Sending fewer emails will not save the planet! An approach to make environmental impacts of ICT tangible for Canadian end users

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Abstract

Information and communication technologies (ICT) need significant quantities of resources and energy to produce and power all infrastructure that is related to the use of digital data and the users' electronic devices. To inform Internet users of the impacts of ICT on the environment and the benefits of changing their behaviour, we propose a simple, multi-criteria and flexible approach to quantify three environmental impacts caused by the use of digital services in Canada. Our approach consists of quantifying the electricity consumption that is related to the use of digital services and electronic devices. We also consider the carbon footprint of the main electronic devices that are needed to use digital services. The proposed approach was tested through a hypothetical case study including three digital service user profiles, three levels of data transmission and storage performance, and three electricity mixes. Overall, the main sources of impacts are, in order of importance, the manufacture of electronic devices, the use of electronic devices, and viewing of video streaming. Some iconic digital activities, such as sending emails, contribute very little to a user's annual impact. The results also highlighted the importance of the methodological choices and data sources that are used to quantify the impacts of digital services, such as sources of electricity production, energy performance of digital data transmission and storage, and users' behaviour. The relevance and limitations of the proposed approach are discussed extensively in the article. Finally, it is essential to establish a shared action plan between citizens, states and companies to build a digital industry that is compatible with planetary boundaries.

Keywords: Information and communication technology (ICT); Environmental impacts, Methodological issues, Video streaming, Electronic devices; Consumer behaviour.

1. Introduction

The information and communication technologies (ICT) industry has experienced tremendous success over the past few decades. Data traffic has increased from 100 GB per day in 1992 to 46,600 GB per second in 2017 and may reach 150,700 GB per second during 2022 (Cisco, 2019). The explosion in the use of digital data has been accompanied by the extensive use of electronic devices in our daily lives. In 2019, the four billion users of digital services worldwide owned 34 billion digital devices (excluding accessories such as chargers, keyboards, mice, USB keys, etc.) (Bordage, 2019). Although the number of Internet-of-Things (IoT) devices is difficult to estimate, the number of electronic devices that are connected to the Internet is expected to reach 200 billion units by 2030 (Pirson and Bol, 2021).

Driven by the increasing insertion of digital technologies into several economic sectors, together with the proposal for new services and the expansion of digital technologies into developing countries, the digital industry is expected to continue growing over the next decade (Global e-Sustainability Initiative, 2015). The growing number of users of digital services is undoubtedly good news for the economic growth of the sectors concerned. Yet, the growth of this industry is increasingly raising environmental concerns. Indeed, ICT needs significant quantities of resources and energy to produce and power all of the infrastructure that is related to the use of digital data and the users' electronic devices (Belkhir and Elmeligi, 2018; Hischier et al., 2015; Malmodin and Lundén, 2018). Given this high energy consumption, the ICT industry was responsible for emissions of 1.2-2.2 Gt CO_2 in 2020, which represents 2.1%-3.9% of annual global greenhouse gas emissions (GHG) of anthropogenic origin (Freitag et al., 2021).

Despite these significant impacts of ICT, the digital industry provides solutions that significantly reduce CO_2 emissions and the energy consumption of other economic sectors. According to Global e-Sustainability Initiative (2015), substantial digitization of the economy would make it possible to reduce GHG emissions by 20% on a global scale. Yet, there is no consensus on the net benefits of digital technology, especially because of rebound effects, which are not quantified in most studies (Court and Sorrell, 2020; Galvin, 2015; Lange et al., 2020).

For the digital industry to become an ally in reducing environmental impacts, it must reduce its own emissions. For this purpose, it is necessary that digital data providers, manufacturers of electronic devices, and end users implement concrete actions. For the last group, the apparent immateriality of digital services hides the impacts of ICT. It is difficult, therefore, for users to reduce environmental impacts when they do not even know that these exist. The role of consumers is all the more important given the increase in the number of people who are connected to the Internet worldwide: from 17% (1.1 billion users) in 2005 to 51% in 2019 (4 billion users) (International Telecommunication Union, 2021). The number of people who are connected to the internet is expected to reach 66% of the world's population (5.3 billion users) by 2023 (Cisco, 2020). Informing Internet users of the environmental impacts of ICTs and the benefits of behavioural changes, therefore, is an essential task in helping the ICT industry to reduce its environmental impacts (Obringer et al., 2021). In this context, we propose a simplified approach for estimating the environmental impacts of digital service consumers.

The effectiveness of environmental approaches or tools relies, in particular, upon psychological mechanisms of self-confrontation to encourage environmentally friendly behaviours (Mallett et al., 2013). In recent years, several approaches aimed at estimating the environmental impacts of various individual daily activities (transport, food, heating, recycling, purchase of products, and others) have been proposed, especially to quantify their carbon footprints (Mulrow et al., 2019). Other more specific approaches have aimed to raise awareness of a particular audience, such as university students (Auger et al., 2021), researchers (Mariette et al., 2021) and smartphone users (Andersson, 2020). In 2018, The Shift Project created the Carbonalyser to quantify the environmental impacts of digital services (The Shift Project, 2020a). This tool counts the quantity of data passing through a web browser or smartphone and translates it into CO_2 eq. emissions according to the geographical location (five possible regions). However, Carbonalyser does not consider the production of electronic devices or their electricity consumption. Datagir has also created an online calculator that is aimed at quantifying a person's carbon footprint by consumption category (including digital services) (Datagir, 2020). Yet, this calculator assesses a very limited number of digital services. Moreover, these two tools only quantify GHG emissions, which do not help users to understand the other environmental effects of digital technology, such as water consumption and land occupation.

Globally, Canada is among the greatest per-capita consumers of digital data. The country has 35 million Internet users (94% of the country's population) (Hootsuite, 2021) and, in 2019, each household used 192 GB of digital data per month (CRTTC, 2020) . An average Canadian generates 21.2 kg of electronic waste per year (22 kg annually for an inhabitant of the United States) (Baldé et al., 2017). In light of the significant consumption of digital data and electronic products in Canada, it is crucial to make Canadians aware of the environmental consequences of using ICTs. To do this, we propose a simplified, multi-criteria and flexible approach that allows to quantify the carbon footprint, the water footprint and the land footprint related to the electricity consumed by digital services commonly used by consumers in a Canadian context. Through a hypothetical case study on several digital service user profiles, we discuss the applicability of the proposed approach and the methodological limitations associated with assessing the environmental impacts of ICT.

The proposed approach is aimed at all professionals who are familiar with environmental indicators and who wish to popularize the environmental impacts of digital technology with end users. The approach could be applied, for example, to raising awareness among students (universities, high schools, colleges), employees of companies that are committed to reducing their environmental impacts, and participants in events to raise awareness of the environmental impacts of digital technologies. Since the proposed approach is approximate, it is not suitable for companies that develop digital services. Through the use of this approach, we hope that digital end users will become aware of their digital environmental impacts and be able to reduce them.

2. Methods

2.1 General Description

We based our methodological approach partly upon the one that was proposed by Obringer et al. (2021) to quantify the carbon, water and land footprints that are related to the use of digital data (**Table 1**). Note that these footprints do not follow certification standards such as ISO 14067 for carbon footprint and ISO 14046 for water footprint (ISO, 2019, 2014). Indeed, these standards quantify environmental impacts over the entire life cycle of products and services. Our study consists only of quantifying the environmental impacts that are related to the **i)** direct consumption of electricity necessary to transfer and store digital data and to power the electronic devices of the end users, and **ii)** the energy necessary to manufacture the electronic devices of the end users. The scope of our study is consistent with most studies that have quantified the impacts of ICT.

Although the development of our approach is inspired by that of Obringer et al. (2021), there are important differences between them. First, the latter authors did not quantify the impacts associated with the manufacture of end-user electronic devices and infrastructure for the transmission and storage the data (e.g., servers, cables, transmission towers, and others). We have taken this methodological bias into consideration, in part, by adding the carbon footprint of the manufacture of 21 electronic devices commonly purchased by users of digital services. Another limitation to the approach of Obringer et al. (2021) is to overlook the impact of the electricity consumption of electronic devices to use digital services. Finally, these authors only considered the use of a wired network for data transmission. In our case, we have included the transmission of data from a mobile and a WiFi network. We also considered the electricity consumption of electronic devices by users. Given that the objective of this approach is to inform on how the use of digital services affects selected energy-related environmental indicators, it is important to quantify impacts of the use of electronic devices and several types of Internet networks.

There are two approaches to estimating the impacts of digital data usage, i.e., a conventional (or linear) approach and a power (or marginal) approach. The conventional approach expresses the energy consumption of the Internet network based on the average energy used per volume of data (kWh GB^{-1}). In other words, watching a 4k-quality movie (7 GB $hour^{-1}$) has a 2.3-fold greater impact than watching a movie in full HD (3 GB $hour^{-1}$). The power approach consists of assigning a base power per duration of use of a digital service and marginal energy consumption according to the volume of data that are consumed.

Overall, the two approaches have different objectives. The conventional approach quantifies the average impact of a digital service (attributional perspective), while the marginal approach quantifies the impact on networks due to additional data demand (consequential perspective). One of the main criticisms of the attribution approach is its inability to describe the reality of digital network usage (Malmodin, 2020). In our case, the conventional approach is used because of the need to simplify evaluations for a large number of digital activities and also because of the absence of specific data from

Canadian fixed and mobile networks. Indeed, the development of the marginal models requires primary data from data providers in the region where the impacts of digital services are being quantified (Carbon Trust, 2021). In contrast to the conventional approach, the marginal approach attempts to reflect the energy consumption of a network more realistically. To do so, two allocations are made. First, the operating energy of a network (sized to cope with peak demand) is allocated according to the time of use of digital activity and the number of active devices. Then, the energy of dynamic network components is allocated to the additional demand for digital data (e.g., increasing the resolution of a video).

