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Life cycle assessment of ICT in higher education: a comparison between desktop and single-board computers

Philippe Loubet[a*], Adrien Vincent[b], Annabelle Collin[c], Corinne Dejous[b], Anthony Ghiotto[b], Christophe Jego[b]

[a]Bordeaux INP, Univ. Bordeaux, CNRS, ISM, UMR 5255, F-33400, Talence, France
philippe.loubet@u-bordeaux.fr (P.L)
[b]Bordeaux INP, Univ. Bordeaux, CNRS, IMS, UMR 5218, F-33400, Talence, France
adrien.vincent@enseirb-matmeca.fr (A.V.) corinne.dejous@enseirb-matmeca.fr (C.D.)
anthony.ghiotto@bordeaux-inp.fr (A.G.) christophe.jego@enseirb-matmeca.fr (C.G.)
[c]Bordeaux INP, Univ. Bordeaux, CNRS, Inria, IMB, UMR 5251, F-33400, Talence, France
annabelle.collin@u-bordeaux.fr (A.C.)
**Corresponding author: philippe.loubet@u-bordeaux.fr ; +33(0)540003183*

Abstract

Purpose Information and communications technology (ICT) plays a key role in higher education in improving the teaching process. Consequently, the environmental impacts associated with ICT are increasing and innovative solutions must be deployed to reduce these impacts and increase students' awareness. Single-board computers (SBCs) are promising because they rely on less materials and energy than desktop computers (PCs). But additional servers are required to perform large-scale computations. Hence this paper aims at conducting comparative LCA between SBCs and PCs.

Materials and methods The study is conducted in the context of a French engineering school with the following functional unit: "use 600 computers for 5 years in an engineering school". Two scenarios are defined to fulfil this functional unit. Scenario 1 is the use of 600 PCs (current infrastructure), and scenario 2 is the use of 600 SBCs combined with 6 servers (alternative infrastructure). The analysis includes the materials manufacturing, assembly, packaging, transport, use and end-of-life of each device. Life cycle inventory (LCI) of the foreground systems was generated using a variety of sources: disassembly of computers, counting of electronic components, datasheets, estimations, etc. LCI of the background systems is taken from ecoinvent 3.5. The selected life cycle impact assessment methodology is ReCiPe 2016 midpoint and computation of impacts is done with openLCA 1.10.3.

Results and discussion Scenario 2 (SBCs + servers) generates 84% to 92% less impact than scenario 1 (PCs) in all categories. In terms of global warming, scenarios 1 and 2 generate 225 and 18 tCO2 eq per functional unit, respectively. This is explained by the large reduction in material and energy requirements for SBCs which is not counterbalanced by the servers. Equipment manufacturing accounts for the largest share of impacts in most categories for both scenarios (e.g., ~70% for global warming), followed by the use phase. This differs from the results found in the literature, as this study was conducted in the context of France, which has a low-carbon electricity mix.

Conclusions Our analysis has shown that SBCs combined with servers reduce the carbon footprint and other environmental impacts of ICT infrastructure for higher education. This study provides an example of low tech-oriented solution for students. Other prospective solutions (e.g., use of laptops) should be extensively studied in the future. From an LCA point of view, updating the inventory data related to background processes for electronic components is a necessary step forward to improve the certainty of the results.

1. Introduction

Information and communications technology (ICT) is one of the fastest growing sectors in terms of environmental impact. According to the recent estimates, the ICT sector is responsible for approximately 2.1% to 3.9% (Freitag et al. 2021) of global anthropogenic greenhouse gas (GHG) emissions worldwide. Indeed, the demands of the society regarding ICT are increasing in all sectors, which reinforces the need to develop new strategies to reduce the environmental footprint of ICT infrastructure. This is especially true for the education sector to raise awareness and because students will be able to apply such strategies in their professional careers.

In this context, single-board computers (SBCs) such as the Raspberry Pi are promising solutions to decrease the environmental impact of ICTs because they require fewer materials, less energy-intensive devices, and generate less waste at the end-of-life (Johnston et al. 2018). Indeed, a Raspberry Pi is nothing more than a computer reduced to its simplest form: a single processor board. It can be connected to a dedicated server for very computationally intensive tasks. Therefore, it provides the same level of performance as a desktop computer. This solution has several additional advantages: (i) since the computing capacities required at the SBC level are small , the SBC can be an elementary equipment for which the maintenance requirements are reduced, (ii) if any improvement of the equipment must be carried out, it only affects the server, (iii) electricity consumption due to intensive computing activities being centralized, it is possible to reduce energy consumption for equivalent performance (Baun 2016). Also, such a solution is particularly suitable for higher education, as it enables to have a homogeneous and harmonized configuration for all computer labs.

Quantifying the environmental impact of such a solution is important to: i) verify the environmental relevance compared to the current infrastructure in higher education (i.e., the use of desktop computers); ii) identify the main environmental hotspots to improve such strategies. LCA is the relevant tool to assess all environmental impacts related to the life cycle of computers, as it allows the consideration of all aspects of the supply chain, including the production of raw materials, the manufacturing of the computer, logistics, the use phase and the end-of-life. It also provides information on various impact categories that are relevant for the ICT sector: climate change, mineral resource scarcity, water use, toxicity, etc.

LCA has already been applied to analyse the environmental impacts of desktop computers (PCs). (Teehan and Kandlikar 2012) and (Yao et al. 2010) reviewed several studies published between 1998 and 2010 and compared the global warming potential and primary energy consumption of the PCs studied. They found that the use phase dominates the impacts, except in areas with low electricity mix impacts. The manufacturing phase also has significant impacts, whereas distribution and end-of-life phases are always negligible. They also noticed a high variability in manufacturing impacts due to inconsistencies on the impacts of various electronic components, especially mainboards and semi-conductors. Also, Dell publicly provides on its website (Dell 2022a) the product carbon footprint of the computers, monitors and servers they produced, based on a methodology for streamlined LCA named “Product Attribute to Impact Algorithm-PAIA” (Dell 2021).

In terms of comparative LCA studies, Subramanian and Yung (2017) studied two types of devices: PCs and all-in-ones. They determined that the later generates 2 times less environmental impact that the former ones. Also, Maga et al.(2013) compared server-based computing in association with thin clients and PCs. A 65% reduction in GHG emissions was found for the first solution. In addition, manufacturers such as Dell also provide information on their thin client (Chromebook or Wyse) and show lower carbon footprint in comparison with desktop computers. For example, the Dell Wyse 5740 Thin client's carbon footprint is estimated at 121 kgCO_2 eq (Dell 2019) whereas an average desktop computer's carbon footprint is rather around 500 kgCO_2 eq.

Thin client solution is similar to single-board computer but relies on heavier and more powerful devices. Based on this literature review, we can hypothesise that SBCs combined with servers are also relevant in terms of environmental performance compared to PCs. However, such quantification remains to be done, especially in the context of higher education, which also requires dedicated server.

In this context, we propose to conduct an LCA to compare the environmental impact of using PCs (current scenario) with that of using SBCs together with servers (alternative scenario) in order to verify the environmental relevance of such a solution and promote its use in higher education. The paper follows the four LCA phases according to the international standards (International Organisation for Standardization 2006): (i) the goal and scope and (ii) the life cycle inventory (LCI) described in Materials and methods, (iii) the life cycle impact assessment (LCIA) results and their (iv) interpretation provided in the Results section. Finally, the results are discussed with the literature, focusing on their potential use for decision makers.

2. Materials and methods

2.1. Goal and scope

The aim of the study is to investigate and compare the environmental impact of two scenarios for the ICT infrastructure for practical work in an engineer graduate school (ENSEIRB-MATMECA – Bordeaux INP). This study aims to provide quantitative evidence to help decision makers in selecting the most sustainable infrastructure that can help to mitigate impacts of ICT for higher education. It could also help to identify eco-design solutions to reduce the impact of the different devices studied (desktop and single-board computers).

ENSEIRB-MATMECA – Bordeaux INP is a French graduate school in electronics, computer science, telecommunications, and mathematics and mechanics, covering the field of digital technology in its broadest sense. The digital technology plays a central role in the major transformation underway in our society and is the answer to the main industrial challenges. This engineering school trains over 1 200 students in teaching programs focused on innovative projects supported by world-class research laboratories. To this end, 600 computers are required in the school. They enable the students to do all practical ICT work. Furthermore, the depreciation period for the computer equipment is 5 years, which is set under the rules of the budgetary and accounting management of a public institution. Therefore, the functional unit of the study is: "use 600 computers for 5 years in an engineering school". The use of computers includes the following tasks: use of office software, internet browsing, programming, basic scientific computation. The two scenarios studied (and associated reference flows) that satisfy the functional unit are given in that follows:

- 1st scenario: 600 desktop computers [Dell Precision Tower 3620 workstation (Dell 2018a)]
- 2nd scenario: 600 single-board computers [Raspberry Pi 4 Rev B] + 6 servers [Dell 7920 Precision Tower workstation with a Dual Xeon 8168 processor (Dell 2022b)].

In scenario 2, each server (and associated Dual Xeon processor) includes 48 cores, enabling 96 logic threads in parallel. This means that the 6 servers can perform the computationally intensive tasks in parallel, which is sufficient for the needs of practical work. As for the data transmission between the SBCs and the server, the Ethernet protocol allows a network configuration with a bandwidth of 1 Gbps. It means that each server could allow a theoretical bandwidth of 10Mbps for one SBC. In practice, limitations in the network infrastructure of a building may limit the useful bandwidth. However, it is possible to dedicate the bandwidth of a part of a network to a subnet that would be in charge of the data exchange between the SBC and the server (Sommer et al. 2010). It means that the adequate configuration of the network infrastructure can ensure data rates of the order of 5 to 8 Mbps per SBC which is sufficient for the use of most digital tools.

System boundaries for both scenarios are shown in Figure 1 and Figure 2, respectively. The analysis includes the materials manufacturing, assembly, packaging, transport, use and end-of-life of each device (desktop computer, single-board computer and server) that are specific to each system. External devices such as the monitors, the peripherals (mouse and keyboard) are excluded as they are similar for both scenarios.

Intermediate flows required for the foreground system are listed and explained in the life cycle inventory (LCI) section. Resource use and emissions related to the background processes were retrieved from the ecoinvent 3.5 database “Allocation at the point of substitution” (Wernet et al. 2016).

