 28-5nm nodes [19] than for 90-32nm nodes confirms the escalating complexity also reflected by the increasing costs of wafer production [14]. Globally, we estimate that the total energy footprint of semiconductor production has increased annually by 12-20%.

2.3 Cooper's law in mobile Internet access

Mobile data communication has become a significant part of the global Internet traffic over the last decade. Reliable wireless data transfer requires that the available RF spectrum is shared among users in a single location. Thanks to innovation in e.g. digital modulation or adaptive antenna arrays, more bits can be transmitted per second per MHz of RF spectrum bandwidth. In the early 2000s, Cooper observed that the rate of data that can be communicated simultaneously over the useful spectrum in a given area doubled every 30 months, which has since then been referred as Cooper's law.

As reported by Cisco [20], the worldwide mobile Internet traffic has soared with an annual growth rate of 73% between 2010 and 2015, which corresponds to the introduction of 4G communications. The energy and carbon footprint associated to this mobile data traffic is dominated by use-phase electricity consumption and was estimated by Malmodin *et al.* with respective CAGRs of 10% and 8.7% for this period [2].

As shown in Fig. 1(c), the increase in mobile data traffic can be attributed mostly to the increasing data consumption per user, and only for some part to a larger number of people using the Internet [16]. The more efficient utilization of the spectrum reflected in Cooper's law is not sufficient to explain alone the surge of data rate over this period. This suggests that other means were introduced to sustain the traffic increase such as the deployment of more basestations. New communication technologies also tend to use a wider RF spectrum, now targeting the millimeter-wave frequency range for 5G. While energy efficiency increases with communication technology generations, it does not compensate the increased traffic affluence so that the global footprint has increased.

2.4 Koomey's law in datacenter usage

Life-cycle assessment studies of data centers show that their main impact originates from the energy consumption during the use phase [2]. The energy efficiency, i.e. the amount of operations performed with one unit of energy consumed by the IT equipment (J_{IT}), has seen a continuous improvement over 70 years thanks to technological innovation. Koomey's law states that energy efficiency of computing devices doubles every 1.5 years, as he observed from 1946 to 2009 [21].

Recent studies [2, 22] show that despite a significant growth in compute workloads from 2010 to 2018, worldwide datacenter energy has only slightly increased over the past ten years, with a CAGR about 0.7% [22]. However, other studies following a similar approach obtained higher estimates around 6.5% per year [23], mainly due to different assumptions for affluence and the evolution of modeling parameters e.g. hyperscale share, power usage effectiveness (PUE) and maximum power consumption of servers at full load. Regarding the carbon footprint, main datacenter providers such as Google have shown strong commitment for sourcing low-carbon electricity and reported carbon intensity reductions [24].

The data from Masanet *et al.* indicates that, while energy efficiency improvements were significant, they were much slower than expected from Koomey's law [22]. This observation is also confirmed at the equipment level, for example with the SPEC-benchmark measurement data that shows energy efficiency improving at a slower pace from around 2012 [25]. This change could be attributed to *i)* the slowdown of supply voltage scaling below $0.13\mu m$ CMOS technology node (2000) and to *ii)* the bottleneck of storage access and multiprocessor architecture induced by the switch from traditional datacenters to hyperscale. As shown in Fig. 1(d), it is thus the combination of limited technology affluence increase and average energy efficiency improvement that curbed the total energy footprint. Combined with the use of low-carbon energy, this enabled a large cut in the global carbon footprint. However, much of the low-carbon energy used by datacenters is obtained by purchasing it on the electricity market [24] rather than by directly producing it. The resulting reduction in GHG emissions at the global scale can be debated as discussed next.

3 Discussion: hypotheses for the cause of the observed carbon footprint increase

From the analysis in Section 2, we conclude that for the ICT activity sub-sectors we analyzed, the efficiency improvement has not been able so far to compensate the increase in affluence, which leads to an increase of the energy footprint. Reduction in carbon footprint is thus only possible by sourcing low-carbon energy. In this section, we formulate hypotheses to explain the observed energy footprint increase.

