The Sustainability Gap for Computing

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***Abstract*—Computing is responsible for a significant and growing fraction of the world's global carbon footprint. Combating climate change and preserving sustainability in general is a grand challenge. This paper describes the sustainability gap for computing as a result of the socio-economic context (population and affluence growth) versus technology: the status quo in which we keep per-device carbon footprint constant would lead to a 5.4× gap relative to the Paris agreement within a decade. Meeting the Paris agreement for computing requires reducing the per-device carbon footprint by 15.5% per year under current population and affluence growth curves. Based on a select number of published carbon footprint reports, it appears that while (some) vendors indeed reduce the carbon footprint for (some) of their products, it does not seem to be enough to close the gap, urging our community to do more.**

I. INTRODUCTION

Sustainability is undeniably a grand challenge. As the world population and the average affluence per person continues to grow, we are eagerly consuming the earth's natural resources. The *earth overshoot day* marks the date when the demand for ecological resources by humankind in a given year exceeds what the earth can regenerate in a year. While the world's earth overshoot day was end of December in the early 1970s, it has progressively antedated since then, and was computed to be August 2 in 2023. The overshoot day is (much) earlier for many countries, e.g., March 14 for the US, March 15 for Canada, April-May for most European countries as well as South Korea, Australia, Japan, Israel.[1]

The continuously growing consumption of earth resources including materials and energy sources (inevitably) induces climate change. Greenhouse gas (GHG) emissions are detrimental to global warming, and a recent study reports that the contribution of information and communication technology (ICT) to the world's global GHG emissions, currently between 2.1 and 3.9% [9], is growing at rapid pace. While this percentage may seem small, it is not: in fact, ICT's contribution to global warming is on par with (or even larger than) the aviation industry which is estimated to be around 2%.[2]

To combat global warming, the Paris agreement under the United Nations (UN) auspices aims at limiting global warming to well below 2, and preferably to 1.5, degrees Celsius, compared to pre-industrial levels. In 2019, the UN stated that we need to cut global emissions by 7.6% each year over the next decade to meet the Paris agreement.[3] More recently in November 2023, the UN states that insufficient progress is being made to combat climate change.[4]

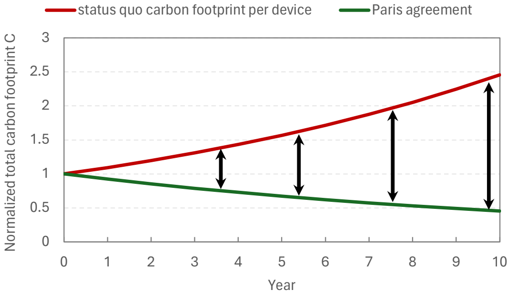

Fig. 1: The sustainability gap for computing.

Given the pressing need to act along with the significant and growing contribution of computer systems to global warming, it is imperative that we, computer system engineers, should ask ourselves the question what we can do to reduce the environmental footprint of computing. To do so, this paper reformulates the well-known IPAT model such that we can reason about the three contributing factors. This includes (1) population growth, (2) increased affluence or number of computing devices per person, and (3) carbon footprint per device over its entire lifetime, which includes the so-called embodied footprint for manufacturing, assembly, transportation and end-of-life processing, and the operational footprint due to device usage during its lifetime [11].

The growth in population and affluence leads to a growing *sustainability gap* as illustrated in Figure 1. If we were to keep the carbon footprint per device constant relative to present time, the total carbon footprint due to ICT would still increase by 9.4% per year leading to a 2.45× increase in GHG emissions over a decade. In contrast, meeting the Paris agreement requires that we reduce GHG emissions by a factor 2.2×. Bridging this widening sustainability gap between the per-device status quo and the Paris agreement requires that we reduce the carbon footprint per device by 15.5% per year or by factor 5.4× over a 10-year time period.

Analyzing the carbon footprint for a select number of computing devices (smartphones, watches, and desktops) reveals that (at least some) vendors do pay attention to sustainability, however, the reduction in per-device carbon footprint achieved in recent years appears to be insufficient to close the sustainability gap. Furthermore, despite the urgency of the problem, not all vendors publish carbon footprint reports for all their devices, resulting in an incomplete view on the significance of the problem and the challenges ahead. The overall conclusion

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[1] https://overshoot.footprintnetwork.org/newsroom/country-overshoot-days/

[2] https://www.iea.org/energy-system/transport/aviation

[3] https://unfccc.int/news/cut-global-emissions-by-76-percent-every-year-for-next-decade-to-meet-15degc-paris-target-un-report

[4] https://unfccc.int/news/new-analysis-of-national-climate-plans-insufficient-progress-made-cop28-must-set-stage-for-immediate

is that a concerted effort is needed to significantly reduce both the demand for computing devices *and* at the same time reduce the carbon footprint per device at a sustained rate for the foreseeable future.