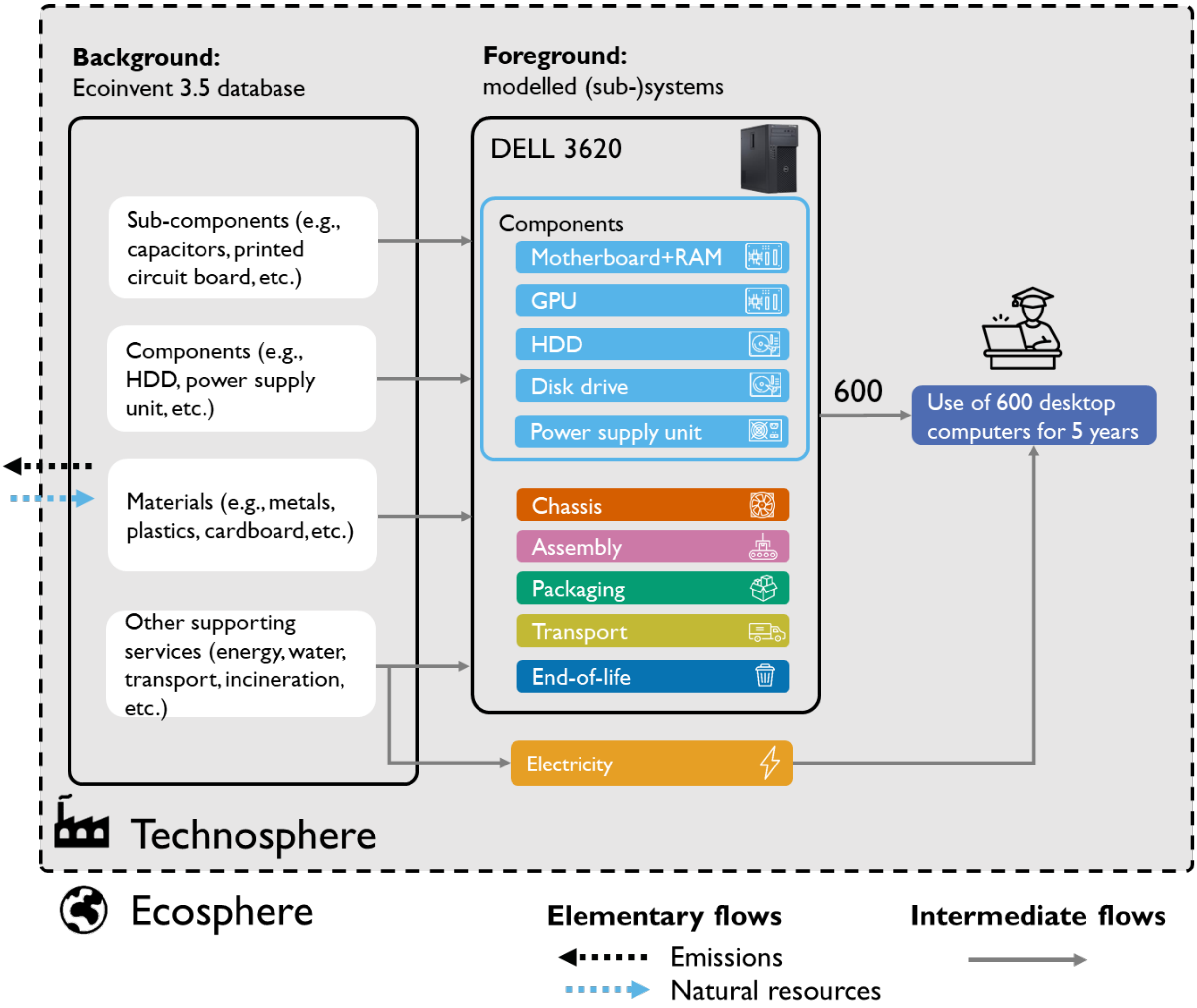

Figure 1. System boundaries for the scenario 1 (600 desktop computers)

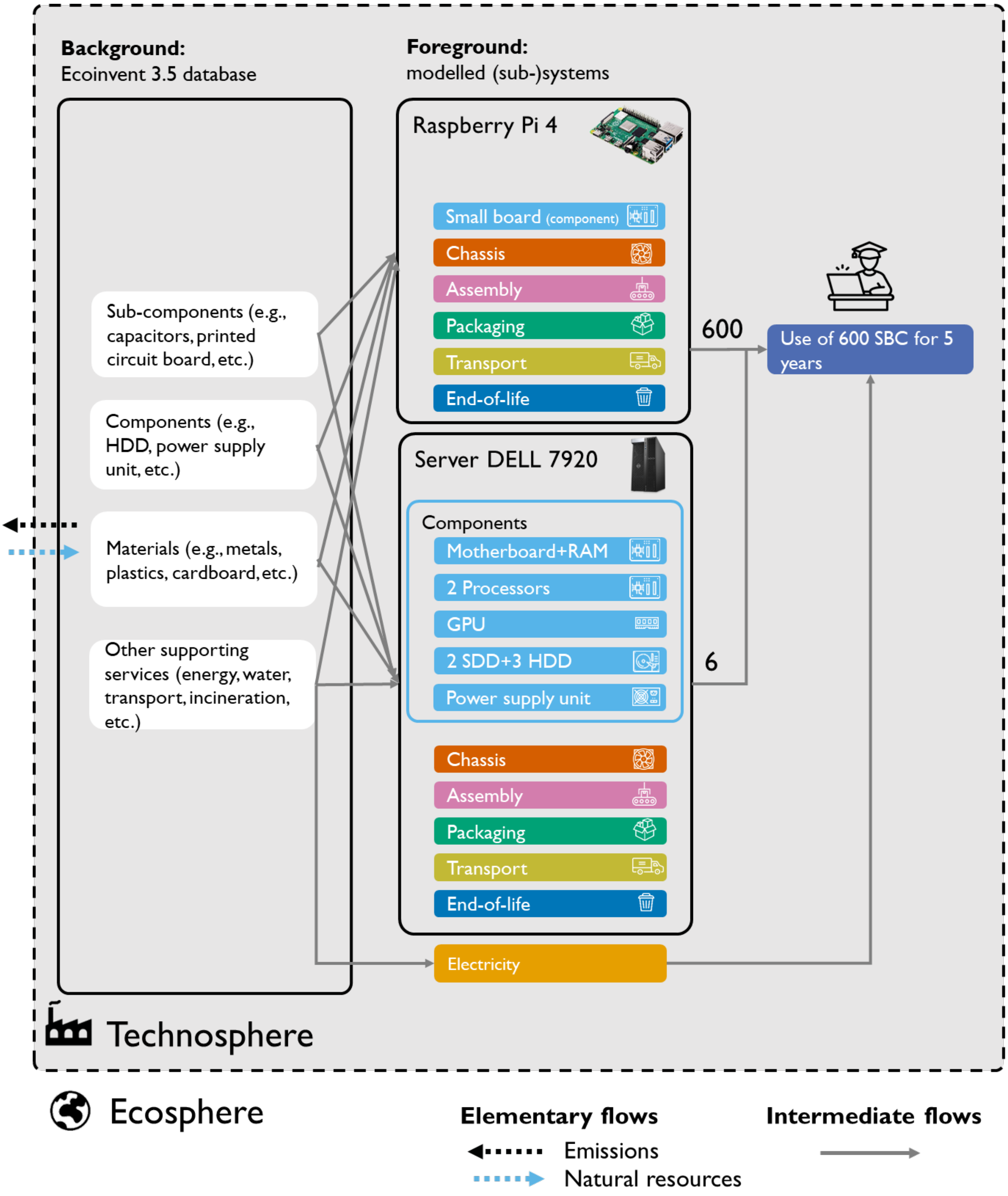

Figure 2. System boundaries for the scenario 2 (600 SBCs and 6 servers)

The environmental impacts are then characterized using the ReCiPe 2016 Midpoint (H) (Huijbregts et al. 2017) LCIA method (Table 1) selected as one of the most up-to-date methods. We used openLCA 1.10.3 to compute the impacts of each system.

Table 1. ReCiPe 2016 midpoint (H) impact categories and list of abbreviations

Impact category	Abbreviations	Unit
Global warming	GW	kg CO_2 eq
Stratospheric ozone depletion	SOD	kg CFC11 eq
Ionizing radiation	IR	kg Co-60 eq
Ozone formation, Human health	OF	kg NOx eq
Fine particulate matter formation	FPMF	kg PM2.5 eq
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FEut	kg P eq
Marine eutrophication	MEut	kg N-Eq
Terrestrial ecotoxicity	TE	kg 1,4-DCB eq
Freshwater ecotoxicity	FE	kg 1,4-DCB eq
Marine ecotoxicity	ME	kg 1,4-DCB eq
Human carcinogenic toxicity	HCT	kg 1,4-DCB eq
Human non-carcinogenic toxicity	HNCT	kg 1,4-DCB eq
Land use	LU	m^2a crop eq
Mineral resource scarcity	MRS	kg Cu eq
Fossil resource scarcity	FRS	kg oil eq
Water consumption	WC	m^3

2.2. Life cycle inventory

LCI data of the foreground system for the 2 scenarios is presented in the following sections related to: components, chassis, packaging, assembly, transport, end-of-life and use of the different devices. Devices refer to desktop computers for scenario 1, single-board computers and server for scenario 2. All data are summarized in Table 3, Table 4,

Table 5 and Table 6, along with the sources of data and the associated ecoinvent processes that are used to model the production, use or end-of-life of the different elements. Full inventory tables are provided in supplementary information (SI), in Tables S1.1 to S1.7.

We consider that the production of components, chassis, packaging, and the assembly of the devices are taking place in China. Therefore, all ecoinvent datasets for these elements are considered with the geography “China” (CN) if available in ecoinvent, and “Rest of the World” (RoW) or global (GLO) if not available. Use and end-of-life phases are considered in France.

Transport is specifically considered only for the final devices (from the computer assembly plant in China to Bordeaux, France). All other transport steps are considered through the use of “market for” processes in ecoinvent.