3.1 Ecological economics: the impossibility of green growth

Green growth i.e. the absolute decoupling of the economic growth (measured in terms of Gross Domestic Product GDP) from resource usage including fossil fuels and thus GHG emissions has been the Holy Grail for mainstream economists. Although examples exist of global relative decoupling or local absolute decoupling [26, 27], recent works in ecological economy point out that there is no empirical evidence of sustained absolute decoupling at the global scale [28]. Ecological economists agree on the low probability of combining significant GDP growth with a GHG reduction rate in line with Paris agreement [28, 29]. Considering that increasing the KPI is a central way to generate economic value in ICT, our first hypothesis to explain the footprint increase is the impossibility of absolute economic decoupling from energy consumption and GHG emissions. Over the observed period, the global revenue of the semiconductor industry have been steadily increasing with 5-10% CAGR [30]. Using this revenue as a proxy for the sector added value, the energy/carbon footprint increase for the semiconductor manufacturing thus indicates an absence of economic decoupling, be it relative. The case is even worse for the telecom industry providing mobile Internet access with rising footprint and stable global revenue [31].

The datacenter sub-sector is a very interesting case. The sector added value increased with a 5-10% CAGR for 2010-2018, which indicates a relative decoupling from the limited increase in energy footprint observed in Section 2.4, in contrast to the period before 2010 where the energy footprint was steadily increasing [2, 22]. The conditions for the limited energy footprint increase are both the energy efficiency improvement and the limited affluence increase. For the carbon footprint, an absolute decoupling is claimed by datacenter operators who shifted from fossil-fuel carbon-intensive energy sources to low-carbon renewable sources. This is the typical green-growth study case for which we have to be cautious. Indeed, when low-carbon energy is purchased on the energy market, the impact on the global carbon footprint depends on market conditions [32]. If we assume that this market is perfect (enough competition, offer-demand equilibrium, full information, integration of externalities, no physical limitation), the purchase of low-carbon energy at the market price will increase the demand and the market will respond by increasing the offer, thereby effectively reducing the use of fossil energy. However, if we consider a non ideal market which is likely to be the reality, the low-carbon energy purchased by datacenter operators may no longer be available for other sectors. In this case, the decoupling remains local and limited GHG reduction is achieved at the global scale because the energy footprint is not decreasing. The renewable energy market conditions is an open debate, which suggests that economic decoupling should be studied at the global scale. Let us mention that a fair evaluation of the economic decoupling should include both the indirect GDP and GHG emissions of the digital services that use the ICT infrastructure, in addition to the direct ICT GDP and GHG emissions. This reinforces the need to study economic decoupling at the global scale.

3.2 Economics of technology: escalating NRE costs

We propose a second hypothesis based on technology/economy interaction. Theoretical physical bounds exists on the efficiency metrics studied in this paper: transistor downscaling is limited by the size of the atom, computational energy efficiency is bounded by Landauer's limit [33], and spectral efficiency is bounded by Shannon's limit [34]. With the exponential efficiency improvement, technology is getting closer to these limits. As a result, further progress in efficiency becomes increasingly more complex, requiring more research and innovation. The associated non recurring engineering (NRE) costs including innovation investments thus increase with technology evolution. This is very clear for CMOS technology scaling since 2000 [14] and is an important factor for Moore's law slowdown. The massive investment in the development of 5G communications is another good example.

Return on these increasing investments could be generated by increasing the selling price of the physical resource for the consumer (e.g. a 10-mm^2 chip or a wireless Internet access subscription), justified by its higher KPI. This practice is not dominant in ICT and return on investment (RoI) are rather generated by increasing the production volume of this physical resource (e.g. sell more chips) [14]. This increases technology affluence and thus the footprint. Let us highlight here two detrimental yet common practices to increase affluence in ICT. First, obsolescence generation is everywhere in the ICT sector with high replacement rates especially for consumer terminals as smartphones. Second, the creation of artificial needs seems to be a modern trend with examples such as 4K video streaming for smartphones or the whole scope of futile IoT applications coined as the *Internet-of-Shit* (IoS).

3.3 Sociology of technology: speculative faith in technology

The human faith in the social benefits brought by technological progress has long been around and pre-exists the age of digital ICT [35]. However, our third hypothesis is that the advent of financial economy in the mid-1970 has instrumentalized this faith in technology to become speculative and that it has unconsciously impacted the innovation habits of engineers and researchers. To develop this hypothesis we need to first expose some economics background.

Financial economy is the component of the economic system where big companies compete to attract capitals through the stock exchange by promising higher growth for the stock value than their competitors [36, 37]. There is a debate amongst economists on the actual correlation between the capacity of companies to attract capitals in the financial economy and their capacity to generate profits in the *real economy* [38]. However, beyond this debate, the impact of the finance drive on the economic system is profound in a way that it tends to shift the capitalist economic target from profit generation to speculative value creation for the stockholders [36, 37]. In such a speculative capitalism, the faith in the future increase of the stock value is the key to accept the present debts from the invested capital.

