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Assessing ICT global emissions footprint: Trends to 2040 & recommendations

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ABSTRACT

In light of the concerted efforts to reduce global greenhouse gas emissions (GHGE) per the so-called Paris Agreement, the Information and Communication Industry (ICT) has received little attention as a significant contributor to GHGE and if anything is often highly praised for enabling efficiencies that help reduce other industry sectors footprint. In this paper, we aim at assessing the global carbon footprint of the overall ICT industry, including the contribution from the main consumer devices, the data centers and communication networks, and compare it with the to the total worldwide GHGE. We conduct a detailed and rigorous analysis of the ICT global carbon footprint, including both the production and the operational energy of ICT devices, as well as the operational energy for the supporting ICT infrastructure. We then compare this contribution to the global 2016-level GHGE. We have found that, if unchecked, ICT GHGE relative contribution could grow from roughly 1–1.6% in 2007 to exceed 14% of the 2016-level worldwide GHGE by 2040, accounting for more than half of the current relative contribution of the whole transportation sector. Our study also highlights the contribution of smart phones and shows that by 2020, the footprint of smart phones alone would surpass the individual contribution of desktops, laptops and displays. Finally, we offer some actionable recommendations on how to mitigate and curb the ICT explosive GHGE footprint, through a combination of renewable energy use, tax policies, managerial actions and alternative business models.

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1. Introduction

Information and Communication Technology (ICT) devices and services have taken a central part in our lives and have fundamentally transformed the way we work, communicate, travel, and play in the last few decades. Indeed, while human population has only doubled in the last 50 years, the global consumption of electronic devices has grown six fold in that same time span (Wann, 2011). According to the cellphone manufacturer Ericsson, 6.1 billion cellphones will be smartphones by 2020 (Reuters, 2020).

The ICT industry has a rather positive image in the eyes of the sustainability community today as it has substantially transformed the way we communicate and work, uncovering opportunities to reduce the human impact on nature. As an example, e-commerce, tele-working, and video conferencing have reduced the worldwide travelling of both people and goods and hence the consumption of petroleum and the emission of greenhouse gases (Yi and Thomas, 2007). Furthermore, wireless sensors and monitoring technology has enabled us to develop the concept of so-called “smart grids”, “smart homes” and “smart buildings” to better optimize energy management in those premises through monitoring of parameters such as temperature, humidity, and sun light (Gharavi and Ghafurian, 2011) (Paetz et al., 2012) (Chwieduk, 2003).

However, this is only one side of the coin to the ICT technology in our lives; the brighter side that is. The darker and more ominous side of the ICT industry is its exponentially growing energy consumption. As our reliance on ICT devices and services grows rapidly, so does our need for energy to manufacture and electricity to power these devices. The generation of this much-needed energy to make and operate all the ICT devices on the market today is a significant contributing cause towards the creation of carbon dioxide, a leading Green House Gas (GHG), as well as other global warming pollutants.

In recent years there has been more awareness around climate change and its potentially devastating effects. There are more climate change initiatives than ever with specific action plans and

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strategies intended to mitigate the negative effects of global warming on our environment. A chief example of a recent global initiative is the Paris Agreement that took place in December 2015, where 196 nations approved a landmark global plan to curb climate change in the years to come. The agreement placed strong commitments in place to limit global warming to below 2 °C (Stocker, 2014).

Global greenhouse emissions data shows that the major contributors to global emissions by economic sector in 2015 were electricity production (29%), transportation (27%), industry (21%), followed by commercial and residential (12%) and agriculture (9%) (U.S. Environmental Protection Agency, 2016). Based on these numbers alone, one might think that the ICT industry is not a contributing factor towards the global emissions of greenhouse gases. However, a closer look reveals that the energy consumption of computers, data centers, networking equipment, and other ICT devices (excluding smart phones) amounted to as much as 8% of total worldwide consumption, and is projected to reach 14% by 2020 (Pickavet et al., 2008a). What is even more surprising is the fact that these numbers and projections don't include the manufacturing contribution (Williams, 2004a), especially in light of the fact that ICT devices have a much shorter useful life (2–5 years) than any other piece of hardware. If we are to meet the goals of the Paris Agreement and mitigate the effects of climate change, it is imperative that we pay close attention to the rapid growth of ICT devices and their associated carbon footprint relative to that of the other economic sectors.

The increase in volume of ICT equipment has an associated increase in carbon footprint on our environment. However, there is spotty record in the literature of the global ICT carbon footprint as its environmental impact comes in different forms and from multiple sources. The emissions from the ICT devices and therefore their environmental impact come from energy consumption used both, in manufacturing these devices, as well as running them. In addition, mining for earth metals used in manufacturing of ICT devices and waste disposal are additional contributors to the total ICT industry CO_2 footprint. As such, there are several different methodologies that can be used to calculate the CO_2 footprint depending on which aspects are taken into account.

With our ever-growing demand for ICT devices and the pressing matter of carbon emissions reduction, it is critical that (i) we fully and precisely assess the contribution of ICT to the global GHG emissions both today and in the future, and (ii) explore innovative solutions in the ICT industry that can meet our growing demand without undermining our reductions targets for CO_2 emissions.

2. Previous work

Quite surprisingly, while there have been many studies of the electricity consumption of ICT devices and infrastructure, ranging in scope from a single device or a single region to a broader scope, there is a relative dearth of peer-reviewed articles on the total carbon footprint impact of the overall ICT industry. Some of the early estimations of the global CO_2 emissions and energy use (Gartner, 2007) (Webb, 2008) were based on rough, unspecified and obsolete data, and lacked the necessary transparency required for peer-reviewed publications. More rigorous and recent studies by Malmodin et *al.* have focused mostly on the overall energy consumption of ICT. Results suggested that the ICT sector produced 1.3% of global GHG emissions in 2007 with a corresponding global electricity consumption of 3.9% (Malmodin et al., 2010). However, Malmodin *et* al. greatly underestimated the contribution of the manufacturing process to the total carbon footprint, as demonstrated by the detailed and transparent estimations of the contribution of manufacturing of ICT devices done initially by Williams (2004a) and corroborated more recently by Ciceri et al. (2010). Pickavet et al. have estimated the total power consumption of the ICT industry, including PC's, network equipment, data centers and other ICT equipment, such as audio equipment, telephone handsets, gaming consoles, printers, copiers and fax machines. They estimated the total power consumption in 2008 to amount to 168 GW, corresponding to a total energy consumption of 1470 TWh per year (Pickavet et al., 2008a). The authors also projected that this electricity consumption will grow to about 430 GW or 3766 TWh by 2020 representing a 156% increase in the span of 12 years. A somewhat similar exercise was done more recently by Van Heddeghem et *al.* who did a more detailed analysis of the electricity consumption by PC's, data centers and communication networks from 2007 to 2012. A comparison of their actual 2012 results with those of Pickavet et *al.* show that the actual and projected results are within 2–3% of each other (Van Heddeghem et al., 2014). Fehske et al. undertook one of the rare assessment of the global footprint of mobile communication (which included laptops in addition to smartphones and mobile phones), and projected a 3-fold increase in GHGE, from 86 in 2007 to 235 Mt–CO_2-e by 2020. The authors took into account and provided a breakdown of the individual contribution of the production and energy consumption of the devices, as well as that of the radio access network (Fehske et al., 2011) and other networking infrastructure. Their findings reveal that by 2020, the production of mobile devices, the operation of radio access networks, and the operation of data center and data transport will account for 30%, 29% and 19% of the total carbon footprint of mobile communications respectively.

The only two pertinent studies that directly addressed ICT global carbon footprint that we could find are those by Malmodin et al. who estimated the total ICT carbon contribution to reach 1.1 Gt–CO_2–e by 2020 (Malmodin et al., 2013), and another extensive study of the global electricity consumption by ICT, trending to 2030, was done by Andrae and Edler and published the carbon footprint in their supplemental material (Andraea. and Edler, 2015). Andrae and Edler presented three different scenarios (expected, best and worst cases), comprising the combined contribution of the electricity consumption of consumer devices, communication networks and data centers. Their devices scope included desktops, laptops, monitors, smartphones, ordinary mobile phones, tablets, phablets, TV's, and DVD players. Admittedly, the scope of this study is the broadest being considered to date and certainly broader than our study. However, Andrae and Edler relied on unsupported values of device lifetimes, underestimated the electricity intensity improvement of Fixed Access Networks, did not use a common baseline starting point for all scenarios for 2010, and likely overestimated the total global CO_2-e emissions and the total global electricity consumption. In sum, while the Andrae & Edler paper provides an extensive study of ICT devices, their study lacks somewhat in rigor and consistency. As expected, this leads to 2030 projections that exhibit as high as an order of magnitude difference between their best and worst case scenarios. For instance, their Fig. 7, shows the ICT total share of global electricity consumption ranging from 8% in best case scenario to 51% in worst case, with an expected baseline of 21%. Both baseline and worst case numbers are so high, that an extrapolation of even the baseline to 2040 will exceed 50% of the global electricity consumption, while an extrapolation of the worst case scenario will exceed 100% of total electricity consumption! Another example is their projections that Fixed Access Wired Networks will reach an expected scenario of 2641 TWh by 2030, but with a variance ranging from a minimum of 825 TWh to a max of 7912 TWh, or in other words an order of magnitude in variability (Fig. 2(a) of (Andraea. and Edler, 2015)). As such, we believe the literature still lacks a more rigorous and methodical study that yields a narrower range of the projected global carbon footprint of the ICT sector, hence helping inform some sensible recommendations and mitigation measures.

Considering that the global GHG emissions from energy sources are forecast to stay flat at about 36.2 Gt–CO_2–e beyond 2015 (US Environmental Protection Agency, 2017; Statista, 1975), while the ICT emissions continue to grow rapidly, we believe that even an approximate idea of what that contribution might be will provide valuable early warning and help inform effective mitigating action plans. Hence a reasonably accurate forecasting of the industry's overall contribution is critically urgent. This urgency is further exacerbated when one considers that the ongoing explosion of IoT devices will only serve to accelerate this growth.

In the first part of this paper we shall first fully assess the current contribution of the ICT industry to the global carbon footprint, taking into account the contribution from manufacturing as well as the operational contribution of the main categories of the ICT industry, including both the devices as well as the infrastructure. On the device side, we shall highlight the contribution of smart phones and tablets into our analysis, and compare them with Andrae and Edler estimates. We shall then estimate, based on historical growth data, how that contribution is expected to grow through 2020. On the infrastructural side, we will follow the previous work of Van Heddeghem et al. (Van Heddeghem et al., 2014), which projected the infrastructural energy consumption through 2020. We shall then sum up all the contributions, converted to carbon footprint, and project them out through 2040.

The original contributions of our study are three-fold: (i) all the parameters used in estimating the footprint of each of ICT device are either based on peer-reviewed literature or in the case of device useful life, inferred from reliable industry sources using our novel method of minimization of variance. This allows us to arrive at a narrower range of variability when summing up the contributions of all the in-scope devices and infrastructure equipment; (ii) we make explicit and transparent the contribution of each major device within our scope, as well as the key parameters behind its estimate, to allow future researchers to build on our work and further expand it and/or refine it; (iii) our study also helps reveal the trends in the relative contributions of the various devices within the big picture, and in particular the emergence of smart phones as a major future contributor to the ICT global footprint; and finally, (iv) our discussion provides some actionable recommendations for policy makers, corporate managers, as well as directions for future work in the fast changing ICT landscape, especially as we pass the cusp of the explosive growth in Internet of Things and cryptocurrencies.