2.2.1. Components of the devices

Desktop computer. The different components have been identified from the manual (Dell 2018a) and after disassembly of a Dell tower 3620 (Table 4). Key components of the desktop computer (motherboard, GPU, RAM) have been modelled at a sub-component level by identifying the amount of printed circuit board and electronics. This is because these components are specific to the studied computer in terms of electronics used. We assume they represent a large share of impacts. The quantification of each electronic component (integrated circuit, capacitor, inductor, etc.) has been made through the use of the Python script DotDotGoose (Ersts 2022) that assists in counting objects in an image such as the picture of the motherboard (Figure 3). Mass of each sub-component has been estimated based on (i) specific information on the sub-component found on the internet, (ii) density of the metal used in the subcomponent, and (iii) rough estimation. Since there are many different sub-components (e.g., more than 1000 capacitors), it was not possible to identify the unitary mass of each element. From this quantification, the total mass of the motherboard is evaluated to 700 g which is consistent with the real mass of the board. Then the manufacturing of each sub-component is directly taken from ecoinvent datasets. It should be noted that ecoinvent datasets related to electronic components are outdated as they were developed more than 15 years ago (Hischier et al. 2007). However, we decided to rely only on ecoinvent background datasets for consistency and because we conduct comparative LCA on systems that rely on the same types of electronic components.

List of all sub-components of the motherboard, GPU, RAM is available in Table 3. Other components (hard disk drive, disk drive (CD/DVD), power supply unit) are directly taken from ecoinvent as they are generic components that do not differ significantly between PCs.

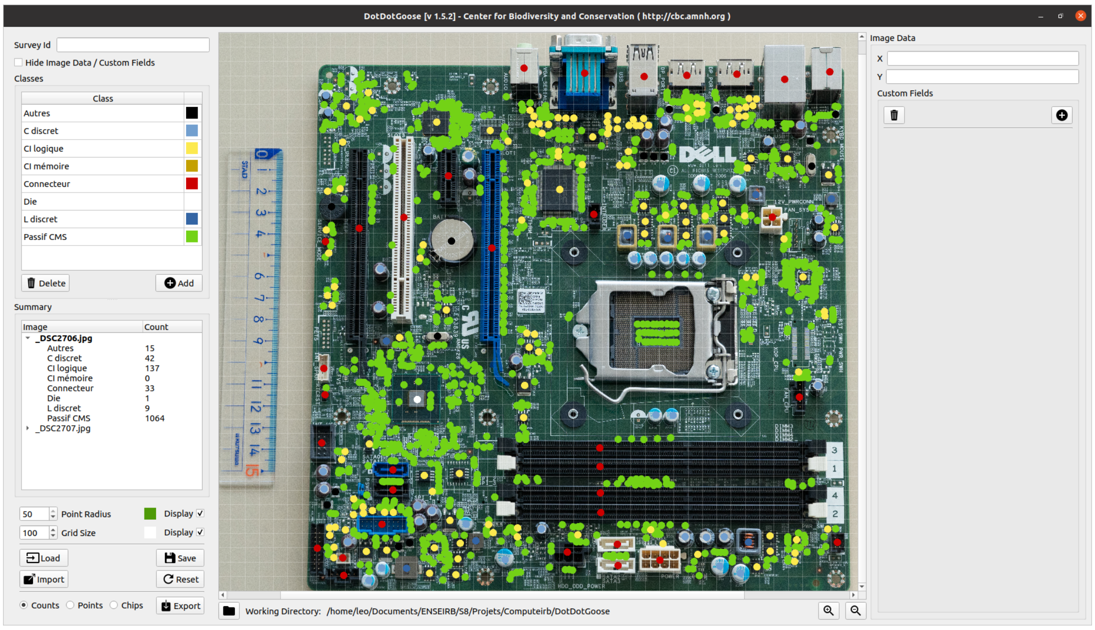
DotDotGoose [v 1.5.2] - Center for Biodiversity and Conservation (http://cbc.amnh.org)

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Figure 3. Identification of each component of the Dell computer's motherboard with DotDotGoose.

SBC The Raspberry Pi 4 is only composed of a single board which is rather simple as shown in Figure 4. The quantification of each sub-component has been made from a comprehensive list that is available for the Raspberry Pi 2 Model B[1]. This model is similar to the Pi 4, for which some elements such as the connectors have been improved. Mass of each sub-component has been estimated based on the same approach used for the PC. From this quantification, the total mass of the motherboard is evaluated to 48 g which agrees with the documentation. The list of sub-components is given in Table 5.

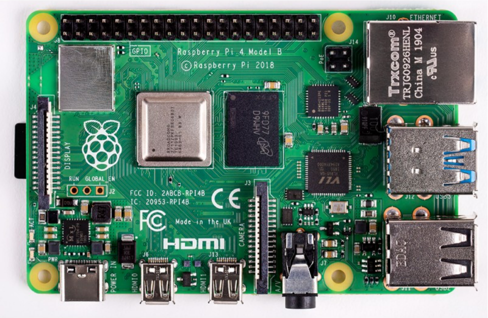

Figure 4. Picture of the Raspberry Pi 4 Rev B

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[1] https://elinux.org/RPi_Partial_BOM_Rev2.0_ModelB).

Server The different components of the Dell 7920 server are retrieved from a server already installed at ENSEIRB-MATMECA and are described in Table 6**.** The 2 motherboards used in each server are considered equivalent as the ones used in the PCs, except for the processors. The processor has been modelled according to their area, and considered as a combination of wafer and integrated circuit (logic type) from ecoinvent. RAM and GPU have also been considered equivalent as the ones used in PCs, except that a server contains 8 units of RAM and 2 GPUs. The manufacture of other components is directly taken from ecoinvent.

2.2.2. Chassis of the devices

For each device (PC, SBC or server), we model a chassis that we believe is representative of what could be encountered in practice for each scenario. As detailed information about chassis are often not so easily available, we build our models by means of educated guesses and of values averaged over a few models of the relevant subsystems when possible. Due to limited information about their exact sub-components and for the sake of simplicity, we only account for the mass of plastic, when modelling fans as it is the main material by far. More information on the different chassis models and their subcomponents are given in SI.

Desktop computer The chassis of the desktop computer is composed of the following elements: 5 kg of steel (mostly for the enclosure) with powder coating (for protection against corrosion and for aesthetic purpose); 150 g of plastic (for decorative elements, component positioning and possibly air blower); one 120 mm diameter fan; an air-cooling system for the Central Processing Unit (CPU), with copper heat pipes leading to an aluminium heatsink and a 120 mm diameter fan; some ribbon cable for internal wiring. For simplicity sake, we also account for the 1.8 m power cable and the 3 m network cable in the chassis subsystem for the desktop computer. Details about the model are given in Table 3.

The mass of the enclosure is estimated based on an average of models of chassis on the market at the time of the study (Table S2.1 in SI), slightly beyond 5 kg, which includes neither the CPU air-cooling system nor the power and network cables. The data for each chassis sample have been retrieved from the manufacturer data sheet or documentation.

Similarly, the CPU air-cooling system is an average model (Table S1.7 in SI) based on a small set of systems on the market at the time of the study (Tables S2.5 and S2.6 in SI). The data for each sample has been retrieved from the manufacturer data sheet or documentation.

SBC We have considered the scenario of a custom 3D-printed enclosure. We have chosen acrylonitrile-butadiene-styrene (ABS) for its overall good mechanical properties and durability. The total mass of ABS is estimated to be 50 g per enclosure considering the expected overall geometry. Relying on educated guesses, we consider a three-hour-long printing process per enclosure with a 3D-printer (with a power of 125 W). Because of the low power consumption of such a thin client approach, we assume that the chassis does not need any fan or heat sink for active air-cooling. For simplicity sake, we also account for the 3 m network cable and for the external 15 W power supply unit in the SBC chassis subsystem. Details about the model are given in Table 4.

The significant amount of enclosures to print is likely to require an unreasonable amount of time for in-house production with only one or a few 3D-printers. For example, based on the previously estimated printing duration, it would take at least 2,5 months to produce 600 units with a single 3D-printer. That is why in this work we have considered a scenario, where the SBC enclosures are printed by a third-party service in China equipped with a farm of 3D-printers.

Server We use an approach similar to the desktop computer chassis for the chassis of the server. It contains: 13 kg of steel (mostly for the enclosure); 350 g of plastic (for decorative elements, components positioning and possibly air blower); three 140 mm diameter fans; an air-cooling system for the CPU, with copper heat pipes, an aluminium heat sink and two 140-mm diameter fans; some ribbon cable for internal wiring. For simplicity sake, we also account for the 1.8 m power cable and the 3 m network cable in the chassis subsystem for the desktop computer. Details about the model are given in Table 5.

The mass of the enclosure is estimated based on an average of models of chassis on the market at the time of the study (Table S2.2 in SI), slightly beyond 13 kg, which includes neither the CPU air-cooling system nor the power and network cables. The data for each chassis sample has been retrieved from the manufacturer data sheet or documentation. Without accounting for the fans, we have kept the same ratio steel mass over plastic mass as for the chassis of the desktop computer.

Similarly, the breakdown of the CPU air-cooling system is an average model (Table S1.7 in SI) based on a small set of systems on the market at the time of the study (Table S2.5 in SI). The data for each sample has been retrieved from the manufacturer data sheet or documentation.

2.2.3. Assembly of the devices

We assume that each device is assembled in China. Energy, tap water and waste water treatment required for assembly have been directly taken from the generic ecoinvent process “computer production, desktop, without screen” considering a ratio based on the mass of each device and the mass of the computer modelled (Hischier et al. 2007).

2.2.4. Packaging of the devices

The packaging is considered similar for the desktop computer and the server. It is composed of corrugated board box and foamed polypropylene. The packaging of the Raspberry Pi is only composed of corrugated board box. The different masses of packaging materials have been roughly estimated and are available in the LCI tables.

2.2.5. Transport of the devices

For each device, we considered the same distance for transport: 1000 km of truck in China, 15000 km of transoceanic ship between China and France, and 1000 km of truck in France.

2.2.6. End-of-life of the devices

The end-of-life of the devices is considered as the same of the ecoinvent process “market for used desktop computer” that is defined in relation to the mass of the device. We kept the same ecoinvent end-of-life treatment processes that consider that 77 % of the device is treated mechanically and 23 % is manually dismantled, based on global average. Then, the different parts of the computer (metals, electronics, plastics, etc.) are considered either incinerated, landfilled or recycled.