Analogous to Obringer et al. (2021), we also used the conventional approach. Indeed, we propose a methodological approach that provides an overview of the annual impact of digital users according to their behaviours. In this case, the more bandwidth a user consumes, the more they are responsible for the impacts that are associated with data consumption. However, the use of the electronic devices and the WiFi router depends on the hourly usage and not on the data consumption. The advantages and disadvantages of two approaches are further discussed in this paper. The following sections describe the methodological bases used to quantify the environmental impacts associated with the use of digital services.

2.2 Quantification of Environmental Impacts Related to the Use of Digital Data

Knowing that that our approach consists of quantifying the environmental impacts from the final electricity consumption that is required to transfer and store the data, we use the emission factors of the electricity mix of the country where a user is located to calculate the impacts of data storage and transfer. This choice is necessary because mobile networks and WiFi routers use electricity sources of the region in which the end users are situated. Regarding data storage and fixed networks, we based our choice on the operation of the Netflix distribution network, where connections are physically located at the interconnection points that are geographically closest to the user (Netflix, 2016). Netflix copies each file once from its transcoding repository in the United States to storage locations around the world. This is an optimistic hypothesis, but it allows us to verify the influence of each Canadian province's electricity mix on environmental impacts. Indeed, the electricity production profile varies substantially depending upon province (Requia et al., 2017). For this reason, we have refined the analysis by using the electricity mix at the provincial level. The electricity mix refers to all of the electrical sectors (e.g., nuclear, hydraulic, oil, natural gas, and others) that are used by a region to produce and distribute electricity to consumers. Yet, in a manner analogous to Obringer et al. (2021), we consider only the domestic production of each province. In other words, imports and exports of electricity have not been accounted for. Given that Canada is a net exporter of electricity (Canada Energy Regulator, 2020), this methodological bias should only marginally affect our results.

The first step was to identify the electricity production mix of each Canadian province. For this purpose, data that are provided by the Canadian government were used (National Energy Board, 2018). Knowing that solar and wind electricity production data are grouped together, we have allocated production according to their respective market shares. In 2015, Canadian wind farms delivered 28,561 GWh, or 4.4% of national electricity production. In turn, solar parks produced 3,007 GWh, or 0.5% of national electricity production (National Energy Board, 2016). Therefore, we have allocated 90% of total production of the solar/wind branch to wind production and 10% to solar production. The data also include electricity that is produced from biomass and geothermal energy. Yet, we only considered production from biomass, given that geothermal energy remains a very marginal technology in Canada. As shown in Appendix B, most electricity produced in Canada is derived from renewable energy, particularly hydropower (59%) and wind power (5%). Next comes nuclear (15%) and fossil fuels (19%). Bioenergy, solar and geothermal energy account for about 2% of national electricity production. The carbon, water and land-use intensities of electricity generation sources are summarized in **Table 1**. These figures represent average impacts from meta-analyses of the impacts of electricity production from several technologies and countries.

Table 1
Carbon, water and land-use intensities of electricity generation sources.

Source	Carbon footprint (kg CO_2 eq. kWh^{-1})[a]	Water footprint (m^3 GJ^{-1})[b,c]	Land footprint (m^2 MWh^{-1})[b]
Coal	0.82	1.148	5
Oil	0.675	0.82	0.4
Natural Gas	0.49	0.582	0.2
Nuclear	0.012	0.248	0.1
Hydro	0.024	9.305	10
Bioenergy	0.23	35.29	500
Wind: Onshore	0.011	0.118	1
Solar PV	0.048	0.179	10

[a]Emission factors for oil production and combustion are taken from Obringer et al. (2021). For other energy sources, we used emission factors that were proposed by Schlomer et al. (2014).

[b]Obringer et al. (2021).

[c]This characterization factor is the sum of the quantity of water required to produce electricity from a given energy source (m^3 GJ^{-1}) and the water used for the air conditioning of data centers (m^3 TJ^{-1}). According to Obringer et al. (2021), the air conditioning of data centers requires an average of 118 m^3 TJ^{-1}.

The next step was to determine the energy intensity of storing and transmitting digital data. Due to the lack of data on the energy intensity of data storage and transfer in Canadian mobile and fixed networks, a range of values was used to show the variability of results depending on the level of technological maturity of ICT infrastructures. In **Table 2**, the lower values represent the more efficient and modern networks. In contrast, the higher values represent less efficient and older digital infrastructures.

Table 2
Values used to quantify the impacts of digital infrastructures related to data storage and transmission

ICT infrastructure	Unit	Performance scenarios			Sources/comments
		Low	Average	High	
Data centres	kWh GB^{-1}	0.072	0.02	0.01	Kamiya (2020). Calculated for 2019.
Fixed transmission network	kWh GB^{-1}	0.29	0.06	0.0065	Low: Shehabi et al. (2014). Calculated for 2011. Average: Aslan et. al (2018). Calculated for 2015 High: Carbon Trust (2021). Calculated for 2020
Mobile transmission network	kWh GB^{-1}	7.53	0.75	0.01	Pihkola et. al (2018). Values represent the years 2011, 2015 and 2020
WiFi router[a]	W	15	10	5	Carbon Trust (2021).

[a]We consider a WiFi router as an individual electronic device of digital users. Therefore, the WiFi router depends on the hourly usage of digital services and not on the data consumption.

2.2.1 Electricity Consumption

Electricity consumption of transmission and storage of digital data, together with the use of electronic devices by users, were used as intermediate data to quantify environmental impacts. Equation 1 quantifies the annual electricity consumption that is attributable to the use of digital services.

$$EC_{j,r,e} = VD_j * T_j * 52 * \left(DC_j + TN_{r,j}\right) + T_j * 52 * ED_{e,j} \quad (1)$$

where $EC_{j,r,e}$ is the amount of electricity required to use the digital service *j* with the network *r* and the electronic device *e* for one year [kWh yr^{-1}], VD_j is the volume of data that is mobilized by the digital service *j* [GB h^{-1}], T_j is the time of usage of the digital service *j* (hours per week), 52 is the number of weeks in a year, and DC_j is the electricity consumption by a data centre to store 1 GB of data to provide the digital service *j* [kWh

GB^{-1}]. $TN_{r,j}$ is the electricity consumption that is needed to transfer 1 GB of data through a network r to provide the digital service j [kWh GB^{-1}]. $ED_{e,j}$ is the electricity consumption of an electronic device e that is required to use the digital service j [kWh device hr^{-1}].

It should be noted that we attribute 100% of the use of a digital service to a single user. However, it is possible to add a multiplying factor to formulas 1, 2 and 3 to consider activities that are conducted in groups. For example, it could be considered that three people, on average, watch the same film when a television is used. Therefore, this total impact would be divided by three. If the objective is to quantify unitary digital activities (sending an email, downloading a photo, downloading a film, and others) rather than time-of-use of a digital service (watching an hour of film, listening to one hour of music, one hour of videoconference, and others), the equation can be modified to quantify the electricity consumption of unitary digital activities (see Appendix B).

2.2.2 Carbon Footprint

The emission factors that were proposed by Schlömeret al. (2014) and Obringer et al. (2021) (**Table 1**) were selected to quantify the carbon footprint of the electricity mix of each Canadian province. The emission factors that were used to quantify the carbon footprint of each electricity production source are based on a life cycle perspective, where direct and indirect emissions and infrastructure are taken into account (Schlomer et al., 2014). Equation 2 yields the annual carbon footprint of a digital service that is used in a Canadian province.

$$CF_{j,p} = \sum_{i=1}^{energy\ sources} CI_i * ratio_{i,p} * EC_{j,r,e} \qquad (2)$$

where $CF_{j,p}$ is the quantity of CO_2 eq. attributable to electricity use of a digital service j in province p [kg CO_2 eq. yr^{-1}], CI_i is the carbon intensity of the energy source i [kg CO_2 eq. kWh^{-1}], $ratio_{i,p}$ is the proportion of energy source i in the electricity mix of province p [%].

2.2.3 Water Footprint

The water footprint sums the amount of water that is required to generate electricity from a given energy source (m^3 GJ^{-1}) with the water that is used for cooling data centres (m^3 TJ^{-1}) (**Table 1**). Equation 3 yields the partial water footprint of a digital service. The water footprint refers to the volumes of water that are consumed and polluted at different stages of the production of an electricity source (fuel supply, construction and operation) (Mekonnen et al., 2015). Note that fuel supply is only relevant for electricity generated from fuel (coal, oil, gas, uranium and biomass).

$$WF_{j,p} = \sum_{i=1}^{energy\ sources} WI_i * ratio_{i,p} * 3.6 * EC_{j,r,e} \quad (3)$$

where $WF_{j,p}$ is the amount of water attributable to electricity use of a digital service j in province p [L yr^{-1}], WI_i is the water intensity for energy source i [m^3 GJ^{-1}], $ratio_{i,p}$ is the proportion of energy source i in the electricity mix of province p [%], 3.6 is the multiplier used to convert WI_i from m^3 GJ^{-1} to L kWh^{-1}.

2.2.4 Land Footprint

The characterization factors that have been proposed by Obringer et al. (2021) (**Table 1**) were used to quantify the land footprint of the electricity mix of each Canadian province. Equation 4 yields the partial land footprint of a digital service. The land footprint includes the area that is occupied by the power plants and upstream life cycles (e.g., mining and fuel supply) (Fritsche et al., 2017). It should be noted that areas occupied by data centres are not included in our analysis.

$$LF_{j,p} = \sum_{i=1}^{energy\ sources} LI_i \times ratio_i * 0.001 * EC_{j,r,e} \quad (4)$$

where $LF_{j,p}$ is the area, in square metres, attributable to electricity use of a digital service *j* in province *p* [m^2 yr^{-1}], LI_i is the land-use intensity of the energy source *i* [m^2 MWh^{-1}], $ratio_{i,p}$ is the proportion of energy source *i* in the electricity mix of province *p* [%], 0.001 is the multiplier that is used to convert LI_i from m^2 MWh^{-1} to m^2 kWh^{-1}, and WI_{world} is the average water intensity of the world electricity mix [m^2 kWh^{-1}].