We will conclude with some further analysis and recommendations on how to dramatically reduce the global carbon footprint of the ICT industry in order to curb its unsustainable growth.

3. Research methods

The ICT industry is composed mainly of two categories of electronic equipment; namely (i) the electronic devices, such as PC's including desktops and laptops, along with the associated CRT and LCD displays, and handheld devices such as tablets and smart phones, and (ii) the infrastructural facilities such as data centers, comprising servers, networking gear, power and cooling equipment and communication networks, comprising customer premises access equipment (CPAE), office networks, and telecom operator networks (including cooling and power provisioning overhead). This represents the total scope of our study. Excluded from this scope are all TV's, set-top boxes, and printers. Fig. 1 depicts our scope in a more graphical form.

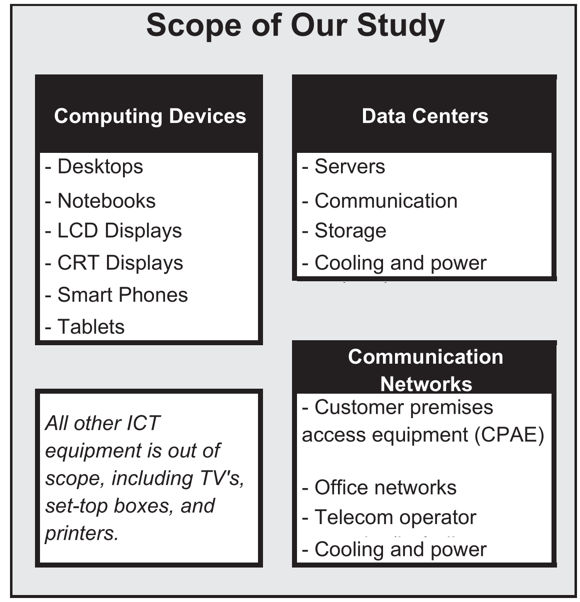

Fig. 1. Scope of our study categorized by Computing devices, Data Centers and Communication Networks.

In order to accomplish our task we need to estimate the following quantities for each of the components comprising the ICT industry: (i) the Production Energy which includes the material extraction and the manufacturing energy; (ii) the Useful Life of the component, including any secondary use, before it is totally dismissed; (iii) the Use Phase Energy which is the average annual energy consumption from operation; (iv) the active installed base since 2007 and onward.

Production Energy (PE): The production energy of any device is usually the subject of a careful lifecycle analysis (LCA), that includes a full inventory of the materials and processes involved, from the material extraction all the way to shipment to the final customer. LCA's however are notoriously prone to widely differing results depending on the choice of the LCA framework, the material extraction and manufacturing processes, the interpretation process of the completeness, and the sensitivity and the consistency of the LCA study. Because of the extensive amount of data collected in the process, different assessment by different authors of the key elements that contribute significantly to the outcome may lead to very high variations in results (Teehan and Kandlikar, 2012) (Curran et al., 2005). Also, the problem of incomplete data for processes continues to plague those calculations for computer devices in particular (Williams, 2004b). Finally, as manufacturing processes become more efficient, the production energy of computer devices is expected to trend down, although it is partly offset by the ever-increasing power of the computers' micro-processors, and increased memory. In this paper, we shall use the most recent data to bound the PE of each component between the minimum and maximum values reported in the literature.

Use Phase Energy (UPE): Here also, the UPE, defined as the annual energy consumption of computing devices is also prone to wide variations and has been subject to several extensive studies, focusing mostly on desktops, laptops and LCD/CRT displays (Teehan and Kandlikar, 2012) (US Environmental Protection Agency, 2017) (Williams, 2004a). Here too, we use the same approach as for the production energy and assign a bounding range of a minimum and maximum value for each component.

For each of PE and UPE, we convert those energies to their corresponding carbon footprint in kg of CO_2-e, using the appropriate conversion ratios for electricity and fossil derived energy (EPA, 2017). We will assume for the sake of simplicity that most electric energy derives from fossil fuel, accounting for the energy losses from production and transmission to the manufacturing site.

Useful Life (UL): This is one of the least documented metric in the literature, and perhaps the most difficult one to accurately assess. Even for desktop computers, which have enjoyed the most extensive studies to date, the literature varies considerably in estimating their useful life, with estimates ranging from 3 to 8 years per device based on 21 different regional and global studies (Teehan and Kandlikar, 2012). As for other devices, such as CRT and LCD displays, let alone tablets and smart phones, the literature is almost totally silent on the subject. The techniques to measure useful life may include customer surveys, waste stream monitoring, or purchase monitoring, may not always be able to differentiate between actual use and passive storage, hence leading to wide variations in lifetime estimates. This is however a key parameter in the estimation of the carbon footprint of any device (Teehan and Kandlikar, 2012). Andrae and Edler chose to systematically pick a wide range of useful life for their worst, expected and best-case scenarios. This in turn can leads to artificially excessive gaps between the various scenarios, and which are unsupported by the available data. In this paper, we introduce a new method that allows us to more accurately infer the average useful life (UL) of a particular device based on its documented global installed base and its historical annual shipments. This method is described below:

- Denoting the Installed Base and Annual Shipments in year N as IB(N) and AS(N), and Useful Life as UL
- We have a series of actual IB(N) and AS(N) for N ranging from 2007 to 2016.
- Assume a seed value of UL to start with,
- Calculate $IB_c(N+1) = IB_c(N)*(1\text{-}1/UL) + AS(N+1)$, where the “c” subscript of IB(N) denotes the calculated rather than the actual value.
- Calculate the variance between the actual and the calculated IB(N+1) for each year in the known range
- Solve for the UL that minimizes the total variance over the whole set of known values.

The reliability of the value for the UL of a particular device is determined by the number and the quality of data points available for each of the global installed base and the annual shipments. In the cases where the UL of a particular device has been determined in the literature, we shall determine the UL by our method as a way of verifying if our calculated value falls within the literature range, and if so, we use the minimum and maximum values of the literature range for our best and worst-case scenarios. This is the case for desktop computers. In the case where our calculated value is outside the literature range, we use our calculated value as the new minimum or maximum of that range. Such is the case for laptop computers and tablets. In cases where the literature is silent on the UL, such as the case for smart phones, we rely primarily on our method to estimate the UL, and use it for both the minimum and maximum. The advantage of our method over the other documented methods is that it relies on global numbers rather than localized and country-specific surveys or monitoring that may not be globally applicable. Its disadvantage, on the other hand, is that it requires a significant number of data points in order to be reliable.

Following earlier authors (Williams, 2004a), we use the concept of *Lifecycle Annual Footprint (LAF)* defined as the sum of the Use Phase Energy (UPE) and Production Energy (PE) divided by the product Useful Life (UL), or in other words the annual energy consumption plus the production energy overhead amortized over its useful life; or in mathematical form: $LAF = UPE + PE/UL$. In other words, the Lifecycle Annual Footprint accounts for the annual footprint of both the use phase as well as the production energy, depreciating the production energy over the useful lifetime of the device.

For the carbon footprint of data centers and communication networks, with the exception of the servers, we shall ignore the contribution of their production energy due to their relatively longer useful life and relatively much larger consumption energy which is driven by their much more intensive operation.

4. Data collection

In order to estimate the overall GHGE footprint of the devices and equipment within our study's scope, we will need to collect a significant amount of key data about each of the main devices in order to estimate the annual lifecycle footprint for each device, as well as its corresponding global number of units in use over enough years to yield a reliable projection over time. More specifically, we need to collect the following key metrics for each of the consumer devices: (i) the production energy, (ii) the useful lifetime, (iii) use phase energy, (iv) the global number of devices in use (actual and projected) from 2007 to 2020 and the annual global shipments of those devices (actual and projected) from 2007 to 2020. With the exception of the device lifetime, we found that all of the other data is available from high-quality secondary sources. In the case of disagreement, we use the lower and upper bounds of that data to bound our minimum and maximum scenarios. For the lifetime of devices, when not available from secondary data, we calculate it through our minimization of variance, using the installed base and the annual shipment data as described in the previous section.

For the data centers and networking equipment, we show that the production energy has a negligible impact relative to the consumption energy of that equipment, and hence ignore its contribution altogether.

Finally, once we have all the above data collected, we aggregate it to determine the actual and projected total GHGE impact of ICT relative to the global worldwide GHGE.

4.1. ICT devices

4.1.1. Annual lifecycle footprint

In this section, we shall estimate the annual lifecycle footprint for each of desktops (home and office), notebooks (home and office), CRT and LCD displays, tablets and smart phones.

Desktops: Teehan et al. performed a comprehensive review of more than 32 studies about the Use Phase Energy, the Production Energy and the Useful Life of desktops, excluding the display contribution to limit variations (Teehan and Kandlikar, 2012). We use their study along with that of Williams (Williams (2004a) (Williams, 2004b), Van Heddeghem et al (Van Heddeghem et al., 2014). and Urban et al. (2014). to support our findings.

Production Energy: Teehan et al. decided to take into equal consideration all the quality studies without imposing any low or high boundaries on the results. They did however dismiss Williams' results from their final range of values, and concluded that desktops' Production Energy ranged from 120 to 250 kg CO_2-e, the Use Phase Energy ranged from 50 to 175 kg CO_2-e per year and a Useful life of 3–6 years. However, Teehan et al. assumed a constant conversion factors of 11MJ/kWh and 0.5 kg CO_2-e/kWh in all their calculations. We agree with their use of 0.5 kg CO_2-e/kWh for the conversion from Grid delivered electricity use to carbon footprint as a fairly accurate and appropriate average to use on a global basis, as it is well supported by a wide range of government-sanctioned conversion calculators such as the EPA Greenhouse Gas Equivalencies Calculator (EPA, 2017) which suggests 0.7 kg CO_2-e/kWh and the UK-based National Energy Foundation which suggests using 0.4 kg CO_2-e/kWh (National Energy Foundation, 2017). On the other hand, the authors provide no literature citations for their use of 11 MJ/kWh except for stating that most studies use between 10 and 12 MJ of primary energy to produce 1 kWh of delivered electricity. Given that the energy conversion from MJ ot kWh is 3.6 MJ for 1 kWh, an 11 MJ/kWh assumes that the energy losses due to production and delivery of electricity account for 2/3 of the energy consumed to produce it. We think this number is a bit excessive, and based on our research and both the EPA and NEF calculators, a 7 MJ/kWh is far more accurate (EPA, 2017) (National Energy Foundation, 2017).

Use Phase Energy: Because of their significantly different purpose, setup and length of use, we treat home and office computers on a separate basis when it comes to their energy consumption. Urba et al. estimated that the average use phase energy for home and office desktops was 137 and 186 kWh/yr respectively (Urban et al., 2014), while Van Heddeghem et al. estimated those averages to be 149 and 231 kWh/yr respectively (Van Heddeghem et al., 2014). For the purpose of our calculation, we shall use their estimates as lower and higher bounds. We note in passing here that the Van Heddeghem numbers were for 2007 devices, showing a slight decrease of about 8% by 2012. Since we're using their numbers as upper bounds, we shall ignore that reduction.