2.2.7. Use of the devices

The energy (electricity) use of the devices has been estimated based on the state-of-the-art values computed according to EU regulations with regard to ecodesign requirements for computers and computer servers (European Commission 2013). In this framework, yearly energy use (E_{TEC} in kWh) is computed according to the following formula:

$$E_{TEC} = 8760h \times (0.55 \times P_{off} + 0.05 \times P_{sleep} + 0.4 \times P_{idle})$$

with P_{idle}, P_{sleep} and P_{off} (kW) being determined from Energy Star website or directly in the manufacturer’s datasheets for the Dell workstations. Raspberry Pi 4 datasheet does not include regulatory energy use value according to European Commission (2013). Therefore, we estimated P_{idle} P_{sleep} and P_{off} of SBCs according to values found on the internet. Power (W) and energy (kWh) for both scenarios are reported in

Table 2.

Table 2. Usage pattern, power of devices, and energy use of each scenario

			Scenario 1			Scenario 2				
			PC			SBC		Server		Total
Type of usage	Usage pattern (% and h)		P* (W)	E_{TEC} (kWh/yr/PC)	E_{total} (kWh/FU)	P** (W)	E_{TEC} (kWh/yr/SBC)	P*** (W)	E_{TEC} (kWh/yr/server)	E_{total}(kWh/FU)
Idle	40%	3504	28.1	98.3	303 258	2.7	9.5	201.4	705.7	50 535
Sleep	5%	438	2.4	1.1		0	0.0	11.4	5.0	
Off	55%	4818	0.4	1.7		0	0.2	0.3	1.4	

* https://i.dell.com/sites/doccontent/shared-content/solutions/en/Documents/prec_tower_3620_d13m002.pdf

** https://www.pidramble.com/wiki/benchmarks/power-consumption

*** https://www.energystar.gov/productfinder/product/certified-computers/details/2359366Sensitivity analysis

2.2.8. Sensitivity analysis

In the baseline scenario 2, we considered that 6 servers are sufficient for 600 SBCs, since each server has 96 logic cores and the Ethernet protocol enables 5 to 8 Mbps per SBC which is sufficient for the use of most digital tools. However, it can be necessary to have two supplementary servers to protect against lack of services. Furthermore, we considered in the baseline scenarios that SBCs have the same lifetime than PCs (5 years). However, lifetime of SBC in the context of higher education is uncertain and we propose to study the sensitivity of the results to a conservative assumption: lifetime of 2.5 years for SBCs. Therefore, we considered a worst-case “scenario 2” with the following assumptions: manufacture of 8 servers instead of 6; manufacture of 1200 Raspberry Pi instead of 600, in order fulfil the functional unit.

We also conducted a sensitivity analysis on the electricity mix for the use phase since SBCs could be used in higher education worldwide. We selected the European mix (446 gCO_2 eq/kWh) and the Polish mix (1099 gCO_2 eq) which are more carbon intensive than the French one (58g CO_2 eq). For these additional analyses, we considered exactly the same supply chain and end-of-life for the devices.

Table 3. Inventory data for the key components (Motherboard, GPU, RAM) and their associated ecoinvent 3.5. processes

Components	Elements	Quantity	Unit	Source of data	ecoinvent processes
Motherboard	Processor	6.78	g	Quantification of the number/area of the elements: Dotdotgoose Unitary mass: rough estimation based on documentation and size of sub-components (see SI)	market for integrated circuit, logic type | integrated circuit, logic type | GLO
	Wafer (8*8mm area)	64	mm2		market for wafer, fabricated, for integrated circuit | GLO
	42*electrolytic capacitors	54.18	g		market for capacitor, electrolyte type, < 2cm height | GLO
	1064*SMD (mainly capacitors)	91.504	g		market for capacitor, for surface-mounting | GLO
	9*inductors	17	g		market for inductor, low value multilayer chip |GLO
	137* integrated circuits	50	g		market for integrated circuit, logic type | GLO
	1*PCB (259*259mm area)	67081	mm2		market for printed wiring board, for surface mounting, Pb free surface | GLO market for mounting, surface mount technology, Pb-free solder | GLO
	3*PCIE + 7*RAM slots	81.2	g		market for electric connector, peripheral component interconnect buss | GLO
	26*remaining connectors	182	g		market for electric connector, peripheral type buss | GLO
GPU	4*electrolytic capacitors	5.16	g		market for capacitor, electrolyte type, < 2cm height | GLO
	258*SMD, mainly capacitors	22.18	g		market for capacitor, for surface-mounting | GLO
	2*inductors	3.77	g		market for inductor, low value multilayer chip | GLO
	24*ICs	10	g		market for integrated circuit, logic type | GLO
	4*memory ICs	8	g		market for integrated circuit, memory type | GLO
	1*die of approx. 9mm*9mm area	81	mm2		market for wafer, fabricated, for integrated circuit | GLO
	1*PCB of 152*68mm area	10336	mm2		market for printed wiring board, for surface mounting, Pb free surface | GLO market for mounting, surface mount technology, Pb-free solder | GLO
	3*connectors	20	g		market for electric connector, peripheral type buss | GLO
RAM	1*Integrated circuit	8	g		market for integrated circuit, memory type | GLO
	1*printed circuit board	4000.5	mm2		market for printed wiring board, for surface mounting, Pb free surface | GLO market for mounting, surface mount technology, Pb-free solder | GLO

Table 4. Inventory data for the Dell 3620 desktop computer life cycle, and their associated ecoinvent 3.5 processes

Dell 3620	Elements	Quantity	Unit	Source of data	ecoinvent processes
Components	Motherboard	1	unit	Computer disassembly and Dell Factsheet	see Table 3
	GPU	1	unit		see Table 3
	RAM	1	unit		see Table 3
	HDD	1	unit		market for hard disk drive, for desktop computer | GLO
	Disk drive	1	unit		market for disk drive, CD/DVD, ROM, for desktop computer | GLO
	Power supply unit	1	unit		market for power supply unit, for desktop computer | GLO
Chassis	steel, low-alloyed, hot rolled	5	kg	educated guesses and of values averaged over a few models of the relevant subsystems when possible	market for steel, low-alloyed, hot rolled | APOS, U - GLO
	sheet rolling, steel	5	kg		market for sheet rolling, steel | APOS, U - GLO
	powder coat, steel	0.53	m2		market for powder coat, steel | APOS, U - GLO
	acrylonitrile-butadiene-styrene copolymer	0.15	kg		market for acrylonitrile-butadiene-styrene copolymer | APOS, U - GLO
	stretch blow moulding	0.15	kg		market for stretch blow moulding | APOS, U - GLO
	cable, ribbon cable, 20-pin, with plugs	0.05	kg		market for cable, ribbon cable, 20-pin, with plugs | APOS, U - GLO
	cable, connector for computer, without plugs	1.80	m		market for cable, connector for computer, without plugs | APOS, U - GLO
	plug, inlet and outlet, for computer cable	1	unit		market for plug, inlet and outlet, for computer cable | APOS, U - GLO
	cable, network cable, category 5, without plugs	3	m		market for cable, network cable, category 5, without plugs | APOS, U - GLO
	plug, inlet and outlet, for network cable	1	unit		market for plug, inlet and outlet, for network cable | APOS, U - GLO
	Desktop 120 mm air-cooling system	1	unit		See Table S1.7
	120 mm diameter fan	1	unit		See Table S1.6
Assembly	Electricity	2.77	kWh	ecoinvent report: proxy based on mass	market group for electricity, medium voltage | CN
	Production of tap water	1.60	m3		market for tap water | RoW
	Treatment of waste water	1.60	m3		market for wastewater, unpolluted | RoW
Packaging	Corrugated board box	2.20	kg	Estimation	market for corrugated board box | RoW
	Polypropylene	0.16	kg		market for polypropylene, granulate | GLO
	Polymer foaming	0.16	kg		market for polymer foaming | GLO
Transport	Transport, lorry	11*2000	t·km	estimation: 1000km in France + 1000km in China	transport, freight, lorry 16-32 metric ton, EURO5 | RoW
	Transport, ship	11*15000	t·km	estimation: distance between China and France	transport, freight, sea, transoceanic ship | GLO
Use	Electricity, FR	505.43	kWh	see section 2.2.7	market for electricity, low voltage | FR
End-of-life	End-of-life of the computer	8.45	kg	mass of device	market for used desktop computer | GLO
	End-of-life packaging	2.20	kg	mass of packaging	market for waste packaging paper | FR
	End-of-life packaging	0.16	kg	mass of packaging	market for waste polypropylene | FR

Table 5. Inventory data for the Raspberry Pi 4 single-board computer life cycle, and their associated ecoinvent 3.5 processes