2.3 Quantifying the Carbon Footprint of Electronic Devices

Data from ADEME (2017) were used to quantify the carbon footprint of electronic device production (**Table 3**). ADEME data were selected because they are freely accessible and robust, and they include a wide variety of products. However, it is important to note that the carbon footprint and electricity consumption (Schien et al., 2013) can vary significantly depending on the type, brand and model of electronic devices (see section 4.3.3). Since life cycle inventories of the products that are analyzed by ADEME are not available, it was not possible to quantify the other impacts (the respective water and land footprints) with this database.

Table 3
Carbon footprints of selected electronic devices and their electricity consumption

Electronic devices	Production (kg CO_2 eq.)[a]	Electricity consumption (kWh)[b]
Basic mobile phone	16	0.0012
Smartphone (< 4.5 in.)	27	
Smartphone (5 in.)	33	
Smartphone (> 5.5 in.)	39	
Mini tablet (< 9 in.)	41	0.0028
Regular tablet (9-11 in.)	63	0.0035

Detachable tablet (10-13 in.)	82	
Unbacklit e-reader	38	-
Backlit e-reader	45	-
Laptop	156	0.027
Desktop	169	0.13
High performance desktop	295	0.30
Screen (21.5 in.)	222	0.04
Screen (23.8 in.)	248	0.05
LCD TV (30-40 in.)	340	0.11
LCD TV (40-49 in.)	371	0.14
LCD TV (> 49 in.)	500	0.18
Home video game console	74	0.165
Mobile video game console	31	0.018
Connected watch	10	-
Bluetooth speaker	9	-

[a]ADEME (2017)

[b]See **Appendix B** and references therein. The values represent the electric consumption of the devices for one hour of use.

The carbon footprint has been quantified from *cradle-to-gate*, i.e., from extraction of raw materials to the finished product leaving the factory. ADEME (2017) considers that the manufacture of products is spread over several Asian countries from the manufacturing and assembly stages throughout the production chain, including logistics. In our study, the stages of transport from the production plant to Canada and the end of life of electronic devices were not considered. Equation 5 quantifies the annual carbon footprint of an electronic device.

$$CF_{device} = \frac{CF_{electronic\ products}}{T} \quad (5)$$

where CF_{device} is the annual carbon footprint of an electronic device [kg CO_2 eq. yr^{-1}], $CF_{electronic}$ products is the carbon footprint of electronic device manufacturing [kg CO_2 eq.]

and T is the time of possession of an electronic device by its owner before buying another one [years].

We consider that the time of possession of an electronic device (T) corresponds to its total lifespan. Therefore, we allocate the entire carbon footprint of an electronic device to its first user, even if the device is perfectly functional for second-hand use (second user). The formula can be modified to consider the purchase of a used electronic device by simply adding the time of possession of its first user to T.

2.4 Usage Scenarios of Electronic Devices and Digital Data

Due to the lack of data for Canada regarding the time that is expended for specific digital activities, we made assumptions based upon a usage profile. For this purpose, we created three digital user profiles: conscientious, moderate and intensive. Here, the notion of "conscientious user" refers to the conscious effort to reduce the digital footprint of one's daily digital lifestyle. The difference from one user to another is not only related to the number of hours of use of specific digital services, but also depends upon how ICTs are used (e.g., changing smartphones frequently, watching videos at very high resolution, holding meetings in HD and with the camera on, and others). We assume that the three types of users are teleworking due to health constraints that have been imposed by the COVID-19 pandemic. For this reason, the number of hours in videoconferencing is the same for the three types of users. In contrast, the way of attending meetings changes according to the profile of use. For example, an intensive user will tend to never turn off their camera. Conversely, a conscientious user will turn on the camera only when it is essential. **Table S1 (Appendix A)** presents assumptions that are related to the use of digital services, together with the time of possession of electronic devices according to each user profile.

In order to illustrate the influence of the electricity mix of the Canadian provinces on environmental impacts, we also selected three situations: Province of Alberta, Province of Québec, and the Canadian average. The choice of Alberta (4.4 million inhabitants) and Québec (8.5 million inhabitants) is based upon their contrasting proportion of electricity from renewable energy sources. Alberta has only about 9% renewable energy in its electricity mix, while 98% of the electricity that is produced in Québec comes from hydropower (National Energy Board, 2018). Therefore, it would be possible to verify the effect of using a carbon-intensive electricity mix, a mainly renewable mix, and the Canadian average on environmental impacts. Although only three electricity scenarios are compared in the results, we have quantified environmental impacts for all Canadian provinces (**Appendix B**).

3. Results

Changes in the behaviour of users of digital services are proving to be very effective in reducing their environmental impacts. The performance of ICT infrastructure and the composition of the electricity mix, even if these parameters are beyond the reach of consumers, also play a fundamental role in reducing impacts. We can observe that high performance of digital data transmission and storage significantly reduces the impacts (**Fig. 1** and **Table S2 - Appendix A**). In contrast, impacts are very high when low ICT infrastructure performance is associated with intensive consumption of digital services in regions, for example, with a carbon-intensive electricity mix. Despite its importance, efficient ICT infrastructure use alone is not enough to reduce the sector's impacts. In the case of the carbon footprint, for example, the main source of impact is the production of electronic equipment. In this case, even highly efficient digital services cannot compensate for the purchase of a lot of electronic equipment, which is why it is important to adopt environmentally friendly behavioural changes.

Moreover, since the energy intensity of ICTs decreases rapidly as the energy performance of digital infrastructure improves and the number of users on the networks increases (Aslan et al., 2018), it is important to know the technological maturity level of the networks being evaluated so as not to overestimate or underestimate the impacts of digital services. For example, using older data to quantify the impacts of current digital services in regions with efficient infrastructure overestimates the impacts of digital services.

When we compare an intensive profile vs. a conscientious profile in Québec, for the average ICT scenario, we observe a ~270% difference in the carbon footprint. This difference is about 310% in Alberta. These results reveal that a Québec resident could consume between 5% (conscientious user) and 17% (intensive user) of their annual carbon budget through the use of ICTs. This concept refers to the annual CO_2 emission limitation for each citizen in the world (between now and 2030) to limit the temperature increase to 1.5 degrees Celsius (United Nations Environment Programme, 2020). By dividing the carbon footprint of each user by 2.1 t CO_2 eq. yr^{-1} (average carbon budget), we can thus estimate the annual contribution of digital services to the carbon budget of users (see **Table S3 – Appendix A** for more information upon converting environmental impacts into equivalent activities). As an indication, average emissions of a Quebecker in 2019 were around 10 t CO_2 eq. (Environment and Climate Change Canada, 2021). Thus, the share of emissions that can be attributed to digital services would represent the equivalent of between 1 and 4% of the emissions of a Quebecker. In the case of Alberta (63 t CO_2 eq. per capita in 2019; Environment and Climate Change Canada, 2021), an Albertan could consume between 10% (conscientious user) and 40% (heavy user) of their annual 1.5 °C carbon budget scenario (between 0.3% and 1.3% of an Albertan's emissions). Regarding the other two indicators (water and land footprint), the difference between intensive and conscientious use is about 350% for both Québec and Alberta. It should be noted that the impact intensities for the water and land footprints are generic and do not accurately represent electricity generation in Canadian regions. Therefore, considering actual local intensities could alter the results.

The results presented here should be interpreted with caution. First, it should be noted that a reduction in electricity consumption at the individual scale (e.g., moving from intensive use of digital services to conscientious use) does not represent an absolute decrease at the network scale of digital data transmission and storage. Indeed, as discussed in Preist et al. (2019), from an attributional perspective, a reduction at the individual scale represents a greater amount of electricity being allocated to other network users. Also, it is important to remember that the attributional approach allocates electricity from the network proportional to the amount of data that are used. In this scenario, intensive users will have a greater impact than moderate and conscientious users. Yet, the usage of individual electronic devices and a router is not proportional to the amount of digital data that are used. When watching an hour of video with the same model of laptop, for example, all users would consume the same amount of electricity to run the router and the laptop.