Useful Life: For the estimation of the Useful Life of desktop personal computers, Teehan et al. reports numbers ranging from 3 to 8 years based on 21 different studies conducted between 1990 and 2010, involving primary and secondary data, and including both first life and secondary use of those desktop computers for home and office use. They conclude that the dataset suggests an average lifetime of 5 years in 2012 (Teehan and Kandlikar, 2012). For the purpose of bounding this estimate, we also estimate the average life of desktop computers by collecting worldwide data of the installed base and annual shipments of PC's using our minimization of variance method. Using various sources from Statista, IDC, Gartner, and other reliable secondary web-based business sources, we collected the actual and projected data on the total global installed base of PC's and annual unit shipments from 2010 to 2020 (Statista, 2017a) (Business Wire, 2004) (Macworld from IDG, 2006) (Gartner, 2008) (Firstpost, 2017) (Digital Home, 2011). We then applied our minimization of variance method described above to the data on installed base and annual shipment collected from the above sources to calculate the actual useful life for desktops. We note that this analysis does not discriminate between home and office desktops, or first life and secondary use, and treats on an equal basis all the desktop computers still in use or being shipped. The minimization of variance yields a useful life of about 5.5 years on average for a desktop computer. Table 1 and Fig. 2 display the numerical data and the graphical fit between the actual and the calculated installed base from 2010 to 2016 respectively, excluding from our calculation the projected numbers from 2017 to 2020. Also, we believe that based on our method, our calculated average life of 5.5 years provides a more accurate estimate, for the purpose of our calculation of the overall ICT footprint, we shall use a minimum of 5 years as suggested by Teehan et al. for the minimum average life of desktop computers and a maximum of 7 years being on the high-end of what the literature suggests for useful life of desktops (Teehan and Kandlikar, 2012).

Finally, we summarize our findings for desktop computers, for both home and office use, in Table 2, leading to the derivation of the minimum and maximum average lifecycle annual footprint for both categories of desktops.

Table 2
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for desktops (not including display).

	Useful Life (years) (Williams, 2004a; Statista, 1975; Van Heddeghem et al., 2014; Curran et al., 2005; EPA, 2017)		Production Energy (kg CO_2-e) (Statista, 1975; Urban et al., 2014)		Use Phase Energy (kg CO_2-e/yr) (Williams, 2004b; Urban et al., 2014)		Lifecycle Annual Footprint (kg CO_2-e/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Home	5	7	218	628	93	116	124	241
Office	5	7	218	628	69	75	100	200

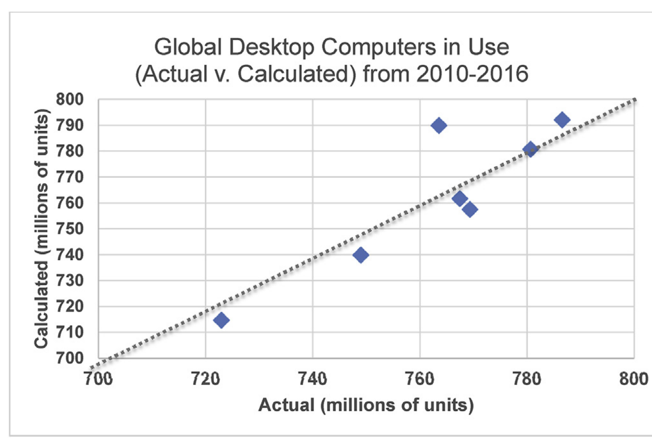

Fig. 2. X-Y fit of actual v. calculated global installed base of desktops, showing the data falls fairly
well on the 45° dashed line, when assuming an average Useful Life of 5.4 years per unit.

Table 1
Global data on desktop computers, showing actual installed base and annual shipments, along with calculated shipments using an average useful life of 5.5 years per computer.

Year	(Millions of Desktop Units)		
	Installed Base (National Energy Foundation, 2017; Statista, 2017a; Business Wire, 2004)	Annual Shipments (Actual) (Macworld from IDG, 2006; Gartner, 2008; Firstpost, 2017)	InstalledBase (Calculated)
2010	780.7	157.0	780.7
2011	786.6	155.0	792.0
2012	763.6	148.0	789.8
2013	769.3	134.4	757.5
2014	767.5	133.9	761.6
2015	749.0	113.6	739.9
2016	723.0	103.5	714.7

***Notebooks*:** Unlike desktops, laptops have not received nearly the same level of attention for their production energy and hence there are hardly any reliable LCA studies available. For the purpose of our estimation of the production energy for laptops as well as tablets and smartphones, we shall be relying to a great extent on the published data by Apple in their environmental report (Apple Inc, 2016), which provides the production footprint of its various computer devices and models, including desktops, notebooks, iPads and iPhones. Their production footprint quoted for their various desktop models ranges from 242 to 570 kg CO_2-e, which falls within the range estimated for desktops in Table 2 above.

Production Energy: For notebooks, the production footprint of Apple-produced notebooks ranges from 281 to 468 kg CO_2-e for their 13-inc MacBook Air and their high-end 15-inc MacBook Pro respectively, with a Use Phase energy ranging from 11 to 25 kg CO_2-e/yr (Apple Inc, 2016).

Useful Life: The IVF Industrial Research & Development Corporation conducted a detailed study of the average life of computer devices in 2007, based on primary and secondary data, and estimated the average economic life of those devices to be 5 years for laptops and 6 years for desktops, CRT and LCD displays (IVF Industrial Research and Development Corporation, 2007). This again falls well within the range of our Table 2 for desktops (IVF Industrial Research and Development Corporation, 2007). Conducting a similar analysis as we did for desktops, after collecting the installed and shipment data for laptops from Statista (2017a), we arrive to an Average Useful Life of 7 years. Table 3 and Fig. 3 show the actual versus calculated in-use computers from 2010 to 2016 respectively,

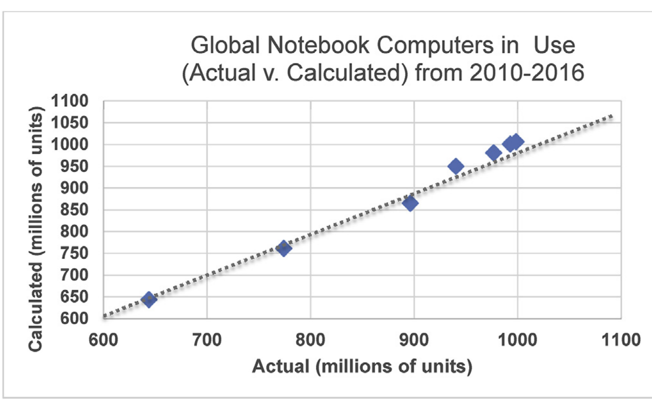

Fig. 3. X-Y fit of actual v. calculated global installed base of notebooks, showing the data falls fairly
well on the 45° dashed line, when assuming an average Useful Life of 7 years per unit.

Use Phase Energy: For the UPE of laptops, we bound it by relying on the studies of (Urban et al., 2014) and (Van Heddeghem et al., 2014) who concluded that the average annual consumption energy for office laptops ranged from was 53 and 70 kWh/yr for home laptops and from 39 to 46 kWh/yr for office laptops. The lower values for the office use may be explained by the connection of most of those laptops to a larger display, whose consumption is not included in these numbers and which we shall be accounting for separately in this study.

For the installed base and annual shipment of laptops, we relied primarily on Statista (2017a).

In summary, Table 4 presents the key data we need for the lifecycle annual footprint of laptops in the equivalent GHGE footprint.

External Monitors: Next, we need to estimate the contribution of CRT and LCD monitors, which are used with desktops as well as laptops. The absence of primary or even secondary data makes this task even more challenging than desktop and laptop computers. We could only find one primary data study done in 2007 that provided the average Useful Life, and use phase energy for 17-inch CRT's and LCD's (IVF Industrial Research and Development Corporation, 2007). The numbers reported in that study were 6.6 years of average useful life for both CRT's and LCD's, essentially matching that of desktops, and use phase energy ranging from 100 to 190 kWh/yr for CRT's and 47–86 kWh/yr for LCD's, corresponding to an equivalent GHGE footprint of 51–95 kg CO_2-e and 23–43 kg CO_2-e for CRT's and LCD's respectively, where the minimum and maximum correspond to the average consumption in the home and office respectively. Clearly, 17-inch monitors today have been mostly replaced by much bigger alternatives going up to 27-inch mostly LCD's, so these numbers may be on the conservative side, although energy efficiency improvements made in the last 10 years could offset some, if not most, of the increase in energy consumption. As for the production energy of LCD and CRT displays, we shall rely on a recent LCA study by Bhakar et al. that estimated

Table 4
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for notebooks (not including display).

	Useful Life (years) (National Energy Foundation, 2017; Apple Inc, 2016)		Production Energy (kg CO_2-eq) (Digital Home, 2011)		Use Phase Energy (kg CO_2/yr) (Van Heddeghem et al., 2014; EPA, 2017; Digital Home, 2011)		Lifecycle Annual Footprint (kg CO_2/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Home	5	7	281	468	27	35	67	129
Office	5	7	281	468	20	23	60	117

Table 3
Global data on notebook computers, showing actual installed base and annual shipments, along with calculated shipments using an average useful life of 7 years per computer.

Year	(Millions of Notebook Units)		
	Installed Base (National Energy Foundation, 2017)	Annual Shipments (Actual) (National Energy Foundation, 2017)	Installed Base (Calculated)
2010	643.9	201.0	643.9
2011	774.1	209.0	761.5
2012	896.4	201.0	865.2
2013	940.3	180.9	950.0
2014	976.8	174.3	981.1
2015	992.9	163.1	1001.2
2016	998.4	154.7	1006.6

Table 5
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for LCD and CRT displays.

	Useful Life (years) (Apple Inc, 2016)		Production Energy (kg CO2-eq) (IVF Industrial Research and Development Corporation, 2007)		Use Phase Energy (kg CO2/yr) (Apple Inc, 2016)		Lifecycle Annual Footprint (kg CO2/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
CRT	5	7	200	200	51	95	79	135
LCD	5	7	95	95	23	43	37	62

that 15-inch LCD and CRT displays had a production footprint of 95 and 200 kg CO_2-e respectively (Bhakar et al., 2015). Table 5 below summarizes the above key numbers leading up to the calculation of the lifecycle annual footprint of both CRT and LCD displays.

Tablets: As we move on to tablets and smart phones, the availability and quality of data from peer-reviewed literature goes from scarce to almost non-existent. We had no other recourse than relying exclusively on data from Apple, which reports about 80 kg CO_2-e for their 10.5-inch iPad Pro (64 GB), 116 kg CO_2-e for their latest 10.5-inch iPad (5th generation) (32 GB) and 100 kg CO_2-e for their iPad mini 4 (Apple Inc, 2016). A non-published study by Teehan suggested that the production energy of iPad (1st gen Wi-Fi) was only of 26 kg CO_2-e. The study however relied on a rough linearity of production energies with the mass of the device, and did not conduct a detailed LCA study. Furthermore, the authors warned that a top-down LCA would produce larger numbers. For the purpose of our calculations, we will rely on the Apple-reported numbers and use 80 and 116 kg CO_2-e as the lower and higher bounds for the production energy of tablets, respectively.

As for the useful life of tablets, Apple uses a 3-year period by first owner. However, our analysis based on reported installed base and annual shipment of tablets, and the calculation of useful life using our minimization of variance yields a much longer life span (>7 years), suggesting essentially that all the tablets sold since 2010 are still being actively used. This actually makes sense since there is little incentive for users to acquire new models, while the functionality of the older models continues to improve with ongoing software upgrades. We shall therefore assign tablets a minimum and maximum useful life of 3 and 8 years respectively.