II. BACKGROUND

IPAT is the acronym of a well-known and widely used equation which quantifies the *impact* I of human activity on the environment as follows:

$$I = P \times A \times T. \tag{1}$$

P stands for *population* (i.e., the number of people on earth); A accounts for the *affluence* per person or the average consumption per person; and T quantifies the impact of the *technology* on the environment per unit of consumption. The impact on the environment can be measured along a number of dimensions including the natural resources and materials used (some of which may be critical and scarce); greenhouse gases (GHG) emissions during the production, use and transportation of products; pollution of ecosystems and its impact on biodiversity; etc. The IPAT equation is used as a basis by the United Nations' Intergovernmental Panel for Climate Change (IPCC) in their annual reports.

The IPAT equation has been criticized for being too simplistic by assuming that the different variables in the equation are independent of each other. Indeed, in contrast to what the above formula may suggest, improving one of the variables does not necessarily lead to a corresponding reduction in overall impact. For example, reducing T in the IPAT model by 50% through innovations that reduce the environmental impact per product, does not necessarily reduce the overall environmental impact I by 50%. The fundamental reason is that a technological efficiency improvement typically leads to a price reduction, which in turn stimulates additional consumption of the resource that was supposed to be conserved. The end result may be an overall increase in impact rather than a reduction. This is the well-known *rebound effect* or *Jevons' paradox*, named after the English economist Williams Stanley Jevons who was the first to report the rebound effect as a result of improving the coal efficiency of the steam engine, which led to an overall increase in coal consumption [2].

The rebound effect can be (partly) accounted for in the IPAT model by expressing each of the variables as a *Compound Annual Growth Rate (CAGR)*, defined as follows:

$$\mathit{CAGR} = \left(\frac{V_t}{V_0}\right)^{1/t} - 1, \tag{2}$$

with V_0 the variable's value at year 0 and V_t its value at year t. The IPAT model can be expressed using CAGRs for the respective variables:

$$\mathit{CAGR}_{\mathit{overall}} = \prod_{i=1}^{N} (\mathit{CAGR}_i + 1) - 1. \tag{3}$$

This reformulation allows for computing the annual growth rate in overall environmental impact or GHG emissions as a function of the growth rates of the individual contributing factors. If the growth rates incorporate the rebound effect, i.e., higher consumption rate as a result of higher technological efficiency, the model is able to make an educated guess about the expected growth rate in environmental impact [3].

Region	**2018**	**2023**	**CAGR**
Global	2.4	3.6	8.4%
Asia Pacific	2.1	3.1	8.1%
Central and Eastern Europe	2.5	4.0	9.9%
Latin America	2.2	3.1	7.1%
Middle East and Africa	1.1	1.5	6.4%
North America	8.2	13.4	10.3%
Western Europe	5.6	9.4	10.9%

TABLE I: Number of connected devices per capita [6].

III. THE ENVIRONMENTAL IMPACT OF COMPUTING

We now reformulate the IPAT equation such that it provides insight for computer system engineers to reason about the environmental impact of computing. We do so while focusing on GHG emissions encompassing the whole life cycle of electronic devices. The total GHG emissions by all electronic devices on earth C can be expressed as follows:

$$C = P \times \frac{D}{P} \times \frac{C}{D}. \tag{4}$$

P is the world's global population. D/P is a measure for affluence in the IPAT equation, and quantifies the number of electronic devices per capita on earth. C/D is a measure for technology, or T in the IPAT model, and corresponds to the total carbon footprint per device. Note that C/D includes the whole life cycle of an electronic device, from raw material extraction, to manufacturing, assembly, transportation, usage, end-of-life processing.