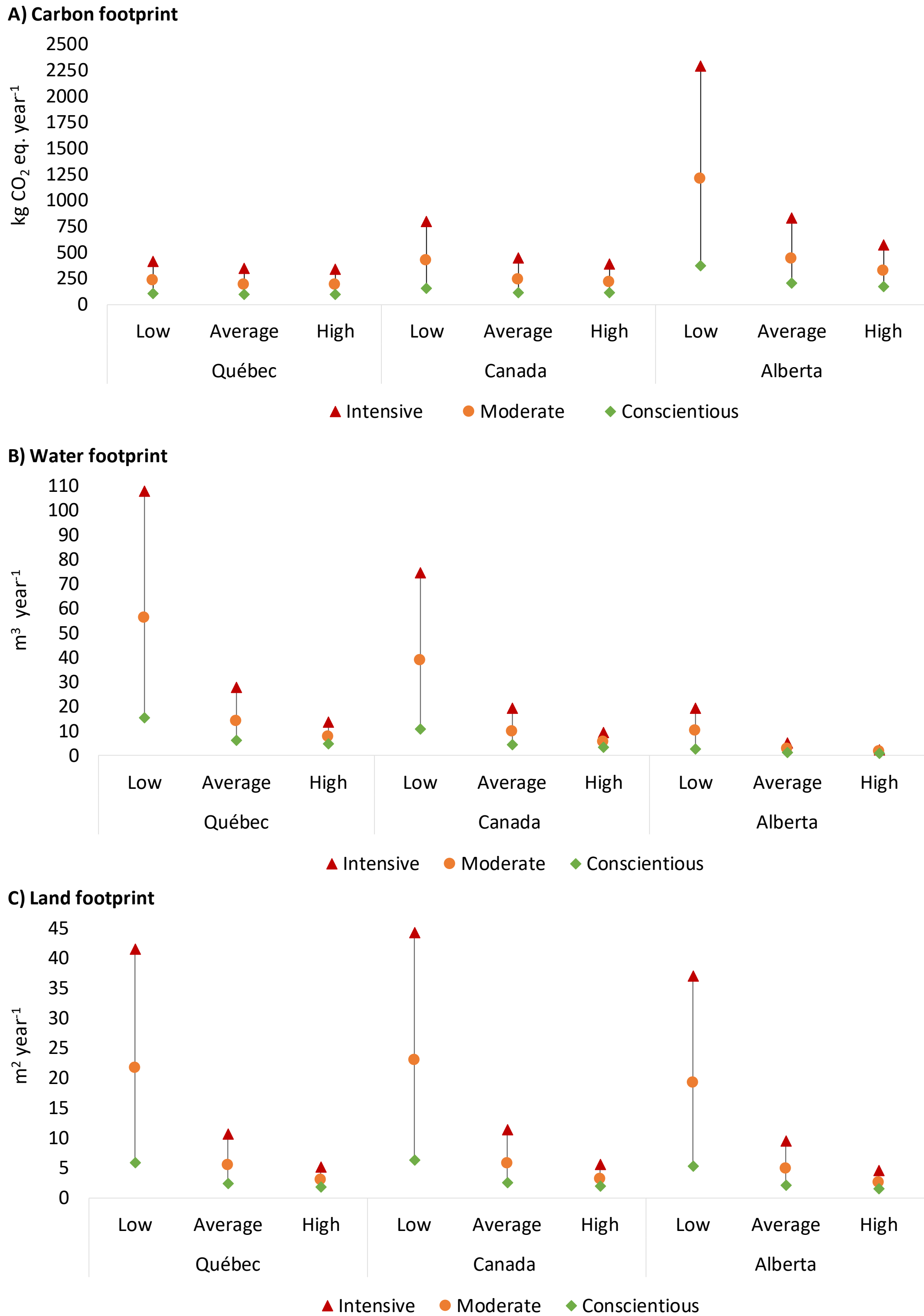


Figure 1. Environmental impacts according to the usage profiles of digital services, electricity mix and ICT infrastructure performance.

Beyond the influence of the user profile of digital services and performance of the ICT, electricity production scenarios strongly affect the environmental impact of digital service use. An intensive user in Alberta, according to the performance of the ICT infrastructure, would reduce their carbon footprint by 70% to 450% using Quebec's electricity mix. If the use of a low-carbon electricity mix reduces the carbon footprint of digital services, the opposite is observed with respect to water and land-use indicators. For example, an intensive user in Québec has a higher water and land footprint than an intensive user in Alberta (**Fig. 1**). The water and land footprint are greater in Québec because of the extensive use of hydroelectric power (98%). In contrast, electricity production in Alberta is based on coal (42%) and natural gas (49%), which requires less water and land. Indeed, production of one gigajoule of electricity from hydroelectricity requires 9.19 m^3 of water and 10 m^2 of surface area per megawatt-hour (**Appendix B**). These values are much lower to produce electricity from coal (1.03 m^3 GJ^{-1}, 5 m^2 MWh^{-1}) and natural gas (0.46 m^3 GJ^{-1}, 0.2 m^2 MW) (**Appendix B**). Yet, these figures need to be qualified. For example, the area that is allocated to reservoirs behind hydroelectric dams can be used for many other purposes (e.g., recreational, fisheries, potable water supplies).

3.1 Hotspot Analysis

The manufacture of electronic devices is the main source of carbon emissions for digital users (**Fig. 2** and **Table S4 - Appendix A**). Among the 27 scenarios that were evaluated for the carbon footprint indicator (3 profiles x 3 electricity mixes x 3 ICT performances), the production of digital devices is not the main source of carbon emissions in only 7 scenarios. This is especially the case in Alberta, where the electricity mix is very carbon intensive. The carbon footprint of digital services is likely to be higher than the manufacture of electronic devices in regions where the electricity that is produced and used is very carbon-intensive, the use of digital services is intensive, and the performance of the ICT infrastructure varies from low to moderate. The difference between intensive consumption of electronic products and conscientious consumption is 238 kg CO_2 eq. yr^{-1} (**Fig. 3** and **Table S5 - Appendix A**). The contribution of electronic devices to the carbon footprint changes depending on how each profile uses the devices, on the kind of devices that are actually used to perform each of the tasks being assessed, and on the time spent on them. This contribution is guided by the number of electronic products that a user owns, the category of electronic products (e.g., 23.8″ screen vs. 21.5″ screen; high performance desktop computer vs. ordinary desktop computer, and others), and the duration of use of these devices by a user. In general, screens, desktop or laptop computers and televisions contribute between 70% and 75% (depending upon the profile) of the impact of electronic devices. Screens, notebooks and desktops are the electronic devices with the greatest carbon weight. TVs have a higher individual impact than other devices; however, we consider that televisions are the only collective device in a house. Here, we divided the carbon footprint of television manufacturing by the average number of people in a Canadian household, viz., 2.47 people per residence (**Table S1 - Appendix A**). Only the impact of television manufacturing is adjusted, by dividing by 2.47. The impacts that are related to viewing films were attributed to each user individually, given that we are only interested in individual activities.

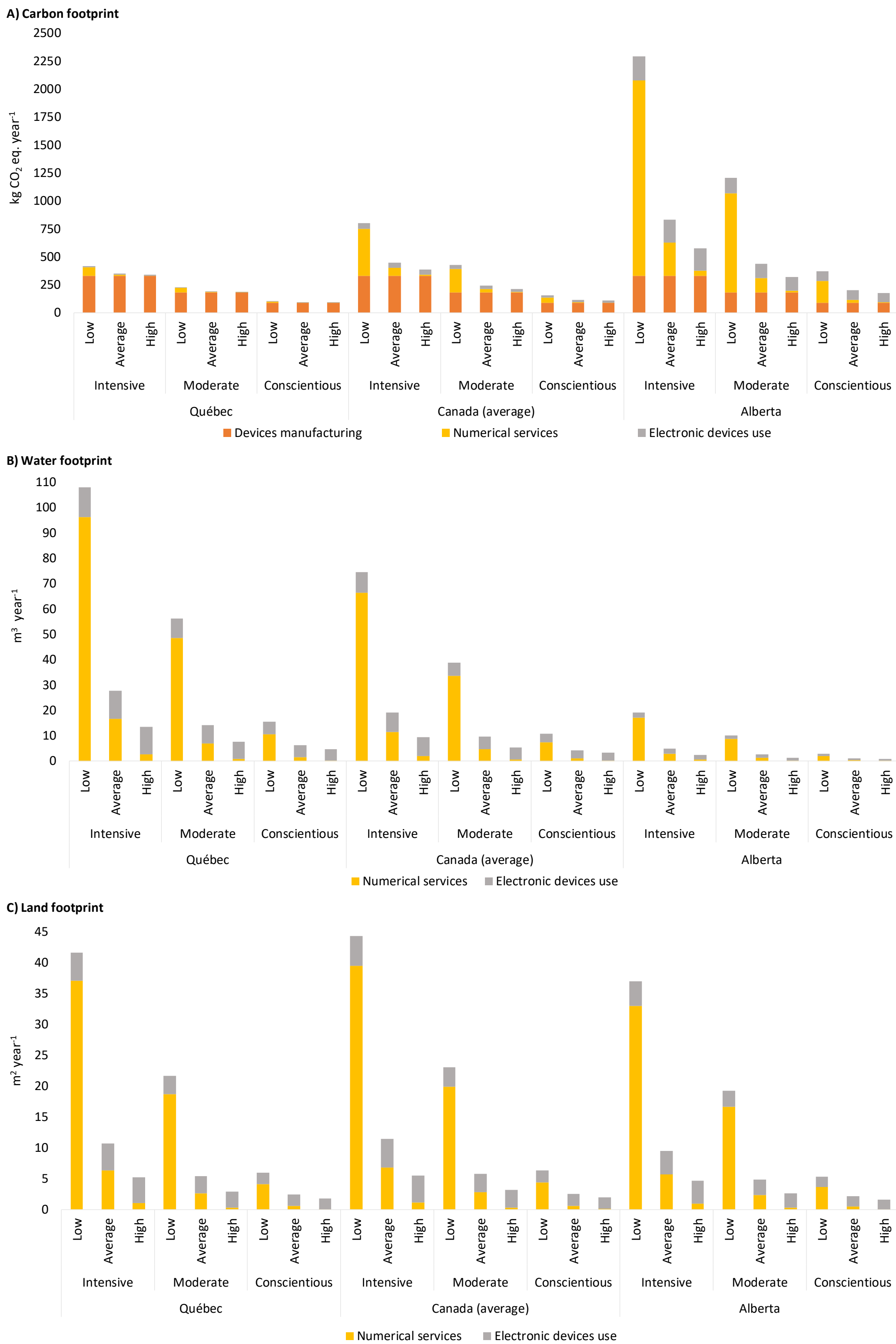


Figure 2. Contribution of the use of digital services (electricity used for data transmission and storage), manufacture, and use of electronic devices (electricity consumed by

electronic devices in the users' home) to the carbon footprint (A), the water footprint (B) and the land footprint (C) of digital users.