For the Use Phase Energy of tablets, we could not find any peer-reviewed literature on the subject. So, we relied once more on Apple Environment Reports, which reports about 4.5 kg CO_2-e per year (Apple Inc, 2016). This number is corroborated by a Forbes article, which reports the equivalent of 5.25 kg CO_2-e in annual energy use for an iPad, citing the Electric Power Research Institute (Helman, 2013). Using 4.5 and 5.25 kg CO_2-e/yr as our minimum and maximum numbers for tablets, our key data for tablets is summarized in Table 6 below.

***Smart Phones*:** Last, but not least, we now turn to the analysis of the key emissions footprint data for smart phones, which to our knowledge and along with the data for tablets, was addressed by Andrae and Edler for the first time in the peer-reviewed literature, using broad ranges for their useful life. We shall use here our described method to calculate the UL of smart phones and then compare our results with those of Andrae and Edler.

Production Energy: For iPhones, Apple reported a production footprint ranging from 43.2 kg CO_2-e for their iPhone 6s model to 52.2 kg CO_2-e for their top of the line, larger format iPhone 7 Plus. In a recent independent LCA study that included iPhone models 4s, 5s, and 6s, it was found that the production footprints of those models were 35.75, 56.7 and 80.75 kg CO_2-e respectively (Suckling and Lee, 2015). This is in fair agreement with the study by Ravaghan et al. which estimated, based on secondary data, the average production energy of smartphones to around 1000 MJ or about 69 kg CO_2-e (Raghavan and Ma, 2011). We could however not find any LCA data on the production footprint of the more comparable Samsung phones. For the purpose of our calculation, and taking into consideration the upward trend in production footprint with ever more powerful models, we will estimate the production footprint of smart phones to range from a minimum of 40 to a maximum of 80 kg CO_2-e.

Table 6
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for Tablets.

	Useful Life (years) (Digital Home, 2011)		Production Energy (kg CO_2-e) (Digital Home, 2011)		Use Phase Energy (kg CO_2-e/yr) (Digital Home, 2011; Bhakar et al., 2015)		Lifecycle Annual Footprint (kg CO_2-e/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Tablets	3	8	80	116	4.50	5.25	14.5	43.9

Use Phase Energy: Urban et al. estimated it to about 5 kWh/yr (Urban et al., 2014), while Helman estimated it to about 2 kWh/year amounting to 1 and 2.5 kg CO_2-e/yr respectively. Apple in its Environment Reports estimates the energy consumption of the iPhone 6s (32 GB) to be about 6.5 kWh/yr or about 3.25 kg CO_2-e/yr on the low end of its current iPhone models, and 8 kWh/yr for the iPhone 7 Plus, amounting to 4 kg CO_2-e/yr on the high end.

Useful Life: For the useful life of smart phones, there was no study we could find, so we relied exclusively on our own minimization of variance method to estimate the effective useful life of smart phones. Fortunately, we were able to find accurate data on both smart phones in use, as well global annual shipments of smart phones since 2007 through 2016 and projected through 2021 (Statista, 2017b). Our minimization of variance yields an average useful life of 1.8 years. Table 7 and Fig. 4 show the actual versus calculated number of smart phones in use and the fit between the two when assuming an average life of 1.8 years. For the purpose of our calculations, we will use 2 years as average life for both the minimum and maximum values.

We summarize our findings for smart phones in Table 8 below.

Finally, for the reader's convenience, we recapitulate our findings for all the devices into the master Table 9 below.

4.1.2. Units in use

The data of the total units in use, along with their annual growth from 2007 through 2016 for personal computers (PC's), was available and collected from the sources mentioned in the above sections. Similarly, for smart phones and tablets, the available data started from 2010 to 2013 and onward respectively.

For desktops and laptops, the use phase energy is significantly different between the home and the office use, and thus we had to estimate the total number of units in each one of those categories separately. For that purpose, we assume a constant split of 60/40 between home and office PC's (for both desktops and notebooks) based on US-based 2005 data reported by Roth and McKenney (2007), and used by Malmodin et al. (2010). This split was further corroborated by the more recent study by Urban et al. of the energy consumption by consumer electronics in the US (Urban et al., 2014). In the absence of more global data, we will assume the 60/40 split

Table 7
Global data on smart phones, showing actual installed base and annual shipments, along with calculated shipments using an average useful life of 1.89 years per computer. Raw data for phones in use and annual shipments courtesy of Statista.

Year	(Millions of Smart Phones Units)		
	Installed Base (Actual)	Annual Shipments (Actual)	Installed Base (Calculated)
2008	271		
2009	342	173.5	301.7
2010	485	304.7	466.8
2011	771	494.5	724.3
2012	1136	725.3	1090.7
2013	1580	1018.7	1556.6
2014	1833	1301.7	2050.1
2015	2246	1437.2	2305.3
2016	2594	1470.6	2534.5
2017	2807	1517.0	2745.9

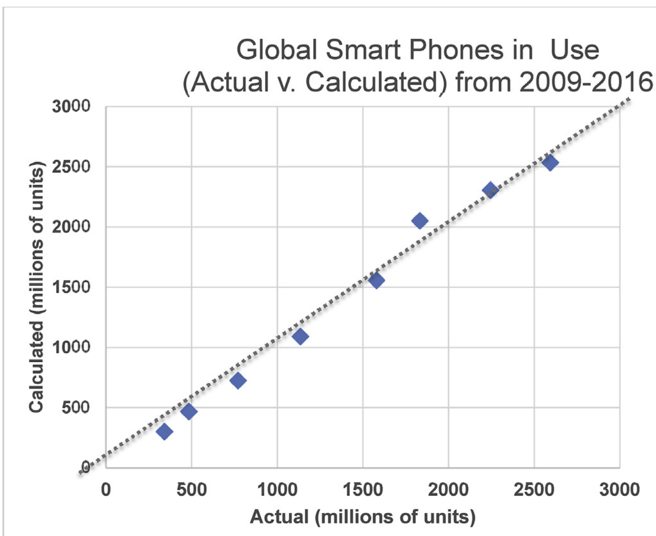

Fig. 4. X-Y fit of actual v. calculated global installed base of smart phones, showing the data falls fairly
well on the 45° dashed line, when assuming an average Useful Life of 1.8 years per unit.

Table 8
Minimum and maximum values for Production Energy, Useful Life, and Use Phase Energy for Smart Phones.

	Useful Life (years) (Raghavan and Ma, 2011)		Production Energy (kg CO_2-e) (Helman, 2013; Suckling and Lee, 2015)		Use Phase Energy (kg CO_2-e/yr) (EPA, 2017)		Lifecycle Annual Footprint (kg CO_2-e/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Smart Phones	2	2	40	80	4.50	5.25	24.5	45.3

to apply on a worldwide basis and be constant in time. For the split of PC's between desktops and laptops, we will follow Van Heddeghem et al. who found that the split between laptops and desktops was 0.32/0.68 in 2007 and grew to 0.54/0.46 by 2012 (Van Heddeghem et al., 2014). Based on forecasted shipments of desktops and laptops, this ratio is projected to reach 0.62/0.38 by 2020 (Statista, 2017a). For the purpose of our calculation and in the absence of annual data, we assumed a linear interpolation between 2007 and 2020 whereby the ratio of laptops/desktops grows smoothly from a 0.32/0.68 in 2007 to 0.62/0.38 in 2020.

Table 9
Summary of key GHGE emissions data for all the devices constituting the scope of our data.

	Useful Life (years)		Production Energy (kg CO_2-e)		Use Phase Energy (kg CO_2-e/yr)		Lifecycle Annual Footprint (kg CO_2-e/yr)	
	Min	Max	Min	Max	Min	Max	Min	Max
Desktops Home	5	7	218	628	93	116	124	241
Desktop Office	5	7	218	628	69	75	100	200
Notebooks Home	5	7	281	468	27	35	67	129
Notebooks Office	5	7	281	468	20	23	60	117
CRT Displays	5	7	200	200	51	95	79	135
LCD Displays	5	7	95	95	23	43	37	62
Tablets	3	8	80	116	4.50	5.25	14.5	43.9
Smart Phones	2	2	40	80	4.50	5.25	24.5	45.3

For CRT and LCD displays, we relied exclusively on the study of Van Heddeghem to estimate the number of units installed in total based on the total energy consumption and the average blended consumption of each unit, regardless of whether it is used for home or office use (Van Heddeghem et al., 2014).

Finally, for tablets and smart phones, we primarily used Statista for the installed base and the annual unit shipment through 2016 and projected through 2020 (Statista, 2017b).

Table 10below summarizes the installed base for each unit with actual numbers through 2016 and projected through 2020.

4.2. Data centers and communication networks

The energy consumption of data centers and communication networks has received quite a bit of attention as they constitute the backbone infrastructure of the Internet and the telecommunication industry (Van Heddeghem et al., 2014) (Vereecken et al., 2009) (Government of Canada, 2013) (Gharavi and Ghafurian, 2011) (Fettweis and Zimmermann, 2008). Data Centers are composed mainly of servers, precision cooling equipment, such as chillers and Computer Room Air Conditioners (CRAC) and power equipment, such as switchgear, UPS and battery backup, that supplies and ensures adequate power supply to both the servers and the cooling systems. The energy efficiency of data centers is typically measured in terms of Power Usage Effectiveness (PUE) which is the ratio of the total energy consumed by the data center divided by the energy supplied to the computing equipment alone (Fontecchio and Rouse,

Table 10
Installed base of in-scope ICT devices from 2007 through 2020 in millions of units. The dotted line marks the border between the actual and the projected data.

	Installed base of ICT Devices from 2007 to 2020 (millions of units)							
	Home Desktop (Malmodin et al., 2010; Van Heddeghem et al., 2014; Urban et al., 2014; Roth and McKenney, 2007)	Office Desktops (Malmodin et al., 2010; Van Heddeghem et al., 2014; Urban et al., 2014; Roth and McKenney, 2007)	Office Laptops (Malmodin et al., 2010; Van Heddeghem et al., 2014; Urban et al., 2014; Roth and McKenney, 2007)	Home Laptops (Malmodin et al., 2010; Van Heddeghem et al., 2014; Urban et al., 2014; Roth and McKenney, 2007)	CRT Displays (Van Heddeghem et al., 2014)	LCD Displays (Van Heddeghem et al., 2014)	Tablets (Statista, 2017b)	Smart Phones (Statista, 2017b)
2007	276	414	130	195	459	594	–	200
2008	291	437	167	250	250	512	–	271
2009	301	451	207	311	233	631	–	342
2010	312	468	258	386	216	750	–	485
2011	315	472	310	464	199	870	–	771
2012	305	458	359	538	168	1482	–	1136
2013	308	462	376	564	166	1108	660	1580
2014	307	460	391	586	149	1227	860	1833
2015	300	449	397	596	132	1346	1000	2246
2016	289	434	399	599	115	1465	1120	2594
2017	280	420	403	605	98	1584	1230	2807
2018	273	409	409	613	82	1704	1320	2981
2019	266	399	416	623	65	1823	1400	3409
2020	255	383	417	625	48	1942	1460	3619

2017). A typical PUE for an average data center is about 1.8 (Miller, 2011).

Data Centers typically run continuously on a 24/7 basis and except for servers, the useful life of their equipment is over 10 years. So, the contribution of the production energy of the equipment tends to be negligible compared to the annual energy consumption, and hence its contribution to the annual lifecycle footprint can be safely ignored for the purpose of our calculation. Even for servers which tend to have a shorter useful life of 3–5 years, the production energy footprint of a typical data center server is estimated at about 328 kg CO_2-e, while the Use Phase energy footprint ranges from 1314 to 3743 kg CO_2-e/yr (Chang et al., 2010). When dividing the production energy by the useful life, we find that its contribution to the annual lifecycle footprint ranges from 1.7% at a minimum to 8% at most. Consequently, in view of the above and the lack of available data, we shall ignore the contribution of the production energy for all data centers and communication networks equipment.