Raspberry Pi 4 Rev B	Elements	Quantity	Unit	Source of data	ecoinvent processes
Components	95*capacitors	2.150	g	Quantification of the number/area of the elements: (1) Unitary mass: rough estimation based on documentation and size of sub-components (see SI)	market for capacitor, for surface-mounting | GLO
	10*diode, glass-, for surface-mounting	0.128	g		market for diode, glass-, for surface-mounting | APOS, U - GLO
	9*electric connector, peripheral type buss	20.00	g		market for electric connector, peripheral type buss | APOS, U - GLO
	8*inductor, low value multilayer chip	0.013	g		market for inductor, low value multilayer chip | APOS, U - GLO
	1*integrated circuit, logic type (processor)	5.000	g		market for integrated circuit, logic type | APOS, U - GLO
	3*integrated circuit, memory type	3.000	g		market for integrated circuit, memory type | APOS, U - GLO
	5*light emitting diode	0.700	g		market for light emitting diode | APOS, U - GLO
	39*resistor, surface-mounted	0.294	g		resistor production, surface-mounted | APOS, U - GLO
	4*transistor, surface-mounted	1.779	g		market for transistor, surface-mounted | APOS, U - GLO
	1*PCB, Pb containing surface	4760	mm2		market for printed wiring board, for surface mounting, Pb containing surface | GLO mounting, surface mount technology, Pb-free solder | GLO
Chassis	acrylonitrile-butadiene-styrene copolymer	0.05	kg	educated guesses and of values averaged over a few models of the relevant subsystems when possible	market for acrylonitrile-butadiene-styrene copolymer | GLO
	electricity, low voltage	0.375	kWh		market group for electricity, low voltage | CN
	cable, network cable, category 5, without plugs	3	m		market for cable, network cable, category 5, without plugs | GLO
	plug, inlet and outlet, for network cable	1	unit		market for plug, inlet and outlet, for network cable | GLO
	External 15 W power supply	1	unit		See Table S1.5
Assembly	Electricity	0.0165	kWh	ecoinvent report: proxy based on mass	market group for electricity, medium voltage | CN
	Production of tap water	9.6	L		market for tap water | RoW
	Treatment of waste water	9.6	L		market for wastewater, unpolluted | RoW
Packaging	Corrugated board box	0.02	kg	Estimation	market for corrugated board box | RoW
Transport	Transport, lorry	0.068*2000	kg·km	estimation: 1000km in France + 1000km in China	transport, freight, lorry 16-32 metric ton, EURO5 | RoW
	Transport, ship	0.068*15000	kg·km	estimation: distance between China and France	transport, freight, sea, transoceanic ship | GLO
Use	Electricity, FR	48.62	kWh	see section 2.2.7	market for electricity, low voltage | FR
End-of-life	End-of-life of the computer	0.048	kg	mass of the device	market for used desktop computer | GLO
	End-of-life packaging	0.02	kg	mass of the packaging	market for waste packaging paper | FR

(1) https://elinux.org/RPi_Partial_BOM_Rev2.0_ModelB

Table 6. Inventory data for the server life cycle, and their associated ecoinvent 3.5 processes

Server Dell 7920	Elements	Quantity	Unit	Source of data	ecoinvent processes
Components	Motherboard	2	units	Computer disassembly and Dell Factsheet	see Table 1
	GPU	2	units		see Table 1
	2*Processors (2* 36.4mm*29.4mm)	0.118	kg		market for integrated circuit, logic type | GLO
	RAM	8	units		see Table 1
	2*SSD	40.0	g		market for integrated circuit, logic type | GLO
	3*HDD	3	units		market for hard disk drive, for desktop computer | GLO
	Power supply unit	2.12	unit		market for power supply unit, for desktop computer | GLO
Chassis	steel, low-alloyed, hot rolled	13	kg	educated guesses and of values averaged over a few models of the relevant subsystems when possible	market for steel, low-alloyed, hot rolled | GLO
	sheet rolling, steel	13	kg		market for sheet rolling, steel | GLO
	powder coat, steel	0.936	m2		market for powder coat, steel | GLO
	acrylonitrile-butadiene-styrene copolymer	0.35	kg		market for acrylonitrile-butadiene-styrene copolymer | GLO
	stretch blow moulding	0.35	kg		market for stretch blow moulding | GLO
	cable, ribbon cable, 20-pin, with plugs	0.13	kg		market for cable, ribbon cable, 20-pin, with plugs | GLO
	cable, connector for computer, without plugs	1.8	m		market for cable, connector for computer, without plugs | GLO
	plug, inlet and outlet, for computer cable	1	unit		market for plug, inlet and outlet, for computer cable | GLO
	cable, network cable, category 5, without plugs	3	m		market for cable, network cable, category 5, without plugs | GLO
	plug, inlet and outlet, for network cable	1	unit		market for plug, inlet and outlet, for network cable | GLO
	Server 140 mm air-cooling system	1	unit		See Table S1.7
	140 mm diameter fan	3	units		See Table S1.6
Assembly	Electricity	10	kWh	ecoinvent report: proxy based on mass	market group for electricity, medium voltage | CN
	Production of tap water	5	m3		market for tap water | RoW
	Treatment of waste water	5	m3		market for wastewater, unpolluted | RoW
Packaging	Corrugated board box	2.2	kg	Estimation	market for corrugated board box | RoW
	Polypropylene	0.16	kg		market for polypropylene, granulate | GLO
	Polymer foaming	0.16	kg		market for polymer foaming | GLO
Transport	Transport, lorry	30*2000	kg·km	estimation: 1000km in France + 1000km in China	transport, freight, lorry 16-32 metric ton, EURO5 | RoW
	Transport, ship	30*15000	kg·km	estimation: distance between China and France	transport, freight, sea, transoceanic ship | GLO
Use	Electricity, FR	3560.72	kWh	see section 2.2.7	market for electricity, low voltage | FR
End-of-life	End-of-life of the computer	8.45	kg	mass of device	market for used desktop computer | GLO
	End-of-life packaging	2.2	kg	mass of packaging	market for waste packaging paper | FR
	End-of-life packaging	0.16	kg	mass of packaging	market for waste polypropylene | FR

3. Results

The LCIA results of scenario 1 and scenario 2 are both presented in sections 3.1 and 3.2, respectively. Then, they are compared in section 3.3.

3.1. Life cycle impact assessment (LCIA) of scenario 1 – desktop computers

For the scenario 1, Figure 5 shows that the majority of the impacts are generated by manufacturing PCs, representing more than 50% of the impacts in 15 out of the 17 categories.

The use phase only dominates the ionizing radiation (92%) category. It also generates large share of water consumption (39%), ozone depletion (25%) and marine eutrophication (21%) impacts. Actually, the electricity from France mostly comes from nuclear energy. It generates radioactive emissions (= ionizing radiation), evaporates water for cooling (= water consumption), and relies on uranium extraction that leads to nitrate leakages to rivers and sea (= marine eutrophication). Ozone depletion is mainly due to the dinitrogen monoxide generated from the ionisation of air molecules from electro-magnetic field near high-voltage aerial lines.

The manufacture of components dominates the impacts of PC fabrication. This is mainly due to electronic components that have complex supply chains requiring many resources (metals, chemicals, etc.) and are energy intensive. Along their supply chain, the energy-related activities such as coal extraction and use in Chinese thermo-electric plants generate most of CO_2 (= global warming), NOx (= ozone formation), and fine particulate formation, ultimately leading to air quality degradation as well as the of fossil resources. The manufacture of electronic components also dominates all toxicity impact categories, freshwater eutrophication, terrestrial acidification, land use and mineral resource scarcity because of mining activities. Such activities emit toxic forms of metals (Chromium VI, Nickel, Lead, Zinc Cadmium), eutrophying substances (Phosphates) and acid substances (sulfur dioxide). They occupy large amounts of land (e.g., for the treatment of sulfidic tailing) and participate to the depletion of metals.

Figure 6 shows that the motherboard is the component that represents the largest share of impact (>50% of the global warming, other impact categories showing similar contributions), even though the power supply unit is the heaviest component in mass. At the sub-component level, Figure 6 also shows that the production of integrated circuits (including the processor) dominates the impacts of the motherboard.

The PC chassis represent 4 to 20% of the total impacts (except for ionizing radiation), with the highest contribution in mineral resource scarcity (9%), terrestrial ecotoxicity (17%) and human carcinogenic toxicity (20%). This is because of the requirements of metals (steel, aluminium, copper) for the chassis and the CPU heat sink. Metals usually have high contribution in toxicity categories because of their high persistence in the environment (including after mining activities).

The PCs' assembly, packaging, transport and end-of-life have low contribution in all categories.

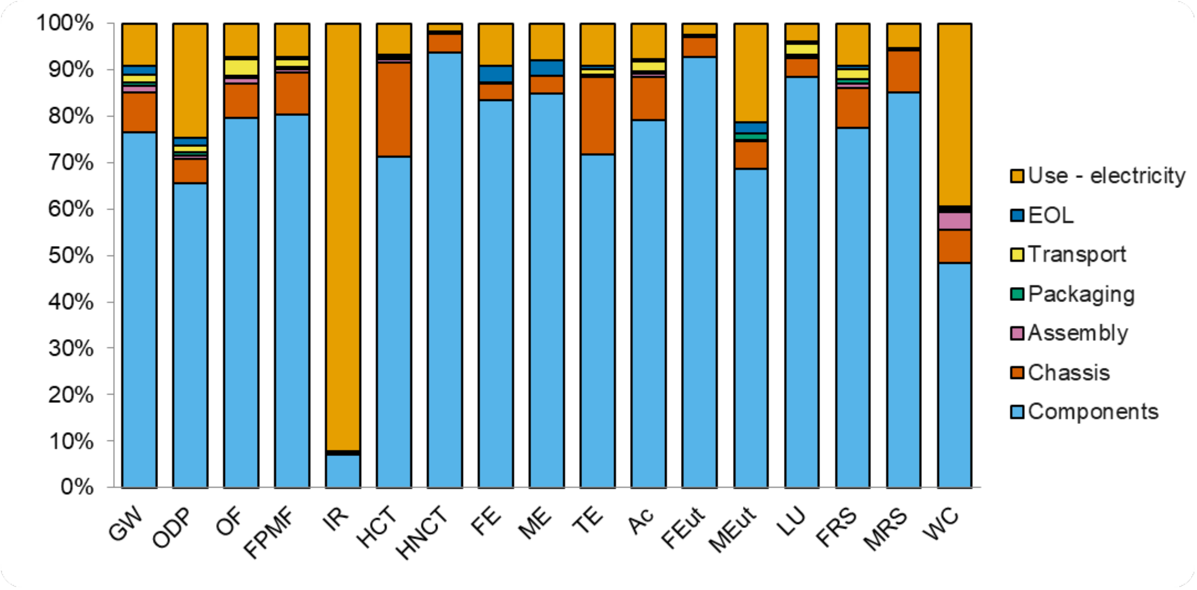


Figure 5. Contribution analysis of scenario 1 – 600 desktop computers (ReCiPe2016 Midpoint H). Abbreviation definitions are given in Table 1.