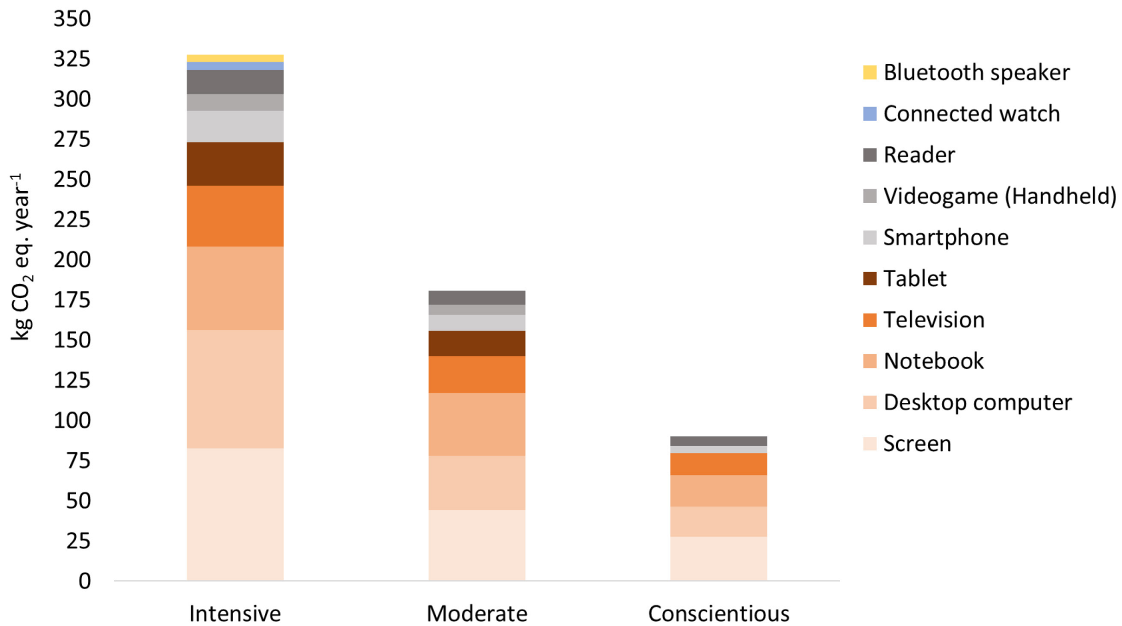


Figure 3. Carbon footprint of electronic device manufacture according to user profiles

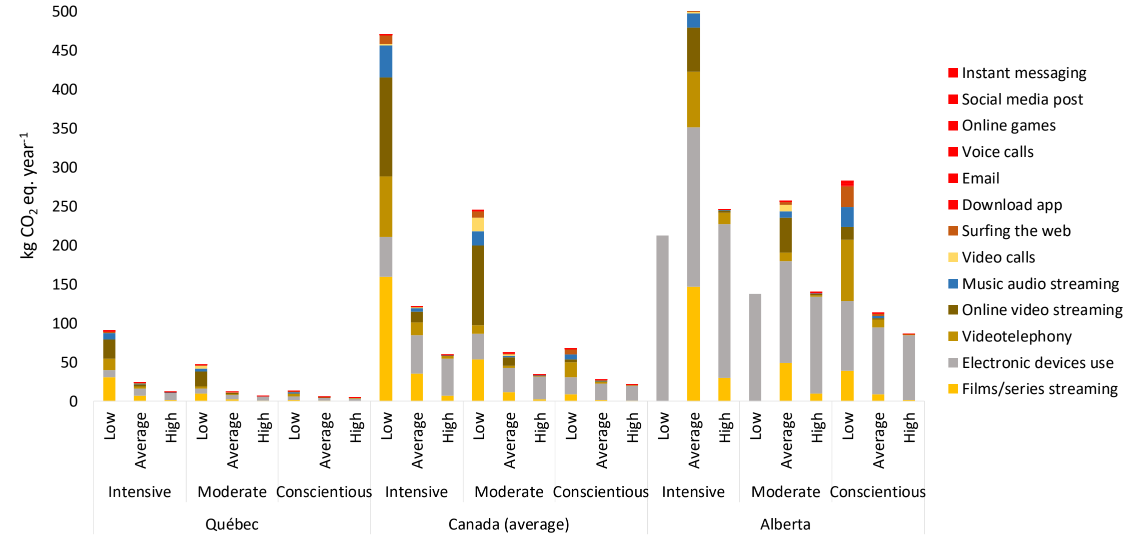
Interestingly, the phase of use of electronic devices by users (electricity consumption) leads to more environmental impacts than the use of digital services for most scenarios (**Fig. 2**). In general, among the 81 scenarios that were evaluated (3 indicators x 3 profiles x 3 electricity mixes x 3 ICT performance), the impacts related to the power consumption of electronic devices are more important than the use of digital services in 45 scenarios. In Québec (average ICT performance scenario), for example, conscientious use of digital services consumes 1.5 m^3 of water per year attributable to the use of electricity (in the case of Québec, supplied mainly by hydroelectricity), while water consumption attributable to the amount of electricity needed for the use of electronic devices by users is about 4.5 m^3 yr^{-1}. The impact related to the use of digital services would be more important in regions where ICT energy performance is low.

The use of the desktop computer (computer and screen) is the electronic device that contributes most to users' environmental impacts (**Table S6 - Appendix A**). The second electronic device that contributes the most to impacts depends on the user profile. In the case of intensive users, it is the television. For moderate and conscientious users, it is the laptop. The difference in impacts between TVs and laptops is due especially to the number of hours of use, together with the power of the electronic devices. For example, a 42″ LCD TV (intensive user) has a 1.2-fold greater impact per hour of use than does a 32″ LCD TV (moderate and conscientious users). Moreover, even if all user profiles use laptops more than televisions, the latter have a 4- to 6.6-fold greater impact per hour of use than do mobile computers. In the case of desktop computers, there is also a substantial difference in power depending upon the model. A high-performance desktop computer (intensive user) generates 2.3 times more impact than does an average desktop computer (moderate and conscientious users). In scenarios where the router has a higher wattage (15 W), the impacts associated with these devices are greater than the use of notebooks. If routers are left on 24 h a day, the impacts associated with their use increase significantly, making it important to turn them off when consumers do not need the Internet. Finally, the use of smartphones was negligible in all scenarios that were evaluated. This can be explained by their low energy consumption.

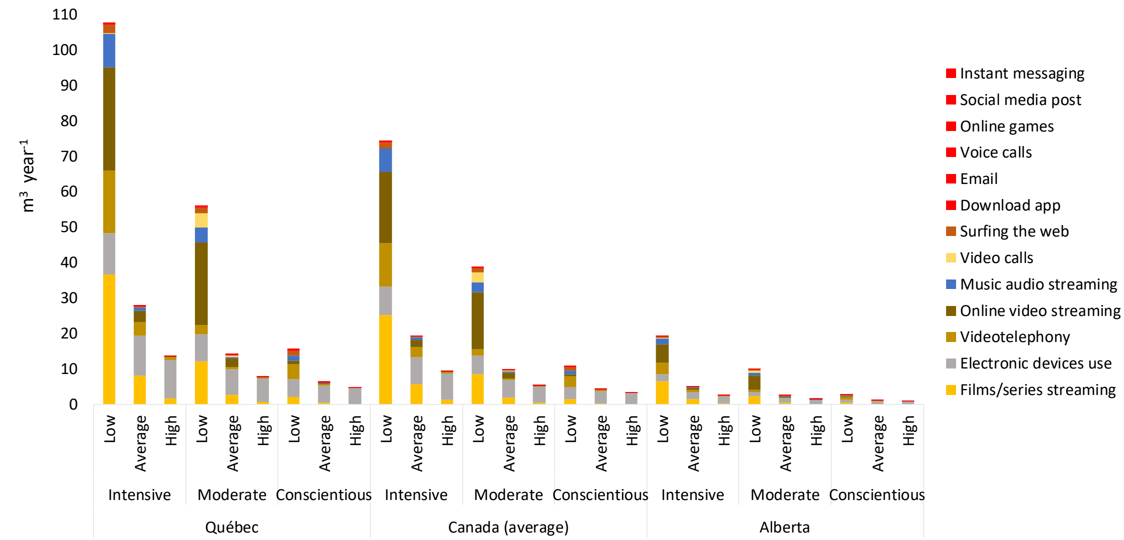
When we turn our attention to the individual impact of each digital service that was assessed in this study (**Fig. 4** and **Table S7 - Appendix A**), only five activities contribute to most environmental impacts. This is particularly the case for viewing streaming films/series and other types of services that use video. Depending upon the usage profile (conscientious, moderate and intensive), watching videos contributes between 28% and 68% of all environmental impacts that were considered (**Table S7 - Appendix A**). In Canada, with an average ICT network performance, the carbon footprint difference between intensive video viewing and conscientious viewing is about 47 kg CO_2 eq. yr^{-1}. This difference is 9 kg CO_2 eq. yr^{-1} in Québec and 194 kg CO_2 eq. yr^{-1} in Alberta, illustrating the major role of electricity mix in reducing the carbon footprint. From this perspective, reduction in the consumption of digital services has a much greater impact in Alberta than in Québec. This contrast is more evident when we observe that the carbon footprint of a conscientious user of digital services in Alberta turns out to have a higher carbon footprint than that of an intensive user in Québec. The energy efficiency of data transmission and storage networks also plays a key role. In regions where the energy efficiency of mobile networks is low and the carbon intensity of the electrical grid is high, the impact associated with these networks is significant. For example, with low ICT performance, watching one hour of streaming video (0.87 GB h^{-1}) in Alberta emits 3900 g CO_2 eq. vs. 200 g CO_2 eq. in Québec. In the scenario where mobile networks are efficient, these values drop to 11 g CO_2 eq. (Alberta) and 0.5 g CO_2 eq. (Québec). The results show that some traditional or iconic digital activities contribute very little to the annual impact of users, i.e., emails, instant messages, voice calls, Internet browsing, and others. Sending e-mails has often been referred to as an environmental catastrophe (CBC, 2021; The financial times, 2020; The Guardian, 2019; Unpointcinq, 2019), but sending and deleting mails would have an almost negligible environmental benefit. On an individual scale, sending emails would also have a limited influence on reducing email traffic. Indeed, spam represents 85% (122 billion) of global daily email traffic (Dataprot, 2021). Even though these figures seem worrying, the exchange of emails represents a tiny part of the global flow of internet data (Roussilhe, 2021). This exaggerated representation of the impact of certain digital activities is misleading regarding the levers of action that would reduce the impact of users. Therefore, misunderstanding the relative effectiveness of pro-environmental behaviours undermines individual efforts (Thøgersen, 2021; Wynes et al., 2020). Therefore, both quality and accessibility of information are essential for guiding digital users in the appropriate direction. This emphasizes the necessity of using approaches or tools that are consistent with the latest methodological advances (e.g., power-based approach) in terms of environmental impact quantification of digital services.