Communication Networks are comprised of three broad categories: (a) telecom operator networks, (b) office networks and (c) customer premises access equipment (Van Heddeghem et al., 2014). Excluded from this category are the data centers that Communication Networks rely on to operate, to avoid double counting of data centers energy consumption.

For data centers, we shall rely on the energy consumption reported by Vereecken et al. of 254 GWh in 2008 (Vereecken et al., 2009) and assume a blended 10% annual growth through 2020 based on Technavio forecast of 10.6% growth between 2013 and 2019 (Technavio, 2014) (Technavio, 2015). We deviate here from Vereecken et al. projection of 12% growth for data centers through 2020 which was an extrapolation and is not born out by the actual data. We also note that the same group later revised that projection to a much smaller number of 5.1% growth.

For communication networks, we shall rely primarily on the extensive studies by Van Heddeghem's group (Van Heddeghem et al., 2014) (Lambert et al., 2012) (Pickavet et al., 2008b). In their latest study, they estimated the energy consumption of data centers and communication networks from 2007 through 2012 and projected their results out to 2020, with an assumed average annual growth rate of 12%. In Table 11 below, we summarize their results in units of millions of tons of CO_2-e/yr (Mt–CO_2-e/yr).

Table 11
Annual energy consumption of data centers and communication networks in units of Mt–CO_2-e from 2007 to 2020. The dotted line marks the border between the estimated data from cited references from the projected data.

	Annual Energy Consumption (Mt–CO_2e/yr)	
	Data Centers (Vereecken et al., 2009; Chang et al., 2010; Technavio, 2014; Technavio, 2015)	Communication Networks (Van Heddeghem et al., 2014; Lambert et al., 2012; Pickavet et al., 2008b)
2007	113.4	101.5
2008	127.0	114.0
2009	142.3	127.0
2010	159.3	138.0
2011	178.5	152.0
2012	199.9	167.0
2013	223.9	178.6
2014	250.7	191.5
2015	280.8	204.4
2016	314.5	217.4
2017	352.2	230.3
2018	394.5	243.2
2019	441.8	256.1
2020	494.9	269.1

5. Results

We're now finally in a position to aggregate all the data collected so far and estimate the global annual GHGE footprint of the ICT industry. In Fig. 5 below, we show the ICT global GHGE footprint relative to the total global footprint on the primary axis, and in absolute values (in units of Mt–CO_2-e) on the secondary axis. Note that the projected data represents the aggregation of the projected data for each of the ICT components, and not based on any fit of the actual data. Note also that the total contribution of ICT to the total carbon footprint grows from a minimum 1.06% and maximum of 1.6% in 2007 to more than double in 2020, reaching a minimum of 3.06% and a maximum of 3.6% of the total worldwide GHGE emissions.

In Fig. 6(a) and (b), we show side by side the individual contribution of each category of devices in 2010 and 2020. It's quite interesting to note that the relative GHGE footprint contribution of smart phones shows by far the biggest increase, almost tripling in the span of 10 years, and by 2020 accounting for more than 50% of all the other ICT devices combined. The second largest increase in relative contribution is the data centers which grew from 33% in 2010 to 45% of total ICT footprint by 2020.

Next, we perform a fit to the 2007–2020 data to figure out the growth rate of the ICT GHGE footprint with respect to the total worldwide footprint, and project out the growth to 2040. We shall assume that, based on the Paris Agreement, the WW total footprint will remain at 2015 level through 2040 in the worst-case basis (Olivier et al., 2016) (United Nations Framework Convention on

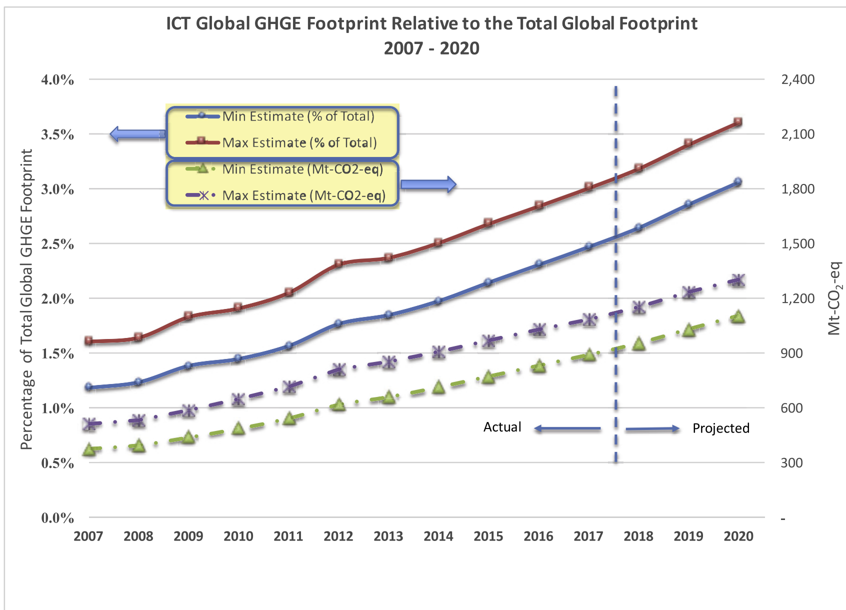

Fig. 5. ICT global GHGE footprint as a percentage of total global footprint (primary axis), and in absolute values in Mt–CO_2-eq on the secondary axis.

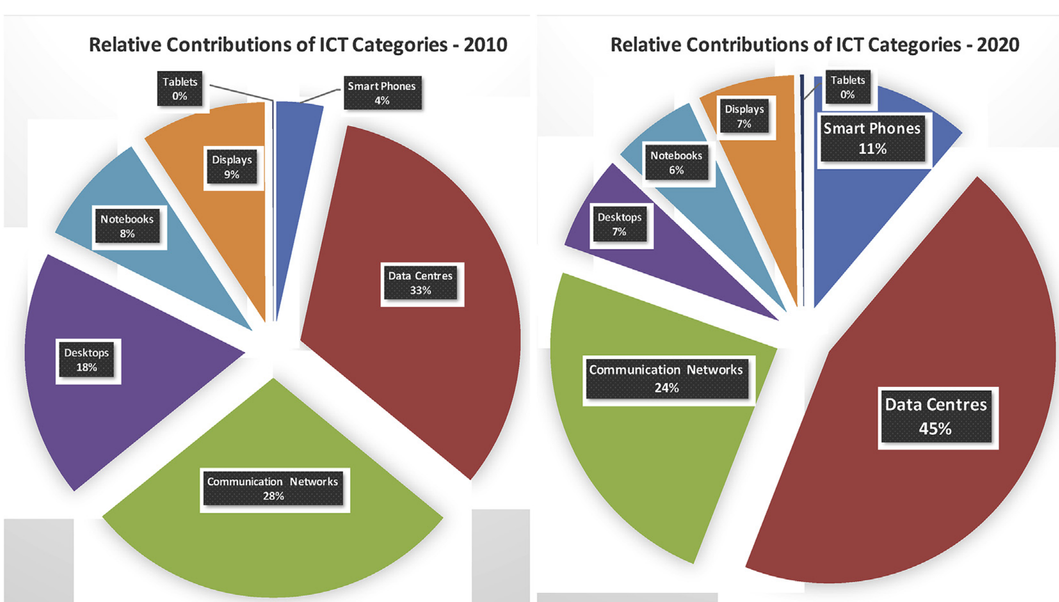

Fig. 6. (a)Relative contribution of each ICT category in 2010. (b): Relative contribution of each ICT category in 2020.

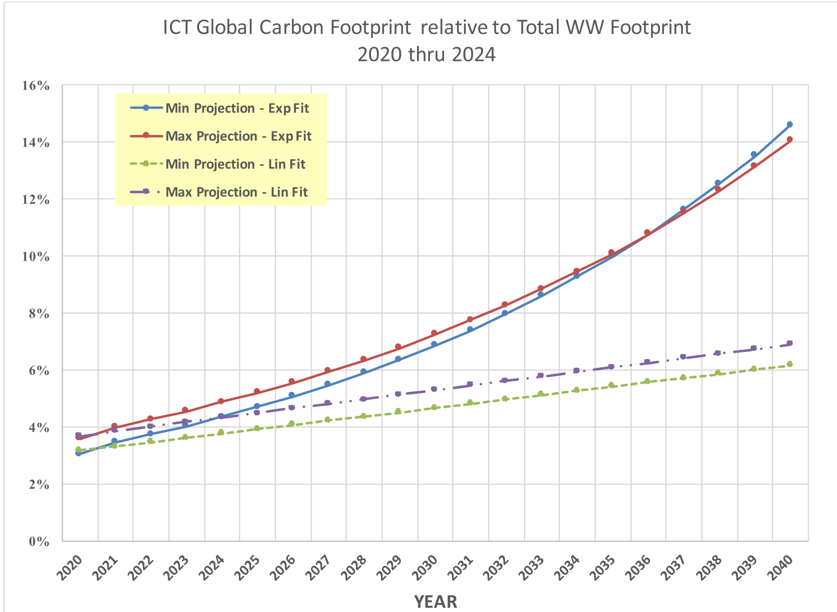

Fig. 7. ICT footprint as a percentage of total footprint projected through 2040 using both an exponential and linear fits.

Climate Change, 2016). We performed both a linear and exponential fit to the data shown in Fig. 7. The coefficient of determination R^2 of the exponential fit was 0.9978 and 0.9957, with an average annual growth rate of 8.1% and 7.0% for the minimum and maximum curves respectively. The R^2 of the linear fit, on the other hand, was 0.9857 and 0.9930, for the minimum and maximum fits respectively. Although the exponential fit is slightly higher and more realistic, we show both fits on Fig. 7 to offer a lower bound of our projections. Both exponential fits predict that by 2040, the ICT carbon footprint could account for as much as 14% of the total worldwide footprint at the 2016 level, and hence exceed the current relative footprint of the Agriculture sector (9%), and almost half of the current total footprint of the industrial sector (29%) in the United States (U.S. Environmental Protection Agency, 2017).

It's interesting to note that the gap between the minimum and maximum projection for the exponential fit appears to close at around year 2035. We remind the reader that the gap between the minimum and maximum projections is due primarily to our large uncertainty about the lifecycle annual footprint of computers (desktops and laptops) and displays. The total combined relative contribution of those devices declined from 35% in 2010 to 20% in 2020, and is expected to continue to decline beyond 2020, and hence it's reasonable to expect the gap between the minimum and maximum projections to eventually become negligible. Our exponential projections through 2040 shows a crossover where the minimum curve surpasses the maximum curve. We surmise this behavior as an artifact of the exponential fit, and the increased error that is inherent to extrapolations over such a long time scale in general. The key message of the exercise however is that both the minimum and maximum projections suggest that continued exponential growth of the ICT footprint, if unchecked, will reach as high as 14% of the total worldwide footprint, a clearly unacceptable level as it will definitely undermine any reductions achieved from the other GHGE emissions sources.

On the other hand, the linear fits show an increase to 6% and 7% for the minimum and maximum projections respectively. While a linear fit is unrealistically conservative, it still shows almost a doubling of the relative contribution of ICT from 2020 levels and a 10-fold increase from the 2007 levels. It's arguable that an incremental increase of 6% of the global levels of CO_2-e emissions from ICT might still seriously undermine the global efforts to curb GHGE emissions overall.