In his work, Gomez defines several speculative practices for companies to promise future stock value increase [39]. In our interpretation, two of these speculative practices have led to mimetic unconscious innovation habits for ICT engineers: 1) the continuous reporting of financial ratios (indicators) and 2) the central role of technological innovation for "creating the future by disrupting the present". Firstly, the focus on financial ratios as strategic company targets has led to the *spreadsheet company* concept where a significant portion of human and computing resources in the company are focused on reporting various types of operation and management indicators in a hierarchical way [40]. It is hard to overlook a potential alignment between the financial target of increasing the stock value and the technological target of increasing the KPIs, supported by the empirical efficiency-improvement laws discussed in Section 2. We thus define *KPI-driven innovation* as the blind habit for ICT engineers and companies to pursue the increase of any KPI such as number of CPU cores, number of artificial neurons, number of pixels in a CMOS imager, number of imagers in a smartphone, with the unconscious faith that it will lead to future valorization. Secondly, disruption of the present by technological innovation is a key speculative practice to invent a future that is supposed to "change everything" and absorb the debts of the present [39]. When the objective of disrupting the presence becomes the sole goal of innovation, we are left with race for innovation. *Buzzword-driven innovation* is the blind habit for ICT engineers that consists in orienting their daily work towards (or in integrating in their daily work ingredients from) hype technological concepts such as AI, Blockchain, IoT, Big Data, Neuromorphic, Quantum Computing, SWIPT with the same faith that the disruption of the present will bring future valorization. Although these technological concepts may find future real-life applications, this is only a hope at the moment of innovation. In such KPI/buzzword-driven conditions for innovation, the faith in future social and economic benefits brought by technological progress becomes speculative.

KPI-driven and *buzzword-driven innovation* have detrimental ecological consequences. Indeed, as ICTs also participate to the real economy, RoI needs to be generated at some point by increasing the ICT affluence, which in turn increases their footprint. Footprint reduction is thus not reached simply because ICT innovation is focused on KPI increase and buzzwords, which detours it from footprint reduction.

4 Conclusion: the Need for an Ecological Transition in ICT Innovation

The progressive deployment of digital ICTs for the last 50 years have led to some undeniable economic, social and indirect ecological progresses that may justify its direct ecological footprint, which is still moderate today. However, we are now in a socio-technical lock-in situation where our society strongly depends on digital ICT and where digitalization of the world is a new de facto human target. It is not clear if this is aligned with the context that we are facing today i.e. climate change and environmental emergency, which calls for rapid reduction of energy and carbon footprints. Several strategies could be leveraged to reach this objective but the one that is usually put forward is energy-efficiency improvements, especially in the ICT community where innovation and optimization play such an important role. The question we raised in this paper is whether the follow-up of these efficiency-improvement trends can lead to enough reduction in GHG emissions to meet Paris agreement objective for the ICT sector.

By analyzing the trends in three ICT activity sub-sectors, this study reveals that efficiency improvements tend to be systematically absorbed and overwhelmed by the increasing technology affluence. We explained this by the impossibility of sustained green growth at the global scale, the need to generate RoI for the escalating innovation costs and the speculative KPI/buzzword-driven innovation habits in ICT. Despite huge energy efficiency improvements over the last decades, global ICT energy and carbon footprints are still on the rise. Efficiency improvement thus *cannot be* the only ecological target as it is used to generate economic profit rather than used for global footprint reductions. This is reinforced in the context of growth policies which amplify rebound effects [41, 42].

Similar conclusions are drawn in other sectors: in transportation, Walnum identifies mobility affluence reduction as a necessary strategy for sustained footprint reduction [41]. Sobriety *both* in ICT usage and innovation must thus be combined with energy efficiency in an ecological transition to tackle the environmental challenges. More fundamentally, we argue that innovation should not serve the increasing ICT affluence that fuel an unbridled economic growth, often disconnected from the limits of our planet. If we accept to curb affluence, the ICT footprint could be quickly slashed thanks to the amazing innovation capability of ICT actors. Technology is not neutral and innovation has socio-ecological impacts as it contributes to shape the future of our society. We thus call ICT companies and engineers to consider a wider picture and rethink their roadmaps to support this necessary transition.

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