The contribution of a digital activity to the environmental impacts may change depending upon assumptions made about the amount of data that are used by specific activities, user habits, and the devices used to perform those digital activities. For example, the time used to prepare an email may be more than three minutes (Table S1). In another example, we assumed that an intensive user plays games online 2 h per week, which is probably an underestimate. We further considered that data consumption is 0.02 GB hr^{-1} to play a generic online game. This generic consumption may nevertheless be higher for certain specific games. This is certainly the case of Fortnite (0.10 GB hr^{-1}), Counter-Strike (0.25 GB hr^{-1}), Destiny 2 (0.30 GB hr^{-1}), Dota 2 (0.12 GB hr^{-1}) and many others (Whistleout, 2021).

A) Carbon footprint



B) Water footprint



C) Land footprint

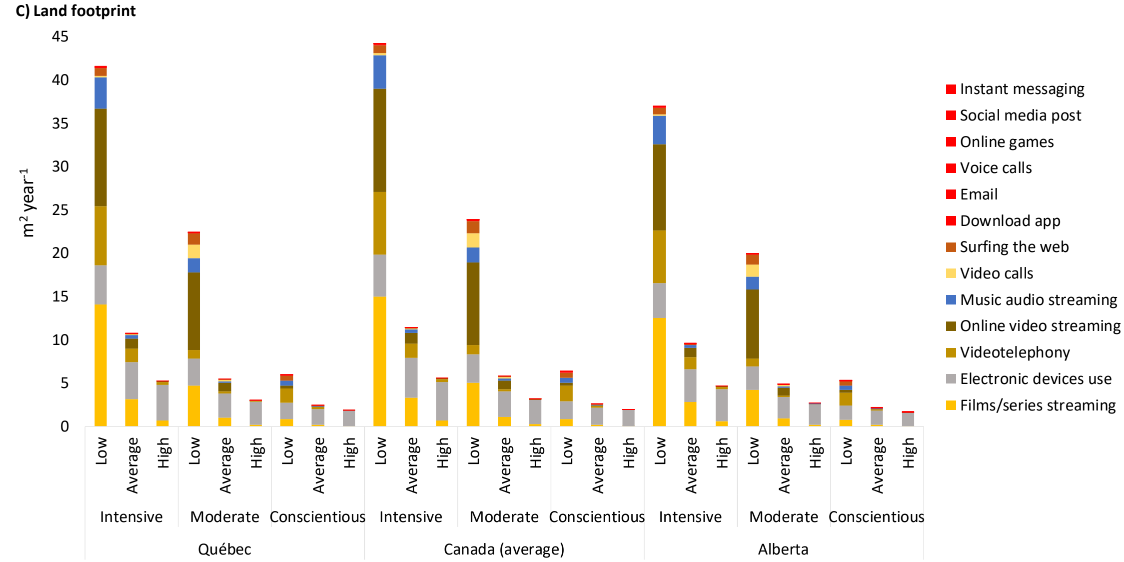


Figure 4. Detailed analysis of the contribution of digital activities to the carbon footprint (A), the water footprint (B) and to the land footprint (C) of a user profile according to the province in which it is located. To improve the visualization of the impacts associated with digital services, the values for the low/intensive and low/moderate scenario for the province of Alberta have been removed from the figure. Indeed, the carbon footprint of these scenarios are very high. The complete results are presented in **Table S7 - Appendix A**.

4. Discussion

4.1 Comparison with Other Studies

Most studies that have quantified the environmental performance of individual digital services have limited their analyses to the carbon footprint. Therefore, the comparison of our results with other studies is limited to the carbon footprint of digital service usage, even though our study included two other indicators. In general, the scientific community has been particularly interested in quantifying the carbon footprint of video streaming (**Table 4**). This choice is due to the pressure that this specific service exerts on internet traffic and its expected growth over the next few years (Cisco, 2019; Morley et al., 2018). In 2019, digital video services accounted for 60% of internet traffic (Sandvine, 2019) and their contributions are expected to increase to 82% in 2022 (Cisco, 2019). Our results regarding video streaming's carbon footprint are consistent with other studies (**Table 4**). Knowing that carbon footprint quantification of a digital service is very dependent upon the assumptions and data that are used, it is important to identify parameters that most influence the results.

For on-demand video streaming, we found values ranging from 3 g CO_2 eq. hr^{-1} to 8.76 kg CO_2 eq. hr^{-1}. As presented in the results of this work, the difference between these two values is notably influenced by the carbon intensity of electricity production and energy intensity of digital data transmission. In the case of the lower value, Carbon Trust (2021) considers that transmission of digital data consumes 0.0065 kWh GB^{-1} and that the carbon intensity of electricity that is produced in Sweden, for example, is around 43 g g CO_2 eq.

kWh^{-1} (Wernet et al., 2016). Nevertheless, Marks et al. (2020) considers that transmission of digital data consumes 4.91 kWh GB^{-1} and that carbon intensity of the electricity that is produced in the United States is 700 g CO_2 eq. kWh^{-1}. The latter considers an image quality of 1080p (2.55 GB hr^{-1}), while the Carbon Trust (2021) considers a mixture of image qualities depending upon the electronic device being used. Shehabi et al. (2014) likewise assessed the carbon footprint of watching streaming movies in the United States and found emissions to be 20 times lower than those of Marks et al. (2020). Again, this difference is explained by the data that are used to quantify the energy intensity of digital data transmission and storage. Yet, it must be remembered that the energy efficiency of data centres and digital data transmission networks is improving rapidly. Aslan et al. (2018) observed that between the years 2000 and 2015, the electrical intensity of data transmission in ICT-developed countries decreased by half every two years, thereby emphasizing the importance of using the most recent data. Yet, network-related energy consumption varies according to geographic location, given that communication network equipment is not necessarily updated every year. This means that there are older networks of which energy performance is not as good. In specific cases where data are available, it would be possible to use more recent data.

Some results that were found in the literature are very similar to one another, such as those that were proposed by The Shift Project (2020b) and by Shehabi et al. (2014). This is more a coincidence rather than a result of methodological homogeneity. Energy intensity of data transmission was higher in the former (0.429 kWh GB^{-1}) compared to the latter (0.290 kWh GB^{-1}). However, Shehabi et al. (2014) included the manufacturing and end-of-life of digital infrastructures and electronic devices, which increased CO_2 eq. emissions per hour of video streaming. Furthermore, they used a US electricity mix (0.690

g CO_2 eq. kWh^{-1}), while The Shift Project (2020b) used a global average (0.519 g CO_2 eq. kWh^{-1}).

As mentioned previously, we have considered that the energy consumption of data increases linearly with the quantity of digital data that are used. This postulate, which is also used in most research, has been challenged by several studies (Carbon Trust, 2021; Koomey and Masanet, 2021; Malmodin, 2020). Carbon Trust (2021) explains that digital data storage and transmission systems operate "24/7" with constant baseline power consumption, even when idle. According to the latter, it would not be desirable to estimate the carbon footprint of an instantaneous change, such as the transition from HD quality to 4k, from the average data traffic. Overall, the two approaches answer different research questions. The conventional approach above all makes it possible to answer the following question: What is the average impact of a digital service? The marginal approach asks: What is the impact of an increase in digital services? Or what is the energy variation in a network when an additional amount of data is used (e.g., change in video quality)? According to results that were obtained by Carbon Trust (2021), increasing the resolution of videos would only marginally increase the energy consumption of network and computing equipment compared to the basic consumption. Yet, the study points out that the power approach is a very recent development, so future research is needed to better estimate short-term marginal effects.

Table 4
Carbon footprints of video and music on-demand streaming

Digital service	Source	Carbon intensity	Unit	Geographic validity	System boundaries[b]
Video streaming	Chandaria et al. (2011)	19–111	g CO_2 eq. viewer-hour	United Kingdom	TS + DC
	Shehabi et al. (2014)	420	g CO_2 eq. $hour^{-1}$	United States	TS + DC + DP + IP

	The Shift Project (2020)	400	g CO_2 eq. hour^{-1}	World	TS + DC
	Marks et al. (2020)[a]	8760	g CO_2 eq. hour^{-1}	United States	TS
	Kamiya (2020)	2–71	g CO_2 eq. hour^{-1}	World	TS + DC
	Tabata and Wang (2021)	0.14–0.16	g CO_2 eq. MB^{-1}	Japan	TS + DC + IP
	Carbon Trust (2021)	10	g CO_2 eq. hour^{-1}	France	TS + DC
		3	g CO_2 eq. hour^{-1}	Sweden	
		76	g CO_2 eq. hour^{-1}	Germany	
		48	g CO_2 eq. hour^{-1}	United Kingdom	
		56	g CO_2 eq. hour^{-1}	Europe	
	Obringer et al. (2021)	28–441	g CO_2 eq. hour^{-1}	World	TS
	Current study (2021)[c]	0.5–179	g CO_2 eq. hour^{-1}	Québec	TS + DC
		3–936	g CO_2 eq. hour^{-1}	Canada	
		11–3900	g CO_2 eq. hour^{-1}	Alberta	
Audio streaming	Tabata and Wang (2021)	0.14–0.59	g CO_2 eq. MB^{-1}	Japan	TS + DC + IP
	Obringer et al. (2021)	2	g CO_2 eq. hour^{-1}	World	TS
	Current study (2021)[d]	0.17–29	g CO_2 eq. hour^{-1}	Québec	TS + DC
		1–151	g CO_2 eq. hour^{-1}	Canada	
		4–628	g CO_2 eq. hour^{-1}	Alberta	

[a]We have corrected a calculation error in the article by Marks et al. (2020). The original value was 76.57 kg CO_2 eq. hr^{-1} streaming videos.
[b]TS (electricity required for the transmission and the storage of numerical data); DC (consumption of electronic devices during the usage phase); DP (production of electronic devices); IP (production of infrastructures, such as transmission networks and data centre(s)
[c]For the lower value, we consider that a user watches a movie in low definition (0.30 GB hr^{-1}) with a smartphone, uses a WiFi network and the ICT infrastructure has a high efficiency. For the higher value, we consider that a user is watching an online video streaming in high definition (0.877 GB hr^{-1}) with a smartphone, uses a mobile network and the ICT infrastructure has a low efficiency.
[d]For the lower value, we consider that a user listens to music in low definition (0.0105 GB hour^{-1}) with a smartphone, uses a WiFi network and the ICT infrastructure has a high efficiency. For the higher value, we consider that a user listens to music in high definition (0.14 GB hr^{-1}) with a smartphone, uses a mobile network and the ICT infrastructure has a low efficiency.