6. Discussion & limitations

The above analysis of the growing impact of ICT industry on the global carbon footprint takes into precise and methodical account the impact of the production footprint in addition to the energy consumption of the ICT devices. It also accounts and highlights for the first time the contribution of smart phones to the overall impact. While most of the reviewed literature has focused on the impact of personal computers, and mostly desktops, we found that by 2020, the contribution of PC's (including desktops and notebooks) accounts for no more than 13% of the total ICT impact, and is expected to continue to decline in relative terms beyond 2020, with most of the decline coming from the desktops sector, which dropped from 18% in 2010 to 7% in 2020, while notebooks dropped from a relative contribution of 8%–6% in the same period. Displays continue to contribute significantly to the overall footprint where they dropped from an overall 9%–7% in the same 10-year period.

The big surprise however in our findings is the disproportionate impact of smart phones by 2020, and its vertiginous growth from 4% in 2010 to 11% in 2020 in relative terms. In absolute terms, the GHGE emissions of smart phones grew from about 17 Mt–CO_2-e in 2010 to 125 Mt–CO_2-e in 2020, representing a 730% increase in the span of 10 years. This impact is clearly driven by the fact that the production energy makes up 85–95% of its lifecycle annual footprint, driven by the short average useful life of smart phones of 2 years, which is driven by the telecom membership business model. Clearly this business model, while highly profitable to the smart phone manufacturers and the telecom industry, is unsustainable and quite detrimental to the global efforts in GHGE reductions.

Furthermore, the contribution of the ICT infrastructure makes up the lion share of the overall industry impact, growing from 61% in 2010 to 79% in 2020. Most of that relative growth comes from the data center industry, which as we move increasingly into a digital age, has become the backbone of both the Internet as well as the telecom industry, and grew its contribution to the overall footprint from 33% in 2010 to 45% in 2020. In absolute terms, it shows an almost 3-fold increase from 159 to 495 Mt–CO_2-eq in the 10-year span.

Most concerning however is the continued growth of the ICT sector relative to all the other sectors and relative to the total worldwide footprint beyond 2020. Based on our regression fit, the exponential growth has a midpoint of 7.3% annual growth which, if unchecked through 2040, will bring ICT total footprint to amount to about 14% of the total global footprint.

To assess the validity of our overall results we compared our projections with the only two studies in the literature that attempted to forecast global ICT footprint. Malmodin et al. forecasted an ICT footprint of 1.1 Gt–CO_2–e by 2020 (Malmodin et al., 2013). Andrea & Edler Supplementary data projects a baseline scenario of 3.4 Gt–CO_2–e by 2030, with a best case and worst scenarios of 1.2 Gt and 13.8 Gt, respectively (Andraea. and Edler, 2015). Our study projects a min/max of 1.11/1.31 Gt–CO_2–e in 2020 and a min/max of 2.48/2.62 Gt-CO2 by 2030, and reaching a min/max of 5.1/5.3 Gt–CO_2–e by 2040 assuming business-as-usual. Our results are consistent with Malmodin et al.'s forecast for 2020, yet materially larger. This is consistent with the fact that Malmodin significantly under-estimated the contribution of the manufacturing energy of some of the key devices (Malmodin et al., 2010). Also, our results are mid-way between the best case and expected scenarios of Andrae and Edler. This is also consistent with the previously reported overestimation of the contribution of fixed access wired networks by Andrae and Edler, and which was acknowledged by the authors themselves (Andraea. and Edler, 2015).

All of the other studies we found only looked at the actual energy consumption of a more limited set of devices, and did not include the contribution of the production energy footprint, nor did any of them include the contribution of smart phones. Also, the projected growth rate of those studies, with the exception of supplemental dataset of (Andraea. and Edler, 2015), compared the energy consumption of a particular category of devices or infrastructure to the worldwide electricity consumption, and did not specifically estimate the actual GHGE footprint.

At a more granular level, our study of smart phones projects about 5.6 billion total units in use by 2030 and 8.7 billion units by 2040. Andrae & Edler, on the hand, project a total of 3.75 (best), 7.3 (expected) and 10.7 (worst) million units (smart phones, mobile phones and phablets) by 2030. However, a recent Mobility Report recently published by Ericcson, projects the total number of smart phone subscriptions at 6.8 billion by 2022 (Ericsson, 2017), or 1.2 billion units more than even our 2030 projections.

Insofar as the infrastructural side is concerned, an earlier study by Pickavet et al. found that Communication Networks and Data Centers would continue to grow through 2020 by 12%, while PCs would grow at 5.2% (Pickavet et al., 2008a). A more recent study by the Global e-Sustainability Initiative estimated that Communication Networks would grow by 11.5%, Data Centers by 7.1% and PC's would actually decline by 1.8% (GeSIBCG SMARTer 2020, 2012). Data Center consumption has been also widely debated but worldwide consumption data has been hard to come. For instance, a 2014 report by the Natural Resource Defense Council estimated that the US data centers consumed a total of 91 TWh in 2013, and projected to reach roughly 140 TWh by 2020, amounting to roughly 45.5 and 70 Mt CO2-eq in GHGE footprint for 2013 and 2020 respectively (Whitney, 2014). On the other hand, another estimation by the US Department of Energy done in 2016 found that US data centers consumed an estimated 70 TWh in 2014, representing 1.8% of total US electricity consumption (U.S. Department of Energy, 2016) (Shehabi et al., 2016). Comparing those estimates with our global projections of GHGE footprint, the US data center footprint would make up 16–20% of the global data center footprint in the world in 2014 and would drop to about 14% by 2020. Given that IP traffic, Internet usage and digital telecommunications are growing much faster in the developing world than in the US, this decrease in the relative energy consumption by US data centers is to be expected. Indeed, Cisco recently forecasted a compound annual growth rate (CAGR) in IP traffic of 42% in the middle east and Africa from 2016 through 2021, versus 20% in North America, with total worldwide IP traffic tripling from 2016 to 2021 and 63% of it generated by wireless and mobile devices by 2021 (Cisco, 2017). As a result, while the US data center sector growth is projected to grow at no more than a CAGR of 4% between 2016 and 2020 (Technavio, 2016a), thanks to efficiency improvements driven mostly by hyper-virtualization, this slower growth will be largely offset by the expected 13% growth in China (Technavio, 2016b) and 11% in the EMEA (Europe, Middle East and Africa) countries (Technavio, 2016c). Therefore, a global blended average growth of 10% from 2008 through 2020 is fairly realistic. Furthermore, when noting that this forecasted growth is in US dollars, and that server power per unit dollar has been consistently increasing, we can expect that a corresponding growth of energy consumption of 12% or more is actually quite conservative. It's further expected that the three major trends of (i) accelerated growth of the wireless and mobile computing, (ii) the emergence of the Internet-of-Things (IoT) and (iii) the massive movement to cloud-based computing will conspire to continue to push the growth in the supporting data center infrastructure and communication networks, especially in the emerging markets where these trends have not yet fully developed as in North America and Europe. Finally, these proportions of data center consumption of US v. World are well aligned with the total US electricity consumption relative to global consumption, which dropped from 23% in 2007 to 18.2% in 2016, and is expected, assuming a linear extrapolation, to drop to 13% by 2020 (Enerdata, 2017).

Perhaps, one of the most surprising finding of our study is the disproportionate contribution of mobile phones (which include smartphones and phablets) to the overall ICT footprint, amounting to 11% by 2020, reaching 3.6 billion units in use by that date, or about 46% of the total world population (United Nations, 2015). This is not only the result of the explosive proliferation of mobile phone around the world, but more so of the combined effect of the high production footprint and the short useful life, i.e. 2 years on average, which is subsidized by the payment plans of most telecom companies. This proportion is bound to continue to increase through 2040 as mobile phone ownership per capita continues to increase as a percent of the total world population which is expected to reach 9.15 billion inhabitants by 2040 (United Nations, 2015). Our calculations project a total number of mobile phones in use to reach a total of 8.7 billion units, or essentially 95% of the total size of the population. While this number may seem unrealistically high, it is so only if we assume an average of one mobile phone per person. The reality is that in developed countries, this average is higher than one. In Australia, for example, the number of total mobile phones subscriptions is higher than the total population, where the average Australian had around 1.31 phone subscription as of June 2015 (ACMA, 2014). This makes a 95% mobile phone ownership worldwide by 2040 a more realistic estimate. This unprecedented growth in mobile phone devices is equally bound to drive in part the continued growth in data centers and communications networks.

Clearly, should this kind of growth in the overall ICT industry go unchecked, it may seriously undermine any efforts to curb climate change. So, we offer in the remaining part of this discussion some recommendations on how to bring this impact under control without compromising economic growth or depriving future generations from the dual benefits of ICT technologies and livable climate.

6.1. Policy implications

Our top priority should be to tackle our biggest sources of CO_2 footprint, namely data centers and communication networks (Fehske et al., 2011). For instance, all new data centers must be required to run 100% on renewable energy, while existing ones must gradually shift towards renewable energy. Data centers must run extremely reliably on a 24/7 basis. They also have a very steady and predictable power consumption. In addition, they tend to be large facilities that can be setup in open land and remote areas. As such, they're uniquely suited to operate with solar energy, combined with a large energy storage for backup and after-hours, or with a solar and wind combination. Indeed, clean power is now becoming price-competitive with utility-sourced power in many markets, with life-cycle costs for Photovoltaic solar being as low as 7.42 cents/Kwh, wind at 5.85 cents/kWh, and geothermal at 4.23 cents/Kwh (U.S. Energy information Administration, 2016). The encouraging news is that we may already be seeing some concrete steps towards this goal. Recently, data center providers signed contracts for more than 1.2 GW of renewable energy power, and according to a survey by AFCOM (Association For Computer Operations Management), 34% of respondents had either deployed or are planning (within 18 months) to deploy renewable energy source for their data centers. Also, of those with existing deployment, 70% had operation solar systems, 50% had wind, and 10% had geothermal (Kleyman, 2016). Furthermore, Google who is by far the largest data center operator in the world, announced recently that 100% of its 2.6 GW of energy in 2017 will be sourced from renewable power (Google, 2017). Facebook's CEO also announced in July 2017 that all of their new data centers will be powered by 100% renewable energy (Zuckerberg, 2017). Facebook electricity consumption grew from 532 GW h in 2011 to 1830 GW h in 2016, amounting to about a 20% average yearly growth (Statista, 2017c).

Greening of communication networks, which is expected to be the second largest GHGE contributor is more challenging and more complex, for the simple reason that unlike data centers, which are massive and centralized infrastructures, communication networks are small, scattered and highly diverse in their characteristics and energy consumption profile. They range from cellular base towers and stations, to switches and routers, to wired, wireless and smart-grid networks. Insufficient data is available as to the penetration of renewable energy in this specific sector, and more research is needed in this area.

Next, we address the largest single contributor to GHGE by 2020 among the ICT devices, which is expected to be smart phones. While for the carbon footprint of ICT, infrastructure is primarily driven by its operating electricity consumption, the smart phones footprint on the other hand is primarily driven by its production energy and its short use life of 2 years. The production energy includes both the material extraction from the mining activities as well as the energy consumed during its manufacturing. Mitigating actions that could significantly reduce this inordinate carbon footprint should include at the very least (i) the switching to renewable energy for the manufacturing process, and even more importantly extending the use life of smart phones to 4 or more years. The latter however could face strong resistance from the phone manufacturers for whom the accelerated obsolescence of their cell phones is central to their business model. One way around that is for telecom companies to sell longer subscription plans at more attractive discounted rates to incentivize customers in keeping the same phone for a much longer period. Also, policy makers could get involved in devising tax incentives that would drive consumers to choose the longer plans.