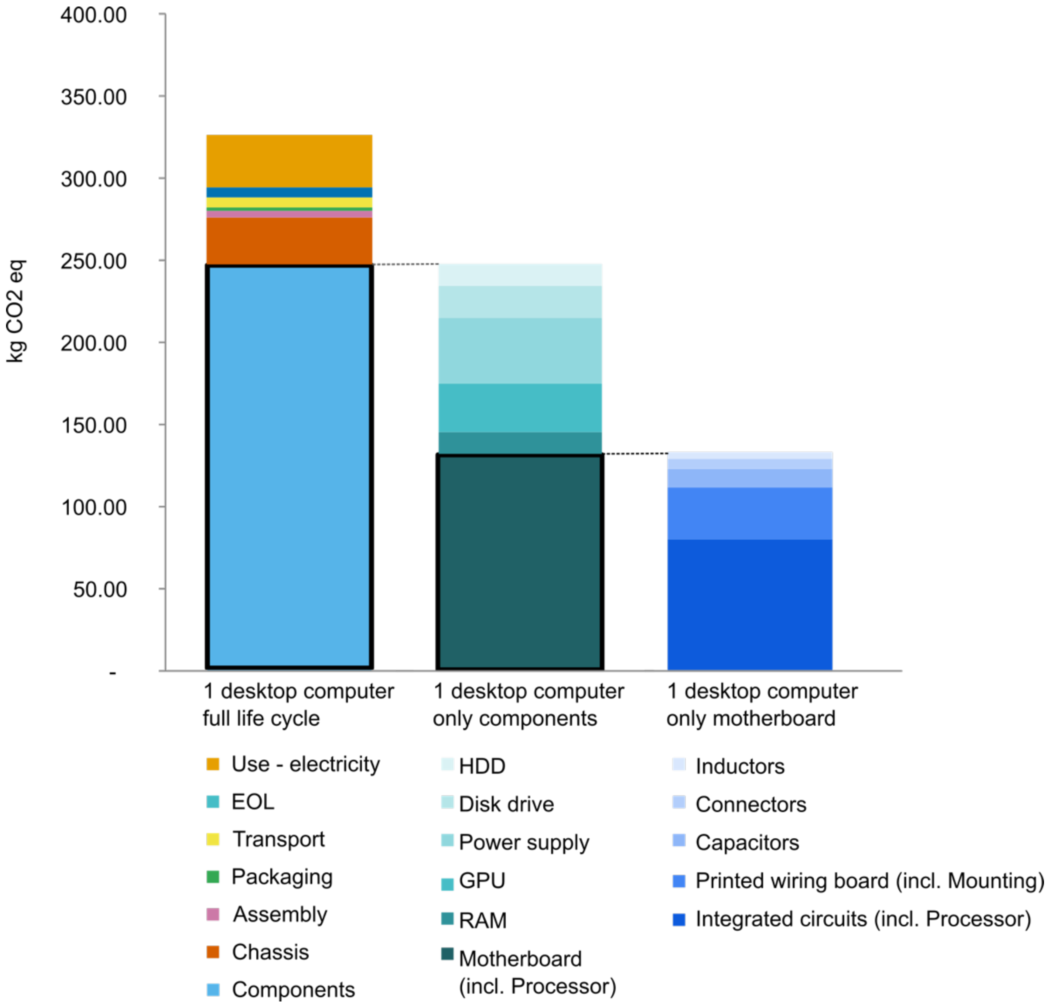


Figure 6. Global warming impacts for one Dell computer over its 5 years' life time for (i) the full life cycle, (ii) the different components, and (iii) the different subcomponents of the motherboard.

3.2. LCIA of scenario 2 – SBCs and servers

Regarding the relative contribution of the different life cycle phases, the analyses drawn for scenario 1 are also valid for scenario 2: the manufacture and the use of devices (SBCs and servers) have similar contributions in all impact categories as for PCs (as shown in Figure 7). The relative share of impacts between components, chassis, assembly packaging and transport for SBCs and servers are not shown for simplicity but are similar to scenario 1. Therefore, the analysis of the results in section 3.1 is also valid here. A complete contribution analysis is available in SI (Table S3.3).

One can note that the SBCs and the servers represent on average 60% and 40% of the total impacts respectively, even though the scenario relies on 600 SBCs and 6 servers. This is explained by the low material requirements and energy consumption of the Raspberry Pi compared to the server (Figure 10)

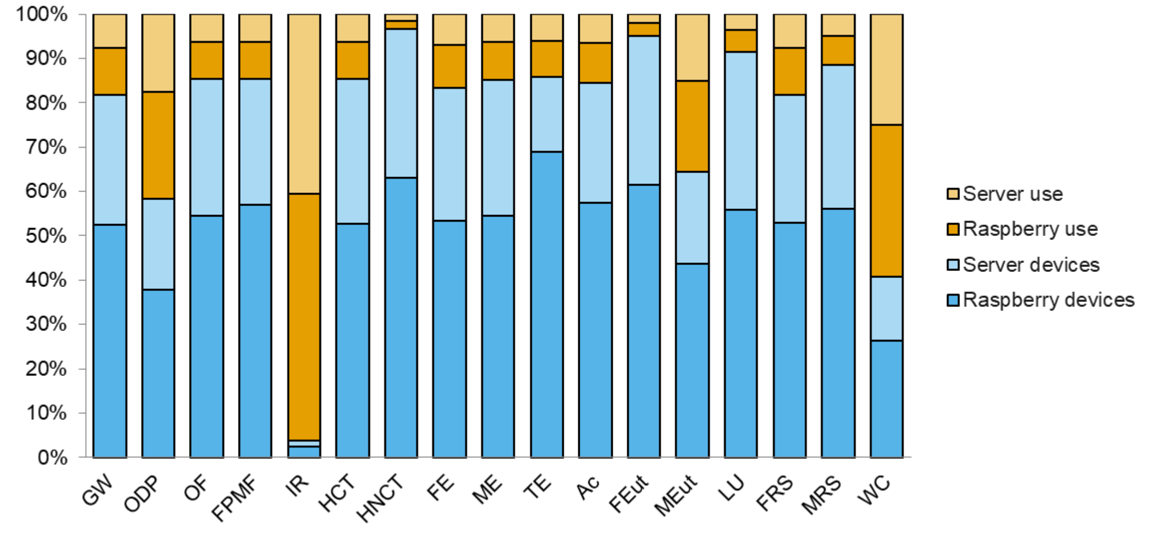


Figure 7. Contribution analysis of scenario 2 – 600 SBCs + 6 servers (ReCiPe2016 Midpoint H). Abbreviation definitions are given in Table 1.

3.3. Comparison between both scenarios

Figure 8 shows that scenario 2 generates 84% to 92% fewer impacts than scenario 1 for all categories. This is due to the low material requirements and electricity consumption of SBCs compared to PCs. The servers do not generate burden shifting because only 6 are required in scenario 2 and their impacts do not counterbalance the benefits of the SBCs. One can note that the impact reduction is similar in all categories because scenario 2 is more eco-efficient both on the manufacturing and the use phases.

Regarding global warming absolute impacts, scenarios 1 and 2 generate 194.5 and 16.5 tCO_2 eq/functional unit (5 years), respectively. On a yearly basis, this is equivalent to 39 tCO_2 eq/year or the GHG emissions of 4 French citizens/year for scenario 1, and 3.3 tCO_2 eq/year or the GHG emission of 0.3 French citizen/year for scenario 2 (assuming that a French citizen is responsible for 10 tCO_2 eq/year). Regarding water consumption, scenario 1 relies on 2772 m^3/functional unit whereas scenario 2 only requires 307 m^3/functional unit.

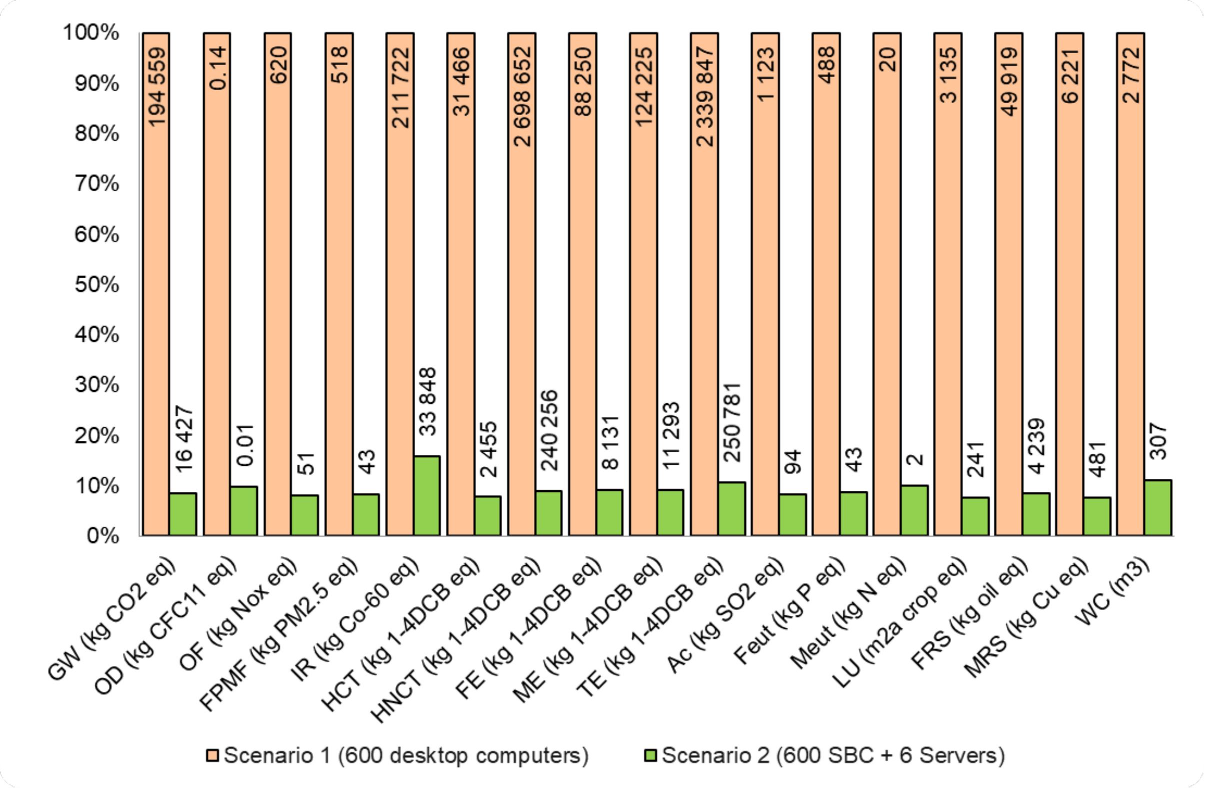


Figure 8. Relative comparison (in %) of scenario 1 and 2 environmental impacts. Absolute impacts for all impact categories are also shown. (ReCiPe2016 Midpoint H). Abbreviation definitions are given in Table 1.