4.1 Role of Users in Reducing the Environmental Impacts of Digital Technology

The results show that environmental impacts of digital users are dominated, in order of importance, by the manufacture of electronic devices, use of electronic devices, and services that use video (films, series, videotelephony and others). In light of these results, buying fewer electronic products and, above all, extending their lifespans are the two most effective actions for reducing the carbon footprint of ICT users, regardless of user profile. It is also relevant to look for information on the carbon footprint and energy efficiency of electronic devices before purchasing them. When this information is available, it is appropriate to choose electronic devices with a lower carbon footprint and greater energy efficiency. These actions are more important in view of the frequency at which electronic devices are renewed. For example, smartphones are replaced, on average, after 2.75 years of use (Statista, 2021). Several studies have also shown that the manufacture of electronic devices dominates the carbon footprint of the digital industry and that of its users (Belkhir and Elmeligi, 2018; Hischier et al., 2015; Keller et al., 2018), which confirms the trends observed here. The high impact of electronic products is incurred especially from the production of power and control electronic boards and components, together with the production of screens for the products concerned (ADEME, 2017; Teehan and Kandlikar, 2013). Indeed, the extraction of certain minerals that are essential to the production of electronic products (i.e., gold, silver, copper, cobalt, lithium, rare earths, and others) requires a very large amount of energy. Moreover, the production of components and assembly of finished products are largely carried out in China (61% of the production in the ICT sector for 2015), where the production of electricity is very carbon-intensive (Freitag et al., 2021; Itten et al., 2020). The long-distance air transport of certain electronic products also has a significant carbon weight (ADEME, 2017).

The use of electronic devices was another hotspot that was identified in our study. For example, using a notebook for three minutes consumes more electricity than transmitting and storing a 30 MB e-mail (0.00135 kWh vs. 0.0002 kWh). The use of a 42" LCD TV to watch a film (standard HD – 1 GB h^{-1}) consumes more electricity than the use of digital data (0.07 kWh vs. 0.14 kWh). Chandaria et al. (2011) showed that the carbon footprint of the use of digital terrestrial television services and video on demand (VOD) is dominated by the use of electronic devices, including televisions, computers (desktops and laptops) and set-top boxes (i.e., cable boxes or TV decoders). Keller et al. (2018) argue that the cumulative energy demand impact due to the use of digital media is dominated by the production and use of users' electronic devices. The authors assert that digital data processing and transmission is negligible for almost all digital activities, except for watching videos. The contribution of electronic devices to the impact of digital services is highly dependent upon the energy consumption of the devices being used (Schien et al., 2013). Televisions and desktop computers consume more electricity than laptops, tablets and smartphones (Malmodin and Lundén, 2018). Product categories also play an important role in environmental impacts. An LED TV consumes less electricity than an LCD TV, for example. In turn, an LCD TV consumes less electricity than a plasma TV. However, the larger the screen, the more electricity the television consumes, regardless of television technology. These findings highlight the importance of using small and energy-efficient devices.

Among the digital activities that were assessed in this study, the viewing of films and videos is the digital activity with the greatest impact. The major impact of this activity relies upon their frequency as well as the quantity of data that they mobilize. Compared to other digital activities, data transfer when watching movies/series varies between 0.3 GB $hour^{-1}$ (low quality) to 7 GB $hour^{-1}$ (ultra HD-4K), while consumption of data for a videoconference ranges from 0.027 GB hour^{-1} (audio only) to 2.4 GB hour^{-1} (group call/high definition-1080p) (**Appendix B**). Therefore, quantitative and qualitative reductions in video streaming are another effective actions for reducing the environmental impacts of users. Indeed, reducing video viewing also reduces the impacts that are associated with the use of electronic devices such as TVs, which increases the effectiveness of this action. Some of the most consumed web video content includes videos on demand, pornography, music videos and videos that are hosted directly by social networks and other sites (Ferreboeuf, 2019). Moreover, Morley et al. (2018) found a relationship between online video streaming, peak internet traffic and national electricity demand. This shows the importance of video to the expansion of internet traffic over the long term. Covid-19 further highlighted the pressure of streaming services on Internet traffic. Due the pandemic, Netflix has been forced to lower the graphic resolution of their content in several countries, including Canada, to free up bandwidth for teleworking (CBC, 2020; The Guardian, 2020). This highlights the strain imposed by streaming services on Internet traffic.

4.2 From Individual to Collective Action

As we have seen, the role of users is essential in reducing the impacts of ICT, especially by purchasing fewer electronic products and extending their lifespans. Yet, the responsibility (and response) of users must be nuanced to reduce the environmental impacts of digital technology. Although individual action can drastically reduce our digital ecological footprint, the role that states and corporations must play in building a digital industry that is compatible with planetary boundaries must not be overlooked. In reality, the consumption of digital services is only the last link in a very complex value chain. For example, the minimal carbon footprint that is allowed by a radical change in individual behaviour in Alberta (moving from intensive use to conscientious use) is equivalent to intensive use of digital services in Québec. This is due to the low carbon footprint of the Province of Quebec's electricity mix. Yet, it is beyond the reach of digital users to demand that all stakeholders who are involved in the value chain of digital services use only low-carbon energies. Furthermore, the speed at which a country, or even a province, deploys low-carbon energies on its territory is a decision that depends upon a set of factors, including political commitment, the socio-economic context, and technological maturity (Solomon and Krishna, 2011). Shehabi et al. (2014) proposed that digital service developers and policymakers focus upon the energy efficiency of data transmission (e.g., making it mandatory to replace obsolete components of internet networks) and electronic devices in users' homes to reduce energy consumption of online video viewing. The results presented here corroborate this observation. The energy efficiency of data transmission and storage appears to be as important as decarbonization of the electricity mix and behavioural changes. Moreover, the business model that is used by suppliers and developers of digital services is largely based upon encouraging consumption of new electronic devices and digital data (e.g., unlimited internet connection, automatic video playback, infinite scroll, increase in video quality) (Preist et al., 2016); this encouragement is in apparent contradiction with current efforts to develop a digital industry that is consistent with a carbon neutral trajectory.

4.3 Limitations of the Approach and Future Developments

4.3.1 Transmission and Storage of Digital Data Across Canadian Provinces

The approach that was proposed by Obringer et al. (2021), and partially followed in our work, has a number of limitations that should be clarified. First, the previous authors quantified only the domestic electricity production of each country. Yet, domestic electricity production can be traded between neighbouring countries, or even between state or provincial jurisdictions within a country, with very different electricity mixes. According to

Marriott and Matthews (2005), it is always desirable to consider exports and imports of electricity to improve the quantification of environmental impacts that are related to the use of electricity. This recommendation has little influence on our study, given that Canada is a net exporter of electricity (Canada Energy Regulator, 2020), but this is not the case for all countries. Even in the case of Canada, electricity consumption might change slightly if we factor in winter peak imports. Therefore, electricity imports and exports must be taken into account so as not to underestimate or overestimate the environmental impacts on a country or even a region (Itten et al., 2014). To overcome this methodological bias, it would be possible to use life cycle databases, such as *ecoinvent* (Wernet et al., 2016). These databases tally the electricity that is imported to and exported from each country/region.

The assumptions that were used to quantify the environmental impacts of digital data transmission and storage significantly affect the impacts of a digital service. It is a simplification to consider that the electricity used to transfer and store data only comes from the electricity mix of the country, or even the region, where the end user is located. This postulate stems from the fact that it is difficult to estimate exactly what electricity mix is being used by data centres and transmission networks at a given place and time to deliver a digital service (Lacoste et al., 2019). For this reason, a large number of studies have used this postulate to quantify the environmental impacts of the use of digital services (Malmodin et al., 2014, 2012; Suski et al., 2020). Other studies have used emission factors that are associated with the global electricity mix (Malmodin et al., 2014, 2012; Preist et al., 2019). In order to reduce the uncertainty that is associated with the choice of an electricity mix, it seems relevant to use several electricity mixes in the same study to determine the variation in the results.

Due to the lack of data regarding the energy intensity of data transfer and storage from Canadian networks, we have used a range of values. Given the importance of these data, it is important to conduct research on the energy efficiency of Canadian networks. For example, our results highlighted that the use of fixed networks is preferable to the use of mobile networks. However, this recommendation is more related to the assumptions made for each type of network than to the reality of Canadian networks (see Table 2). Indeed, the energy performance of fixed and mobile networks presents strongly contrasting energy consumption profiles depending on the specific technologies employed in a territory and the number of users (Andrae and Edler, 2015). For example, Malmodin et al. (2014) estimated the energy consumption of 2G and 3G networks in Sweden that was valid for the year 2010. According to the authors, the 3G network consumed 2.9 kWh GB^{-1}, while the 2G network consumed 37 kWh GB^{-1}, on average. Compared to the energy efficiency of 4G mobile networks, 5G networks are expected to be 100 to 1000 times more efficient (Ge et al., 2017). These figures highlight the speed of energy efficiency improvements in mobile networks. In summary, it is difficult to make a proper comparison between fixed and mobile networks without complete and up-to-date data on the state of the networks under evaluation.

Finally, the energy intensity of other types of digital broadcasting systems can be added to the approach that has been proposed here. This is the case for digital terrestrial television, satellite television and IP television.