Finally, the remaining category of ICT devices, i.e. Desktops, laptops and displays need to be addressed as well. While desktops' footprint received by far the most attention in the past, it is ironically expected to be the least significant of all by 2020, and set to continue to decline going forward. This decline was driven by the increased popularity, power, and convenience of laptops. However, the introduction of powerful tablets is also promising to continue to drive that decline faster, and eventually encroach on the laptops market. Indeed, tablets' portability, comfort of use, enhanced connectivity, touch screen functionality, and longer battery life are well poised to replace laptops once they overcome some of their shortfalls, such as relatively higher costs, lack of physical keyboards, and other software and hardware limitations, which are all transitory in nature (Griffey, 2012). This trend will help further erode the market share of desktops and laptops but not that of displays. If anything, it might drive its growth as more tablet users will seek out the larger form factors displays both at home and in the office to compensate for the smaller form factor of tablets. Hence it's our recommendation that displays need a more focused attention than either desktops or laptops as far as their carbon footprint is concerned. Display manufacturers and policy makers alike should take concerted action to reduce the growing footprint of displays with a combination of a greater level of renewable energy use during the manufacturing process, but more importantly the investment into research and development for the development of next generation low power displays.

6.2. Managerial implications

As the primary consumers of ICT devices and services, corporate managers have an essential role in assisting in the greening of the ICT industry. As computing continues to move rapidly to the cloud, companies must favor renewable-powered data centers and cloud services providers over the traditional ones. This will help accelerate the move to zero emissions data centers which could potentially cut 45% of the total ICT emissions as shown in Fig. 6(b). Next, they should migrate most of their workforce away from desktops and even laptops and towards high-performance low-power tablets, such as the Apple iPad Pro, Samsung Galaxy View, and the Microsoft Surface Pro. These devices consume a fraction of the energy of traditional laptops and desktops, and come with a much lower production footprint as well. Finally, companies that offer free smartphones to their employees must consider the impact of those perks on the environment and explore instead other means to finance the mobile communications of their employees without the need of a dedicated device with a very short lifetime.

6.3. Study's limitations

Some of the key limitations of this study is clearly its scope, where we have excluded some major ICT devices, such as smart TV's and gaming consoles. Because of their increasing connectivity, these devices contribute to the global footprint through their own production and operating consumption, but also through their reliance on communication networks and data centers, which must continue to grow to support their increasing adoption worldwide. Unfortunately, the consumer trend for smart TV's is for ever larger form factors, where they now reach as big as 72″ in size. They range in power consumption between 150 and 170 Watts, amounting to an average of about 140 kg CO_2-e per year, or roughly 3–4.5× the annual footprint of a laptop and almost 2–3x that of a 17-in LCD display (Azzabi, 2017). We could not find any data on the production energy of TV's or their average use lifetime, and hence are unable to estimate reliably their relative contribution to the ICT footprint. However, based on the total number of connected TV sets worldwide of 583.8 millions in 2016 (Statista, 2017d), which is roughly a third of the number of displays in use as of the same date, we can somewhat confidently assume that the GHGE relative contribution of smart TV's is comparable to that of displays, which would increase the total contribution of ICT relative to the worldwide GHGE by another 1%, bringing it to a projected 15% by 2040. Park et al. estimated that by 2015, the global use phase energy of annual shipments of TV's would reach and stabilize at about 36 TWh (Park et al., 2013). Assuming a useful life of 8 years per TV, and a 2% year-over-year increase through 2040, that would bring the total energy consumption from TV's to about 435 TWh, which would account for about 0.6% of the global footprint, which is in line with our rough estimate above. However, more careful estimates have to be made especially as TV size and complexity continues to increase dramatically and may significantly overcome the energy efficiency gains made by the industry. That said, it is unclear today what proportion of the global TV population are Internet-enable TV's and hence it is not fully justified to view all TV's as ICT devices. This is the same position taken by the SMARTer2030 report (GeSI, 2015).

Another limitation of our study, which is inherent to any study that tries to use historical growth to project more than 5 years out, is the high level of uncertainty and variability of our projections. This uncertainty is further exacerbated by the fact that the ICT industry has the fastest rate of change, and new technologies could indeed change dramatically the future GHGE impact of ICT. This however should not detract from the value of a detailed and methodical analysis of the ICT footprint as it stands today, or where it might take us assuming “business-as-usual” behavior. In fact, one certainly hopes that this study might motivate more research and more actions to prevent ICT from reaching those unsustainable and dramatic levels of emissions before its too late.

A final limitation of this study, and one that warrants further research, is the potential impact of the emergence of the Internet of Things (IoT). We are already witnessing Internet-enabled devices, ranging from the smallest form factor such as wearable devices, to home appliances, and even cars, trucks and airplanes. If this trend continues, one can envision every piece of hardware becoming “smart” and hence be Internet-enabled. One can only wonder on the additional load these devices will have on the networking and data center infrastructures, in addition to the incremental energy consumption incurred by their production. Unless the supporting infrastructure moves quickly to 100% renewable power, the emergence of IoT could potentially dwarf the contribution of all the other traditional computing devices, and dramatically increase the overall global emissions well beyond the projections of this study.

6.4. Recommendations for further work

Clearly, the limitations cited above as well as the rapidly evolving field of ICT warrant continued research on the subject. On the computing devices side, we foresee the emergence of ubiquitous IoT, where every device, equipment, appliance or vehicle becomes a “connected smart object”. This will eventually dwarf the footprint of the traditional computing devices. The connectivity of these smart objects will also create a whole new level of load on both data centers as well as networking infrastructure. As far as we know, very little, if any, scholarly work has been attempted in order to forecast what energy consumption or carbon footprint this new world of ICT could entail. Also, another source of concern that has recently emerged is the newly field of cryptocurrency, such as bitcoin, etherum, litecoin and many others, which rely on the trust-minimizing proof-of-work algorithm that uses the blockchain and mining concepts to ensure the integrity and security of all monetary transactions. A 2014 study by Dwyer and Malone found that the power used for bitcoin mining in 2014 was comparable to all of Ireland's electricity consumption in that same period (Malone, 2014). Since then however, the daily number of bitcoin transactions has had a massive growth with an average annual growth of 110% from 2012 through 2016 (Medium Corporation, 2017), which in turn requires a commensurate level of mining to maintain the integrity of the blockchain. Also, as the blockchain grows in size, the electricity consumption of a single bitcoin transaction grows accordingly. It has been estimated that a single bitcoin transaction in November 2017 requires an average of 215 KWh of mining with about 300,000 transactions per day (Malmo, 2017). The Digiconomist website estimated the bitcoin's electricity consumption at 0.13% of the total world's electricity's consumption as of November 21, 2017 (Digiconomist, 2017). These estimates are quite alarming, to say the least, and point to new and significant sources of carbon footprint that ironically are driven primarily by novel and rapidly emerging digital activities that are adding to, instead of replacing traditional industrial activities.

7. Conclusion

We have conducted in this study what we believe to be the most detailed, precise and methodical analysis of the ICT global GHGE footprint, which includes both the production and the operational energy of ICT devices, as well as the operational energy for the supporting ICT infrastructure. We have found that the ICT GHGE contribution relative to worldwide footprint will roughly double from 1 to 1.6% in 2007 to 3–3.6% by 2020. Assuming a continued annual relative growth ranging from 5.6 to 6.9%, ICT's relative contribution would exceed 14% of the 2016-level worldwide GHGE by 2040. Including the contribution of smart phones, we somewhat surprisingly found that smart phones would contribute about 11% to the total ICT footprint by 2020, exceeding the individual contributions of desktops (6%), laptops (7%) and displays (7%). The lion share of the emissions were found however to be generated by the ICT infrastructure with data centers being the largest culprit (45%), followed by communication networks (24%). Furthermore, we offered some actionable policy and managerial recommendations on how to mitigate and curb the ICT explosive GHGE footprint, through a combination of renewable energy use, tax policies, and alternative business models. Finally, we pointed out some directions for future work such as filling some of the obvious gaps of this study, and perhaps more importantly research the impact of novel and emerging digital activities such as the Internet of Things (IoT) and cryptocurrencies.

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References

ACMA, 2014. Communications Report 2013–14 [Online]. Available: https://www.acma.gov.au/theACMA/Library/Corporate-library/Corporate-publications/communications-report [Accessed 31 August 2017].

Andrae, A.S.G., Edler, A.T., 2015. On global electricity usage of communication technology: trends to 2030. Challenges 6, 117–157.

Apple Inc, 2016. Environment Reports. Apple Inc. [Online]. Available: www.apple.