We now discuss how the different factors P, D/P and C/D in the above equation, scale over time. The world population P has grown from 1 billion in 1800 to 8 billion in 2022. The United Nations (UN) expects the world population to reach 9.7 billion in 2050 and possibly reach its peak at nearly 10.4 billion in the mid 2080s.[5] The world population annual growth rate was the largest around 1963 with a $\mathit{CAGR}_P = 2.1\%$. Since then the growth rate has reduced to around $\mathit{CAGR}_P = 0.9\%$ according to the World Bank.[6]

The number of devices per person D/P increases at a fairly sharp rate [6], see Table I. On average across the globe, the number of connected devices per capita increased from 2.4 in 2018 to 3.6 in 2023, or $\mathit{CAGR}_{D/P} = 8.4\%$. In the western world, i.e., North America and Western Europe, the number of devices per person is not only a factor 2 to 4× larger than the world average, it also increases much faster with a $\mathit{CAGR}_{D/P}$ above 10%. The increase in the number of devices is in line with the annual increase in integrated circuits, i.e., estimated $\mathit{CAGR} = 10.2\%$ according to the 2022 McClean report from IC Insights [14].

The carbon footprint per device C/D is harder to quantify because of inherent data uncertainty. The carbon footprint of a device depends on many factors including what materials

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[5] https://www.un.org/en/global-issues/population

[6] https://ourworldindata.org/population-growth

are used, how these materials are extracted, how the various components of a device are manufactured and assembled, how energy efficient the device is, the lifetime of the device, how much transportation is involved, how end-of-life processing is handled, etc. Despite the large degree of uncertainty, it is instructive and useful to analyze Life Cycle Assessment (LCA) or Product Carbon Footprint (PCF) reports that quantify the environmental footprint of a device. All LCA and PCF reports acknowledge the degree of data uncertainty. Nevertheless, these reports provide invaluable information for consumers to assess the environmental footprint of devices. Unfortunately, not all companies publish LCA or PCF reports, and if they do, they do not necessarily publish reports for all their products.

IV. QUANTIFYING THE SUSTAINABILITY GAP

It is instructive to assess how the per-device carbon footprint affects the overall carbon footprint of computing. If we were to keep the carbon footprint per device constant relative to today, i.e., $CAGR_{C/D} = 0\%$, the total carbon footprint would still increase by $CAGR_C = 9.4\%$ per year. This is simply a consequence of the growing population and the increasing affluence or number of computing devices per person. Because this is an exponential growth curve, this implies that the total carbon footprint of computing would increase by a factor 2.45× over a decade. In other words, even if we keep the carbon footprint per device constant, the total carbon footprint of computing would still dramatically increase.

If we want to keep the overall carbon footprint of computing constant relative to present time, i.e., $CAGR_C = 0\%$, we need to reduce the carbon footprint per device by $CAGR_{C/D} = -9.4\%$ per year. This is simply to counter the increase in population and number of devices per person. Reducing the carbon footprint per device by 9.4% year after year for a full decade is a non-trivial endeavor. To illustrate how challenging this, consider a device that incurs a carbon footprint of 100 kg CO2eq. Reducing by 9.4% per year requires that the carbon footprint is reduced to 37.3 kg CO2eq within a decade, or in other words, the carbon footprint needs to reduce by more than a factor 2.6× over a period of 10 years.

To make things even more challenging, to meet the Paris agreement, we need to reduce the global GHG emissions by a factor 2.2× over a decade or by 7.6% per year, i.e., $CAGR_C = -7.6\%$. To achieve this, we would need to reduce the carbon footprint per device by 15.5% per year, i.e., $CAGR_{C/D} = -15.5\%$. This implies that we need reduce the carbon footprint per device by a factor 5.4× over a decade!

Figure 1 illustrates the widening *sustainability gap* between the status quo per-device carbon footprint ($CAGR_{C/D} = 0\%$) leading to a 2.45× increase in overall carbon footprint over a 10-year time period, versus meeting the Paris agreement ($CAGR_{C/D} = -15.5\%$) leading to a 2.2× reduction in total carbon emissions. It is clear that bridging the sustainability gap is a non-trivial and challenging endeavor, which will require significant innovation in how we design computing devices.