As computers rely on many mineral resources that are increasingly scarce, it is also relevant to analyse and compare the different metals required for both scenarios. In terms of mass, scenario 1 requires 9394 kg of metal, whereas scenario 2 only requires 629 kg of metal during the whole life cycle according to the inventory analysis. Iron is the most used in both scenarios (Figure 9). Gold is the most contributing metal to mineral resource scarcity when characterized with the "surplus ore potential" of the ReCiPe2016 method. Gold is mainly used as electroplated coating on connectors and solderable coating for printed circuit boards. Other specific scarce metals used in computers that rank high in mineral resources scarcity are: silver mainly used in printed circuit boards and tantalum mainly used in capacitors.

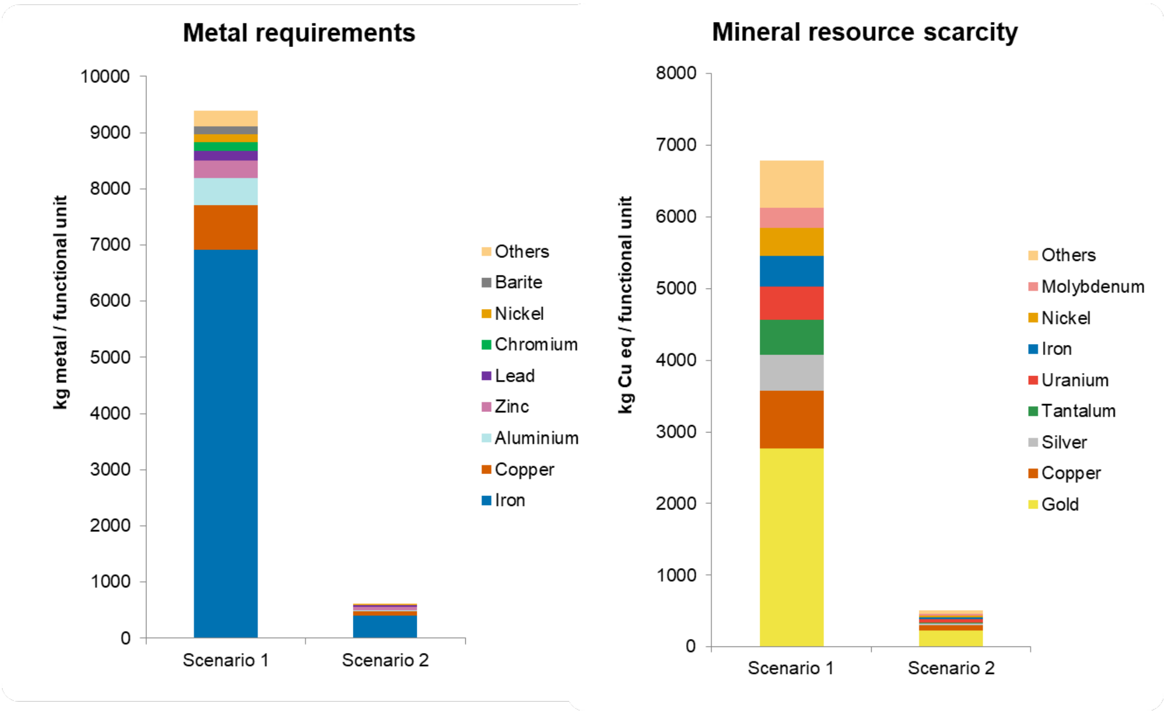
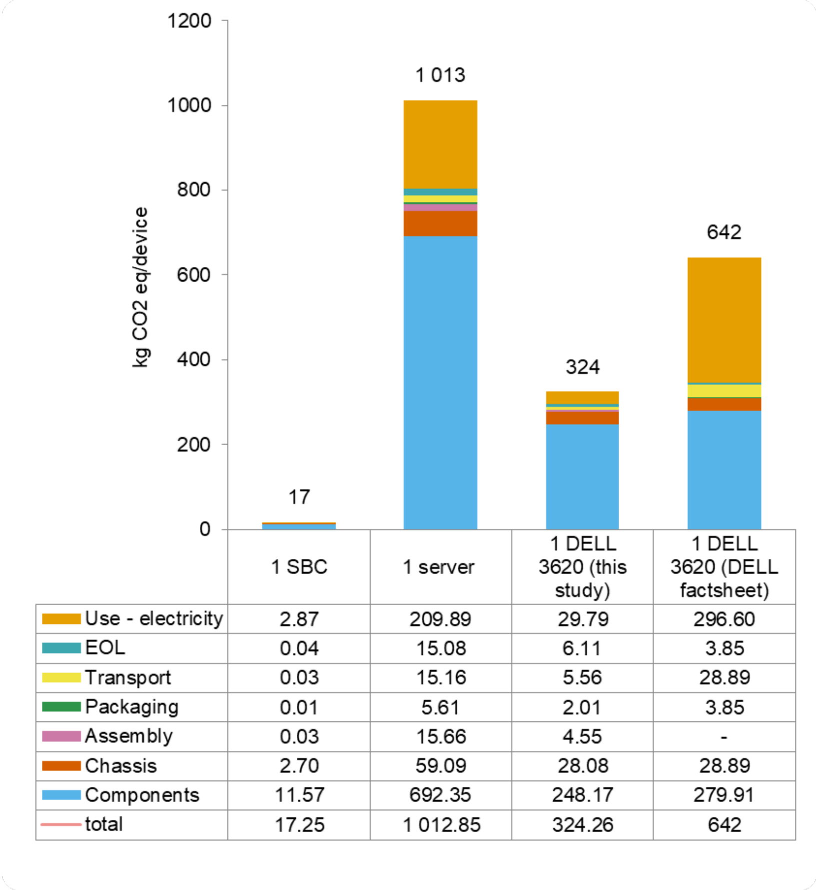


Figure 9. Metal requirements and mineral resource scarcity impact of both scenarios.

As shown in Figure 10, it is also possible to compare all three devices separately. A SBC only generates 17kg CO_2 eq over its life cycle, whereas a desktop computer generates 324 kg CO_2 eq and a server generates 1013 kg CO_2 eq.



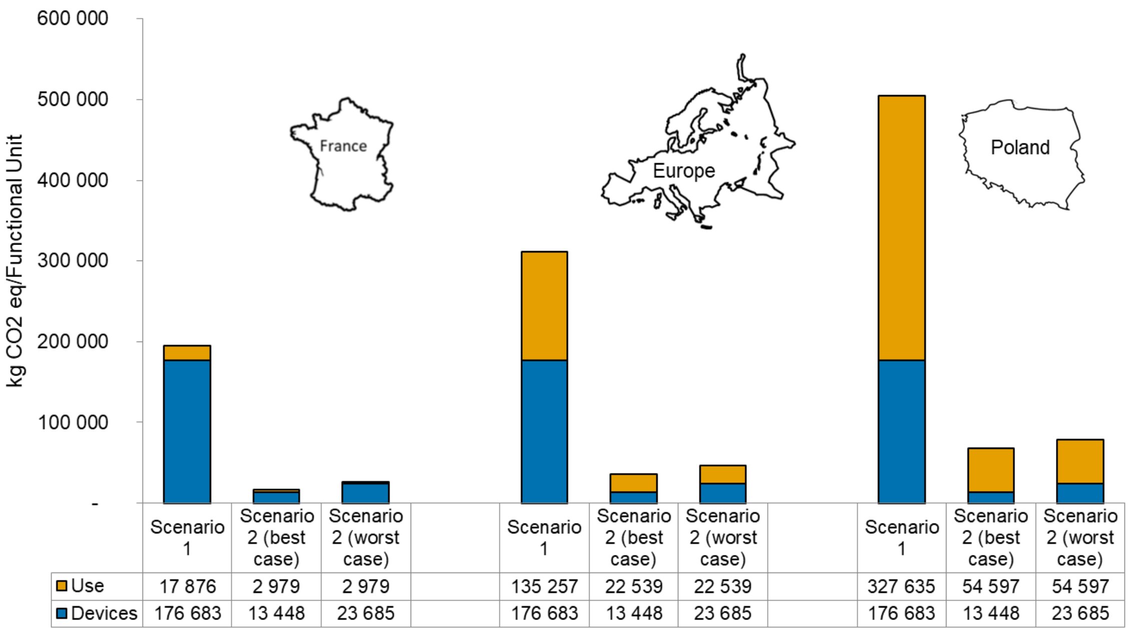
	1 SBC	1 server	1 DELL 3620 (this study)	1 DELL 3620 (DELL factsheet)
Use - electricity	2.87	209.89	29.79	296.60
EOL	0.04	15.08	6.11	3.85
Transport	0.03	15.16	5.56	28.89
Packaging	0.01	5.61	2.01	3.85
Assembly	0.03	15.66	4.55	-
Chassis	2.70	59.09	28.08	28.89
Components	11.57	692.35	248.17	279.91
total	17.25	1 012.85	324.26	642

Figure 10. Global warming impact for the life cycle of the three devices over their lifetime.

3.4. Sensitivity analysis

Figure 11 shows the global warming impact of a worst-case scenario 2. It considers the manufacture of 1200 SBCs + 8 servers. This scenario increases the impact of device manufacturing from 13.5 tCO_2 eq to 23.7 tCO_2 eq compared to the best-case scenario presented previously. However, it is still largely beneficial compared to scenario 1. It means that scenario 2 always generates lower impacts than scenario 1, even if the life time of the SBC is reduced and the server's requirement is higher than expected.

Figure 11 also shows that the use phase has the largest share of impacts in regions where the electricity mix is carbon intensive. However, scenario 2 that uses less energy, is still beneficial in these countries.