com/environment/reports/ [Accessed 15 July 2017].
Azzabi, M., 18 05 2017. OLED and LED TV Power Consumption and Electricity Cost [Online]. Available: http://www.rtings.com/tv/learn/led-oled-power-consumption-and-electricity-cost [Accessed 04 September 2017].
Bhakar, V., Agur, A., Digalwar, A.K., Sangwan, K.S., 2015. Life cycle assessment of CRT, LCD and LED monitors. Procedia CIRP 29, 432–437.
Business Wire, 14 01 2004. A Berkshire Hathaway Company [Online]. Available: http://www.businesswire.com/news/home/20040114005796/en/PC-Shipments-Reach-Record-Levels-Battle-Market [Accessed 15 June 2017].
Chang, J., Meza, J., Ranganathan, P., Bash, C., Shah, A., 2010. Green server design: beyond operational energy to sustainability. Memory 4 (no. 10), 50.
Chwieduk, D., 2003. Towards sustainable-energy buildings. Appl. Energy 76 (no. 1), 211–217.
Ciceri, N.D., Gutowski, T.G., Garetti, M., 2010. A tool to estimate materials and manufacturing energy for a product. In: 2010 IEEE International Symposium on Sustainable Systems and Technology (ISSST).
Cisco, June 2017. The Zettabyte Era: Trends and Analysis, vol. 7. Cisco Inc. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html [Accessed 20 August 2017].
Curran, M., Mann, M., Norris, G., 2005. International workshop on electricity data for life cycle inventories. J. Clean. Prod. 13 (no. 8), 853–862.
Digiconomist, 21 11 2017. Bitcoin Energy Consumption Index [Online]. Available: https://digiconomist.net/bitcoin-energy-consumption [Accessed 22 November 2017].
Digital Home, 18 01 2011. Global PC Sales Top 350 Million in 2010 [Online]. Available: http://www.digitalhome.ca/2011/01/global-pc-sales-top-350-million-in-2010/ [Accessed 15 06 2017].
Enerdata, 2017. Global Energy Statistical Yearbook 2017.
EPA, 27 07 2017. Energy and the Environment: Greenhouse Equivalencies Calculator [Online]. Available. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator [Accessed 07 July 2017].
Ericsson, 2017. Ericcson Mobility Report - June 2017. Niklas Heuveldop.
Fehske, A., Fettweis, G., Malmodin, J., Biczok, G., 2011. The global footprint of mobile communications: the ecological and economic perspective. IEEE Commun. Mag. 49 (no. 8).
Fettweis, G., Zimmermann, E., 2008. ICT energy consumption-trends and challenges. In: Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications.
Firstpost, 31 01 2017. Global PC Shipments on Pace for 6 Percent Decline in 2009: Gartner [Online]. Available: http://www.firstpost.com/business/global-pc-shipments-on-pace-for-6-percent-decline-in-2009-gartner-1872971.html [Accessed 15 June 2017].
Fontecchio, M., Rouse, M., 2017. Power usage effectiveness (PUE) [Online]. Available: http://searchdatacenter.techtarget.com/definition/power-usage-effectiveness-PUE [Accessed 17 August 2017].
Gartner, 2007. Green IT: the new industry shockwave. In: Paper Presented at the Symposium/ITXPO Conference, San Diego, CA.
Gartner, 16 01 2008. Gartner Says Worldwide PC Market Grew 13 Percent in 2007 [Online]. Available: http://www.gartner.com/newsroom/id/584210 [Accessed 15 June 2017].
GeSI, 2015. Global e-Sustainability Initiative, "#SMARTer2030-ICT Solutions for 21 st Century Challenges. Accent.
GeSI, BCG SMARTer2020, 2012. SMARTer2020: the Role of ICT in Driving a Sustainable Future, 2012.
Gharavi, H., Ghafurian, R., 2011. Smart grid: the electric energy system of the future. Proc. IEEE 99 (no. 6), 917–921.
Google, 2017. 100% Renewable Is Just the Beginning [Online]. Available: https://environment.google/projects/announcement-100/ [Accessed 02 February 2017].
Government of Canada, 26 09 2013. Canadian Radio-television and Telecommunications Commission (CRTC), "CRTC Issues Annual Report on the State of the Canadian Communication System [Online]. Available: http://www.crtc.gc.ca/eng/com100/2013/r130926.htm [Accessed 05 July 2015].
Griffey, J., 2012. The rise of the tablet. Libr. Technol. Rep. 48 (no. 3), 7.
Helman, C., 2013. How much electricity do your gadgets really use? Forbes [Online]. Available: https://www.forbes.com/sites/christopherhelman/2013/09/07/how-much-energy-does-your-iphone-and-other-devices-use-and-what-to-do-about-it/#557ab6d22f70 [Accessed 15 July 2017].
IVF Industrial Research and Development Corporation, 2007. Lot 3: Personal Computers (Desktops and Laptops) and Computer Monitors.
Kleyman, B., 19 01 2016. Why Renewable Energy Will Power the Green Data Centers of Tomorrow [Online]. Available: http://datacenterfrontier.com/renewable-energy-will-power-the-green-data-centers-of-tomorrow/ [Accessed 02 September 2017].
Lambert, S., Heddeghem, W.V., Vereecken, W., Lannoo, B., Colle, D., Pickavet, M., 2012. Worldwide electricity consumption of communication networks. Optic Express 20, B513–B524.
Macworld from IDG, 19 01 2006. PC Market Achieved Double-digit Growth in 2005 [Online]. Available: http://www.macworld.com/article/1049005/pcmarket.html [Accessed 15 June 2017].
Malmo, C., 1 11 2017. One Bitcoin Transaction Now Uses as Much Energy as Your House in a Week [Online]. Available: https://motherboard.vice.com/en_us/article/ywbbpm/bitcoin-mining-electricity-consumption-ethereum-energy-climate-change [Accessed 22 November 2017].
Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N., 2010. Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors. J. Ind. Ecol. 14 (no. 5), 770–790.
Malmodin, J., Bergmark, P., Lundén, D., 2013. The future carbon footprint of the ICT and E&M sectors. In: On Information and Communication Technologies.
Malone, K. O. a. D., 2014. Bitcoin mining and its energy footprint. In: 2014 China-Ireland International Conference on Information and Communications Technologies (ISSC 2014/CIICT 2014).
Medium Corporation, 02 02 2017. Bitcoin Continues Exponential Growth in 2016 :: Blockchain Letter, February 2017 [Online]. Available: https://medium.com/@PanteraCapital/bitcoin-continues-exponential-growth-in-2016-blockchain-letter-february-2017-9445c7d9e5a2 [Accessed 22 November 2017].
Miller, R., 10 05 2011. Data Center Knoweldge [Online]. Available: http://www.datacenterknowledge.com/archives/2011/05/10/uptime-institute-the-average-pue-is-1-8/ [Accessed 17 August 2017].
National Energy Foundation, 2017. Simple Carbon Calculator [Online]. Available. http://www.carbon-calculator.org.uk/ [Accessed 27 July 2017].
Olivier, J.G., Janssens-Maenhout, G., Muntean, M., Jeroen, A.P., 2016. Trends in Global CO_2 Emissions 2016 Report. PBL Netherlands Environmental Assessment Agency, The Hague.
Paetz, A.G., Dütschke, E., Fichtner, W., 2012. Smart homes as a means to sustainable energy consumption: a study of consumer perceptions. J. Consum. Pol. 35 (no. 1), 23–41.
Park, W.Y., Phadke, A., Shah, N., Letschert, V., 2013. Efficiency improvement opportunities in TVs: implications for market transformation programs. Energy Pol. 59, 361–372.
Pickavet, M., Vereecken, W., Demeyer, S., Audenaert, P., Vermeulen, B., Develder, C., Demeester, P., 2008. Worldwide energy needs for ICT: the rise of power-aware networking. In: 2nd International Symposium on Advanced Networks and Telecommunication Systems.
Pickavet, M., Vereecken, W., Demeyer, S., Audenaert, P., Vermeulen, B., Develder, C., Colle, D., Dhoedt, B., Demeester, P., 2008. Worldwide energy needs for ICT: the rise of power-aware networking. In: 2nd International Symposium on Advanced Networks and Telecommunication Systems.
Raghavan, B., Ma, J., 2011. The energy and emergy of the internet. In: Proceedings of the 10th ACM Workshop on Hot Topics in Networks.
Thompson Reuters, "Smartphone Subscribers Likely to Double by 2020: Ericsson Forecast.," 18 11 2014. [Online]. Available: http://in.reuters.com/article/2014/11/18/lm-ericsson-mobilephone-idINKCN0J20P120141118.[Accessed 14 April 2015].
Roth, K., McKenney, K., 2007. Energy Consumption by Consumer Electronics in U.S. Residences. Lexington, SC: TIAX LLC. TIAX LLC., Lexington, SC.
Shehabi, A., Smith, S., Sartor, D., Brown, R., Herrlin, M., Koomey, J., Masanet, E., Horner, N., Azevedo, I., Lintner, W., 2016. United States data Center Energy Usage Report.
Statista, "Carbon dioxide emissions from energy consumption in the U.S. from 1975 and 2016 (in million metric tons of carbon dioxide)*," 15 11 2017. [Online]. Available: https://www.statista.com/statistics/183943/us-carbon-dioxide-emissions-from-1999/. [Accessed 23 November 2017].
Statista, 2017. Shipment Forecast of Laptops, Desktop PCs and Tablets Worldwide from 2010 to 2020 (In Million Units) [Online]. Available: https://www.statista.com/statistics/272595/global-shipments-forecast-for-tablets-laptops-and-desktop-pcs/ [Accessed 15 June 2017].
Statista, 2017. Global smartphone shipments forecast from 2010 to 2021 (in million units) [Online]. Available: https://www.statista.com/statistics/263441/global-smartphone-shipments-forecast/ [Accessed 20 06 2017].
Statista, 2017. Electricity Consumption by Facebook from 2011 to 2016 (In Gigawatt Hours) [Online]. Available: https://www.statista.com/statistics/580087/energy-use-of-facebook/ [Accessed 02 September 2017].
Statista, 2017. Number of Connected TV Sets Worldwide from 2010 to 2018 (In Millions) [Online]. Available: https://www.statista.com/statistics/247160/forecast-of-the-number-of-connected-tv-sets-worldwide/ [Accessed 04 September 2017].
Stocker, T., 2014. Climate Change 2013: the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
Suckling, J., Lee, J., 2015. Redefining scope: the true environmental impact of smartphones? Int. J. Life Cycle Assess. 20, 1181–1196.
Technavio, 2014. Global Data Center Market 2014-2018 [Online]. Available: https://www.technavio.com/report/global-data-center-market-2014-2018 [Accessed 20 August 2017].
Technavio, 2015. Global Data Center Market 2015-2019 [Online]. Available: https://www.technavio.com/report/data-center-market [Accessed 20 August 2017].
Technavio, 2016. Ata Center Construction Market in the US 2016-2020 [Online]. Available: https://www.technavio.com/report/usa-data-center-construction-market [Accessed 20 August 2017].
Technavio, 2016. Data Center Market in China 2016-2020 [Online]. Available: https://www.technavio.com/report/china-data-center-data-center-market [Accessed 20 August 2017].
Technavio, 2016 [Online]. Available: https://www.technavio.com/report/middle-east-data-center-data-center-cooling-solutions-market-emea-2016-2020 [Accessed 20 08 2017].
Teehan, P., Kandlikar, M., 2012. Sources of variation in life cycle assessments of desktop computers. J. Ind. Ecol. 16 (no. S1), S182–S194.
United Nations, 2015. UN Department of Economic and Social Affairs [Online].

Available: http://www.un.org/en/development/desa/population/theme/trends/index.shtml [Accessed 31 August 2017].

United Nations Framework Convention on Climate Change, 2016. The Paris Agreement, United Nations Framework Convention on Climate Change [Online]. Available: http://unfccc.int/2860.php [Accessed 13 July 2017].

Urban, B., Shmakova, V., Lim, B., Kurt, R., 2014. Energy Consumption of Consumer Electronics in u.S. Homes in 2013. Fraunhofer USA Center for Sustainable Energy Systems, Boston.

U.S. Department of Energy, 2016. FEMP Data Center Program Overview. U.S. Department of Energy.

U.S. Energy information Administration, 2016. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016. U.S. Energy information Administration.

U.S. Environmental Protection Agency, 2016. Sources of Greenhouse Gas Emissions [Online]. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions [Accessed 15 April 2017].

US Environmental Protection Agency, 2017. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015 [Online].

Van Heddeghem, W., Lambert, S., Lannoo, B., Colle, D., Pickavet, M., Demeester, P., 2014. Trends in worldwide ICT electricity consumption from 2007 to 2012. Comput. Commun. 50, 64–76.

Vereecken, W., Deboosere, L., Simoens, P., Vermeulen, B., Colle, D.D.C., Demeester, P., 2009. Energy efficiency in thin client solutions. In: In International Conference on Networks for Grid Applications.

Wann, D., 2011. The New Normal: an Agenda for Responsible Living. Macmillan.

Webb, M., 2008. SMART 2020: Enabling the Low Carbon Economy in the Information Age, a Report by the Climate Group on Behalf of the Global ESustainability Initiative (GeSI). Global eSustainability Initiative (GeSI).

Whitney, J.A.P.D., 2014. Data Center Efficiency Assessment. National Resources Defense Council.

Williams, E., 2004. Energy intensity of computer manufacturing: hybrid assessment combining process and economic input– output methods. Environ. Sci. Technol. 38 (no. 22), 6166–6174.

Williams, E.D., 2004. Revisiting energy used to manufacture a desktop computer: hybrid analysis combining process and economic input-output methods. In: Electronics and the Environment.

Yi, L., Thomas, H.R., 2007. A review of research on the environmental impact of e-business and ICT. Environ. Int. 33 (no. 6), 841–849.

Zuckerberg, M., 2017. Mark Zuckerberg Facebook Page [Online]. Available: https://www.facebook.com/zuck/posts/10103897271229011 [Accessed 02 September 2017].