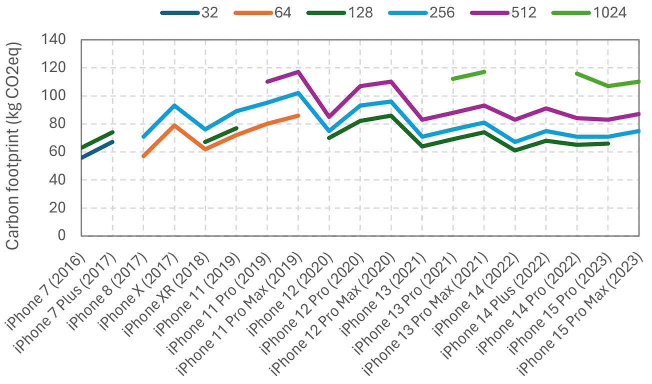

Fig. 2: Carbon footprint for Apple iPhones with different SSD capacities (GB), see the legend.

Note that the above assumes that the world population and the number of devices per person continues to grow at current pace. The task of decreasing the carbon footprint per device by 15.5% per year can be loosened to some extent by embracing a certain level of sobriety, i.e., limiting the number of devices per person. This is hard to achieve though in a linear economy that is driven by maximizing profit by selling devices. Some form of regulation, legislation and/or new business models may be needed to incentivize manufacturers to rely less on selling goods to generate revenue. Likewise, customers would need to take responsibility and buy fewer devices. This could possibly be achieved through a service-oriented business model in which devices are reused, repurposed or remanufactured to reduce the overall demand for new devices such that our computer industry can still thrive and generate welfare.

V. CASE STUDIES

Having discussed how the overall carbon footprint of computing scales, we now discuss a couple concrete cases to get a sense of how the current industry is addressing the sustainability gap. As mentioned above, closing the sustainability gap requires reducing the carbon footprint per device at a $CAGR_{C/D} = -15.5\%$. Keeping total carbon footprint constant relative ro present time would require a reduction in carbon footprint per device at $CAGR_{C/D} = -9.4\%$. Because there is no data available about the carbon footprint of all electronic devices, we consider a selection of devices for which vendors, i.e., Apple[7] and Dell[8], do publish LCA reports.

A. *Smartphones*

The first case study considers Apple iPhones starting with iPhone 7 (release date in 2016) till iPhone 15 Pro Max (release date in 2023). Figure 2 illustrates the total carbon footprint per device with different SSD capacity. It is interesting to note that the carbon footprint per device has generally increased from 2016 till around 2019, while it decreases in more recent years. For example, from iPhone 7 (2016) to iPhone 11 (2019) with 128 GB SSD, the carbon footprint has increased from 63 to 77 kg CO2eq ($CAGR_{C/D} = 6.9\%$); likewise, from iPhone 8 (2017) to iPhone 11 Pro Max (2019) with 256 GB SDD,

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[7] https://www.apple.com/environment/

[8] https://www.dell.com/en-us/dt/corporate/social-impact/advancing-sustainability/climate-action/product-carbon-footprints.htm

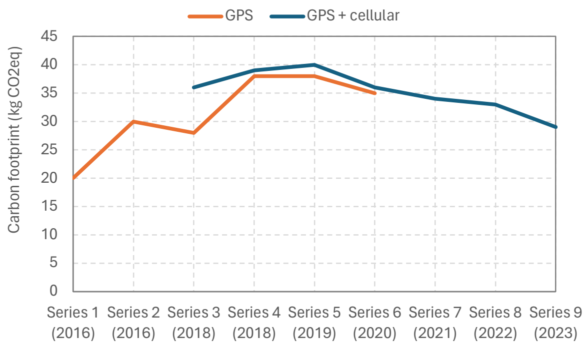
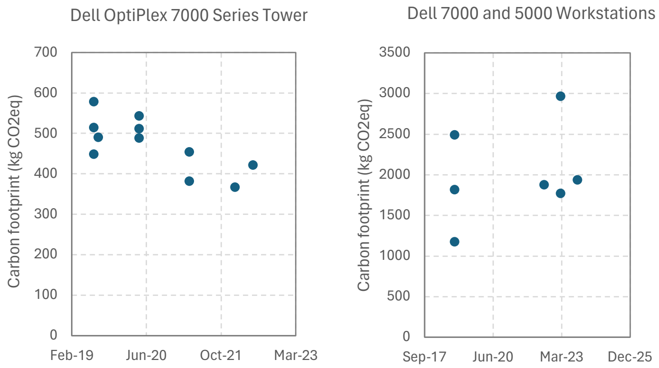


Fig. 3: Carbon footprint for Apple Watches.