4.3.2 The Non-proportionality of the Electrical Consumption of Network Equipment

Reducing the definition of streamed movies has proven to be one of the most effective actions for limiting the environmental impacts of digital service users. As we have seen previously, the change in the image quality of a video could have little influence on environmental impacts given the non-proportionality of the electrical consumption of Internet network equipment (Carbon Trust, 2021; Koomey and Masanet, 2021; Malmodin, 2020). In this case, the qualitative change in a digital service would not constitute a lever for action at the individual level. While it is probably true that reducing the definition of videos only leads to a very small reduction in the network's environmental impacts in the short-term, this gesture seems to restrain the increase in the sector's impacts of ICT in the medium-term. This assertion is based on two observations:

• The continuous improvement of streaming quality directly contributes to the development of new video-oriented electronic device technologies (televisions, smartphones, monitors, cameras). For example, Cisco (2020) estimates that in 2023, 66% of new flat screen televisions being sold will be ultra-high definition (4k), compared to 33% in 2018. Therefore, the manufacture of new television models that offer higher picture quality and additional features to replace old sets will likely have an environmental impact (Freitag et al., 2021). Knowing that the manufacturing of electronic products substantially contributes to the total impact of the ICT sector (Belkhir and Elmeligi, 2018), the incentive for continuous replacement of video-oriented electronic products is not without consequences for the environment. Capping the resolution of streaming videos, in the medium term, may reduce the rate of replacement of users' electronic devices.

• The creative processes that guide the design of digital services are largely based upon a Cornucopian paradigm (Preist et al., 2016). In other words, designers of digital services start from the often-implicit techno-optimistic assumption that digital infrastructure is abundant and will grow to meet future demand. Therefore, user-centred design principles drive the growth of digital infrastructure through a feedback cycle that includes three main components: network infrastructure capacity, new services and demand (Preist et al., 2016). Knowing that data traffic spikes are one of the main drivers of internet network infrastructure growth (Freitag et al., 2021), we can postulate that the more companies stimulate qualitative and quantitative demand for data-intensive services (video games on demand, very high-resolution videos, augmented reality, autonomous vehicles, blockchain applications), the more the network capacity will increase. A recent study by Madlener et al. (2022) supports this assumption. The authors argue that reducing the resolution of videos can significantly mitigate the electricity consumption and CO_2 emissions of video streaming over the medium-term in Europe. The authors also argue that regulations that control resolution choices can be effective in reducing the impact of video streaming. Of course, the expansion of digital infrastructures is not only related to the need to provide additional data, but also to the logic of financial investments and activity concentration. This comes down to the same issue, namely, the expansion of digital infrastructure that anticipates the growing demand for digital services (Cisco, 2020; Global e-Sustainability Initiative, 2015). As mentioned by Freitag et al. (2021), unless demand is capped, demand will always produce more demand. From this perspective, reducing data consumption would slow down the speed of development of digital infrastructures.

The power approach makes it possible to quantify the short-term individual impacts that are linked to the increase in the quality of a digital service, but ignores the long-term effects, at the scale of the ICT sector, of the changes that are induced by ever-increasing video quality and other data-intensive services. Although the conventional approach has its shortcomings, we believe that it is important to encourage people to reduce their use of the network. However, we encourage the scientific community to improve the already existing methods (e.g., power approach) to consider the non-proportionality of the use of data that are associated with the rebound effects that technological improvements can generate.

4.3.3 Carbon Footprint of Electronic Devices

In this work, we did not perform a sensitivity analysis about the carbon footprint of electronic devices and their energy consumptions. Yet, these values are markedly different depending on the brand and model of electronic devices (Malmodin et al., 2014;

Urban et al., 2017). Beyond the use of different methodological approaches, the carbon footprint and the energy performance of electronic devices depend on their technological level, where their components are manufactured and assembled, their sizes, power, and the quantities of materials that are used, among other considerations.

It would have been possible to quantify the carbon footprint of electronic products from specific data. For instance, several manufacturers, including those of smartphones (e.g., Apple, 2022; Fairphone, 2020; Google, 2022; Huawei, 2022), disclose the carbon footprint of their products (see **Fig. 5**). Replacing ADEME's generic data with manufacturers' specific data would help consumers to choose digital products with the best environmental performance. Yet, this methodological choice is not without consequences. When a specific approach is selected, methodological homogeneity must be maintained when comparing products (e.g., system boundaries, processes considered, allocation rules, transport assumptions, data quality, and others). Otherwise, the comparison of specific products is of little relevance. Because of the social issues that are present in the value chain of electronic products (Subramanian and Yung, 2018; Wilhelm et al., 2015), it would also be important to add social indicators to the analysis.

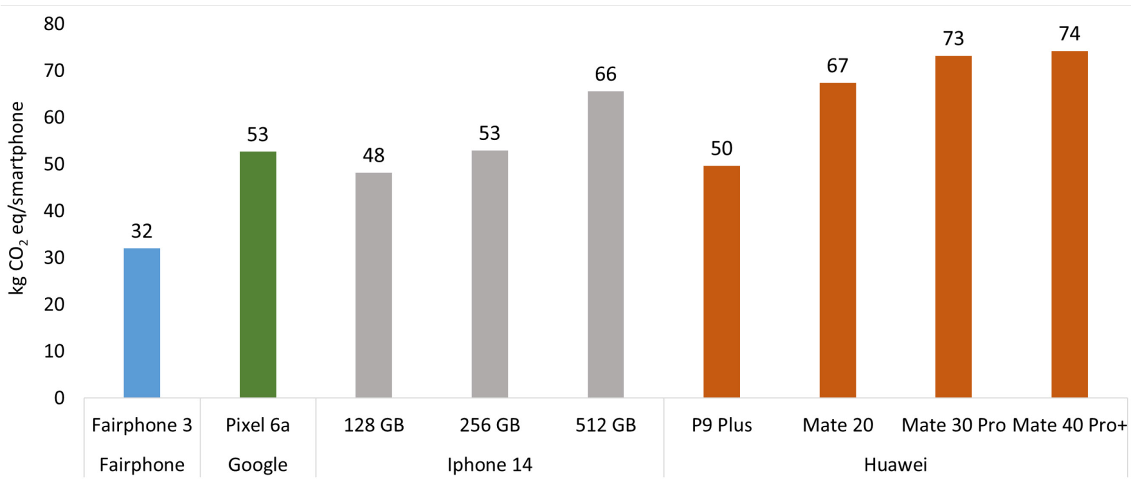


Figure 5. Carbon footprints of the manufacturing of some brands and models of smartphones. Transport, use and end of life stages are not included in the assessment.

4.3.4 Specific vs. Generic Digital Services

The data intensity of the chosen generic activities (video, music, calls) is based upon the use of specific platforms, such as Netflix, Spotify, Zoom, WhatsApp, and YouTube. Yet, our approach is not suitable for comparing the environmental impacts of specific providers (e.g., Zoom vs. Webex, Netflix vs. Prime Video). The structure of each company's computer networks is highly variable, which means that they have different bandwidth requirements. Bandwidth demand directly affects the energy consumption of each platform and, therefore, their environmental impacts. Furthermore, the data that are used to quantify the energy intensity of data centres [kWh GB^{-1}] are also generic. Companies with their own data centres can be more or less efficient than average. The approach that is proposed here should not be used to compare specific activities (e.g., watching an hour of Netflix in HD or Amazon prime in HD), given that the approach's results only refer to generic activities (e.g., watching an hour of HD online video, listening to an hour of streaming songs, doing an hour of group meeting).

5. Conclusions

The approach that was proposed here was constructed and used to quantify three environmental impacts related to electricity consumed by hypothetical patterns of digital service use in Canada, viz., intensive, moderate and conscientious users. The results showed that the environmental impacts of digital users are dominated by the manufacture and use of electronic devices and video streaming (films, series, and others). Buying fewer electronic products and extending their lifespans are the most effective actions for reducing the environmental impacts of users. Although this solution seems trivial, the low price of new electronic devices, limited (and expensive) repair possibilities, rapid technological obsolescence and social pressures encourage users to buy new electronic devices regularly instead of keeping them for a longer period.

Aside from services that use video (streaming movies/series, video conferencing and online videos), other digital services that were assessed had a negligible impact. Moreover, even if the use of video is often criticized in the media, the use of electronic devices is only rarely mentioned in the public debate as a lever for action to reduce the ecological footprint of digital users. Yet, the use phase of electronic devices has a greater impact than the use of digital services for 55% of the assessed scenarios. To reduce these impacts, users need to use smaller, energy-efficient devices and screens. Turning off devices when not in use would reduce energy consumption, e.g., standby mode consumption is at least 5% of the electricity that used in an average Canadian household (Natural Resources Canada, 2014).

The results indicate that power mixes and the energy efficiency of data transmission and storage play a major role in reducing environmental impacts. This result highlights that reduction of user impacts also requires the action of public institutions and the involvement of industrial players that are integral to the ICT value chain. Governments must lead countries towards a low-carbon energy future. Also, and of no less importance, the actors who are involved in the transmission, processing and storage of digital data must design their digital infrastructures in the most efficient way possible in terms of energy consumption.

The discussions in this paper have highlighted the complexity of quantifying the environmental impacts of digital services. On one hand, it is necessary to know the specific data of the countries where an assessment is carried out. This would allow for more accurate estimates of the impacts of digital services. To our knowledge, a comprehensive study of the energy consumption of Canadian fixed and mobile networks is absent from the literature. Future studies should address this need. On the other hand, the impacts of digital services are strongly influenced by the methodological choices and the data being used. For example, we chose to use an attribution methodology for impact quantification based on data consumption (kWh GB^{-1}). However, as explained above, it is possible to use other quantification approaches. The evaluation and comparison of our results with other studies have shown that the variability of the impacts of digital services is affected by six parameters: **1)** the behaviour of users of digital services; **2)** the carbon footprint of the electricity production; **3)** energy consumption of the transmission and storage of digital data; **4)** the magnitude of the data being used that are linked to the evaluated activity (e.g., low definition vs. high definition); **5)** taking into account average impacts or marginal effects depending upon the volume of data that is used; and **6)** the boundaries of the system (e.g., electrical consumption of electronic devices, production and end of life infrastructure and user electronic devices). Although not studied in detail, other parameters could have contributed to variability in the results, such as the carbon footprint and the energy consumption of electronic devices and the emission factors that are associated with electricity use.

Finally, it is necessary to update the values that are used here according to the availability of new data and according to methodological advances. Also, other indicators could be added to the approach to complete this work, for example, by assessing the depletion of biotic and abiotic resources and primary energy.

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