	Scenario 1	Scenario 2 (best case)	Scenario 2 (worst case)		Scenario 1	Scenario 2 (best case)	Scenario 2 (worst case)		Scenario 1	Scenario 2 (best case)	Scenario 2 (worst case)
🟧 Use	17 876	2 979	2 979		135 257	22 539	22 539		327 635	54 597	54 597
🟦 Devices	176 683	13 448	23 685		176 683	13 448	23 685		176 683	13 448	23 685

Figure 11. Sensitivity analysis for global warming results considering worst-case and best-case scenario 2 and different countries of use (ReCiPe2016 H Midpoint)

4. Discussion

4.1. Comparison of the results with the literature

Dell company provides product carbon footprint of most of their computers, based on a streamlined LCA tool (Olivetti and Kirchain 2012). The Dell Precision tower 3620 carbon footprint computed with their approach results in 642 $kgCO_2$ eq over its life cycle (Dell 2018b), as shown in Figure 10. This differs from our estimation (324 $kgCO_2$ eq) mainly because of the use phase (296 $kgCO_2$ eq against 30 $kgCO_2$ eq). Actually, Dell company has considered different electricity mix (more carbon intensive than the French one). As for the other life cycle stages, the results are similar. The slight differences might come from: different LCI background database used in PAIA, and different assumptions mainly for the transportation.

Also, it is to be noted that the precision tower 3620 is a workstation (i.e., a powerful desktop computer). The carbon footprint of such device is higher than middle-range desktop computers, such as the OptiPlex series, which generate 10-15% less GHG emissions than the Precision series (Dell 2022a).

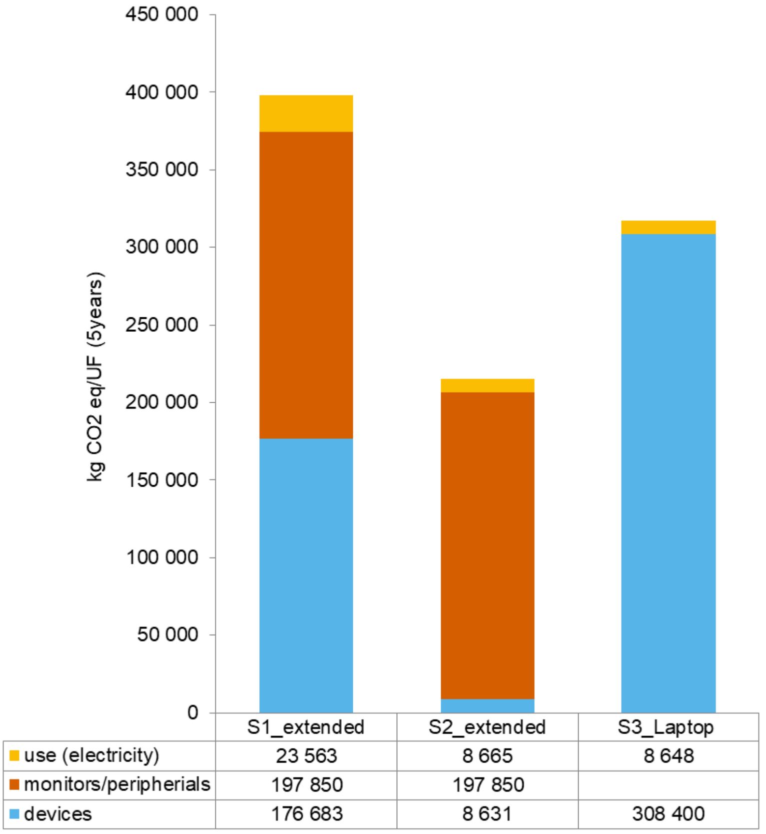
Compared with other types of ICT miniaturization, the literature has shown that all-in-one computers (Subramanian and Yung 2017) and thin clients associated with servers (Maga et al. 2013) enable to decrease the PCs' global warming impact by 50% and 65%, respectively. Due to its low power and mass, SBCs enable an even higher reduction (i.e., 90%).

4.2. Comparison of the results with other potential scenarios

Another option for ICT infrastructure in higher education is the exclusive use of laptops, where each student (1200) gets a laptop from the school instead of using 600 desktop computers. This scenario is currently not envisaged in the studied school in the short term as it would require an important change in the organization of practical work. However, this kind of infrastructure might gain interest in the mid or long-term due to increased flexibility and simplicity in the frame of dematerialization of higher education. Therefore, we propose a simplified comparison between a laptop scenario (S3), S1 and S2 (which are both extended to take into account monitors and peripherals). We gathered carbon footprint data of laptops, monitors and peripherals (assuming a 5-year lifetime) that were available in the literature (Dell 2022a) to compare the following simplified scenarios:

- S1_extended: S1 + 600 monitors (mix of Dell E2216H/E2219H), mouses, keyboards
- S2_extended: S2 + 600 monitors, mouses, keyboards
- S3: 1200 laptops (Latitude 5400 which is the middle range of Dell laptop in term of performance and carbon footprint)

Results are shown in Figure 12 and exhaustive information on this comparison is available in SI.



	S1_extended	S2_extended	S3_Laptop
🟨 use (electricity)	23 563	8 665	8 648
🟧 monitors/peripherials	197 850	197 850	
🟦 devices	176 683	8 631	308 400

Figure 12.Simplfied and prelimary comparison of carbon footprint between extended S1 and S2 (considering monitors and peripherials) and S3-laptop

We found out that the laptop scenario is in-between extended S1 and S2. Therefore, it is a potential solution to decrease the impacts of ICT in higher education. However, this preliminary result should be analysed with caution as it requires additional and crucial information on: the usage pattern of the laptop outside of the school, the lifetime of the laptop, accounting for the fact that providing laptop computer to students might influence their purchase of personal laptop, etc. Also, it requires full LCA computation for consistency and completeness sake.

4.3. Data limitations

Ecoinvent datasets related to electronic components are outdated as they were collected in the 2000's (Hischier et al. 2007). Since both scenarios rely on the same types of components, we assume that this would not change the relative comparison between scenario 1 and scenario 2, but the absolute results shown in this study should be used with caution. An update of such datasets is urgently needed to identify appropriate eco-design solutions for the ICT sector. It should be noted that the EF Database v2.0 contains more up-to-date datasets on electronics. However, these datasets are based on the thinkstep database[2], which provides black box LCIs. They may not have been created using the same approach as the ecoinvent datasets.

Moreover, the quantification of electricity use of the different devices was theoretically estimated based on the power and usage pattern of the different devices. It is necessary to monitor the energy consumption in the practical workspaces to obtain accurate data. In this way, appropriate strategies for reducing energy consumption can be identified. Such quantification is planned for the future. The additional energy consumption for air conditioning in classrooms and server rooms has not been included and should be monitored in further studies.

Regarding end-of-life, we used generic assumptions based on ecoinvent datasets, which may not be representative of the real situation of waste electrical and electronic equipment (WEEE) management in France. As strategies to increase reuse and recycling rates are currently being implemented (European Commission 2012), it is necessary to better describe this phase in further studies. In any case, the fact that SBCs are light and simple devices should ease their management at the end-of-life.

4.4. Implications for decision making

Our study clearly shows that the use of single-board computers can drastically reduce the environmental impact of ICT in universities, even for the worst-case scenario 2. SBCs are also cost-effective due to the low price of the Raspberry Pi 4 Rev B. We evaluated the financial costs of the different options for scenario 1 and 2 (see Tables S6 in SI) considering the investment and the electricity costs. Scenario 1 (PCs) ranges from 636 k€ to 936 k€ whereas scenario 2 (SBCs + servers) ranges from 248 k€ to 382 k€.

However, such a solution is still not deployed. It could represent a poorer quality of service and a less robust system than using PCs. In the short term, our school would like to deploy single-board computers in two classrooms to ensure that all labs in the school are compatible with the proposed infrastructure. Moreover, other single-board computers will be investigated. For example, there are now single-board computers that are an open-source RISC-V alternative to the Raspberry Pi. RISC-V is a 64-bit RISC instruction set architecture (ISA) that is open and free, i.e. it has open specifications and can be freely used by education, research and industry. In the long term, such a solution could also be deployed in the 5 other graduate

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[2] https://gabi.sphera.com/databases/ef-database-v20/

schools of Bordeaux INP. It should be noted that the current case study was proposed in a simplified exercise to introduce LCA to all students of ENSEIRB-MATMECA, as part of a new class on sustainable development. This was an important achievement. Indeed, it enables to introduce the topic to more than 350 students per year, and to train more than 10 professors in LCA and openLCA.

Finally, considering the competitive cost and lower environmental impact of SBCs, they are a promising solution for a better access to ICT in developing countries. Our analysis has shown that in carbon-intensive countries, the use phase is the largest contributor to global warming impacts, but also that SBCs are still the best solution in terms of environmental impact.

5. Conclusions

Our study has shown that SBCs combined with servers provide several benefits to the higher education by (i) reducing the carbon footprint and other environmental impacts of public services, (ii) providing an example of improving sobriety and low-tech solutions for students, and (iii) it is cost-effective. The use of this innovative solution generates 90% less GHG emission than the use of PCs. Due to the low material requirements and energy efficient equipment, all other environmental impacts are also reduced.

Manufacture of devices represents the majority of impacts in both scenarios, which argues for the use of less material-intensive devices, and a longer lifetime. It should be noted that the electronics LCI models should be updated in the future to improve the representativeness of the data, as this industry is rapidly evolving. The use phase, which normally accounts for the largest share of ICT impacts, is only second in terms of impacts due to the low-carbon French electricity mix. With the European electricity mix, the use phase dominates the impact. However, SBCs connected to servers still drastically reduce the impact due to their low energy consumption.

Such a solution will be deployed in two classrooms at the engineering school in question to test the reliability of SBCs, even if there are still bottlenecks to full deployment, mainly related to the capacity to change from teachers and ICT services. Other promising option, such as providing a laptop for each student, should be extensively studied in the future

From an LCA point of view, there are challenges to update and improve the data quality of electronic components since (i) the current data is outdated and (ii) these are the highest contributors to ICT devices' environmental impacts.

Data availability All data generated or analysed during this study are included in this article and its supplementary information files.

Supplementary information The online version contains supplementary information in a spreadsheet containing 6 tabs related to LCI tables (S1), information on chassis (S2), information on energy use (S3), LCIA results for scenario 1 (S4), LCIA results for scenario 2 (S5), LCIA comparison (S6), comparison with laptop scenario (S7) cost comparison (S8).

Conflicts of interest

There are no conflicts to declare.

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