Dell OptiPlex 7000 Series Tower

Dell 7000 and 5000 Workstations

Fig. 4: Carbon footprint for Dell desktops and workstations.

the carbon footprint has increased from 71 to 102 kg CO2eq ($CAGR_{C/D} = 19.8\%$). From 2019 onward, we note a decrease in carbon footprint per device. For example, from iPhone 11 Pro (2019) to iPhone 15 Pro (2023) with 256 GB SSD, the carbon footprint has decreased from 95 to 71 kg CO2eq ($CAGR_{C/D} = -7.0\%$); likewise, from iPhone 11 Pro Max (2019) to iPhone 15 Pro Max (2023) with 512 GB SDD, the carbon footprint has decreased from 117 to 87 kg CO2eq ($CAGR_{C/D} = -7.1\%$). This analysis illustrates that Apple has been steadily decreasing the carbon footprint per device in recent years since 2019. Note though that the annual decrease has slowed down in the most recent years: for example, from iPhone 13 Pro Max (2021) to iPhone 15 Pro Max (2023) with 512 GB SSD, the carbon footprint has decreased from 93 to 87 kg CO2eq ($CAGR_{C/D} = -3.3\%$).

B. Smart watches

Figure 3 quantifies the carbon footprint for different generations of Apple Watches with similar capabilities (GPS versus GPS plus cellular) and sport band. All watches are aluminium case (42 mm in Series 1 to 3, 44 mm in Series 4 to 6, and 45 mm in Series 7 and 8) or stainless (Series 9). It is interesting to note that also here, the carbon footprint has increased from 2016 (Series 1) till 2019 (Series 5), i.e., $CAGR_{C/D} = 23.9\%$ for the GPS watches. The carbon footprint has decreases from 2019 (Series 5) till 2023 (Series 9), i.e., $CAGR_{C/D} = -7.7\%$ for the GPS-plus-cellular watches.

C. Desktops and Workstations

Figure 4 reports the carbon footprint for Dell OptiPlex 700 Series Tower desktop machines (left) and Dell Workstations 5000 and 7000 Series (right). Based on the limited amount of available data, the carbon footprint per desktop decreases at a rate of $CAGR_{C/D} = -8.1\%$, while the carbon footprint per workstation increases at a rate of $CAGR_{C/D} = 4.0\%$.

VI. DISCUSSION

While it is hard to reach precise conclusions based on a limited case studies and imprecise data, there are a couple observations we can make. First, vendors do pay attention to sustainability since recent years, as reflected in a decreasing carbon footprint per device for several of the above case studies. Second, despite these efforts, it seems that the reduction in carbon footprint per device is not high enough to fully close the sustainability gap. The reported CAGRs do not reach the required -15.5% (to meet the Paris agreement) nor -9.4% (to keep total carbon footprint constant relative to present time) annual growth rates. Third, vendors should be encouraged to publish LCA reports for all of their products. The above case studies illustrate a couple vendors for a limited number of devices — many more vendors need to publish LCA reports for all of their devices to obtain a more complete and comprehensive view on the carbon footprint across the entire computing spectrum from the smallest Internet-of-Things (IoT) devices to the largest high-end servers.

VII. RELATED WORK

Our community recently started considering sustainability as a design goal, and prior work focused mostly on characterizing [7, 10, 11, 16], quantifying [8, 12, 13] or reducing [1, 4, 5, 15, 17] the carbon footprint *per device*. However, as argued in this paper, to comprehensively and fully understand and temper the environmental footprint of computing, one needs to include the socio-economic context within which we need to operate. Population growth and increased affluence (increasing number of computing devices per person) is current reality which we should not be blind to and which impacts what we should do to reduce the overall environmental impact of computing.

VIII. CONCLUSION

This paper described the sustainability gap and how it is impacted by population growth, the increase in affluence (increasing number of devices per person), and the carbon intensity of computing devices. Considering current population and affluence growth, the carbon intensity of computing devices needs to reduce by 9.4% per year to keep the total carbon footprint of computing constant relative to present time, and by 15.5% per year to meet the Paris agreement. Several case studies illustrate that while (some) vendors successfully reduce the carbon footprint of devices, it appears that more needs to be done. Also, *all* vendors should be encouraged to publish carbon footprint for *all* of their devices. A concerted effort in which both the demand for electronic devices *and* the carbon footprint per device is reduced appears to be inevitable to keep the rising carbon footprint of computing under control and, if possible, drastically reduce it.

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