UCLouvain

Why do we need life cycle thinking in the context of the Internet-of-Things (IoT) ?

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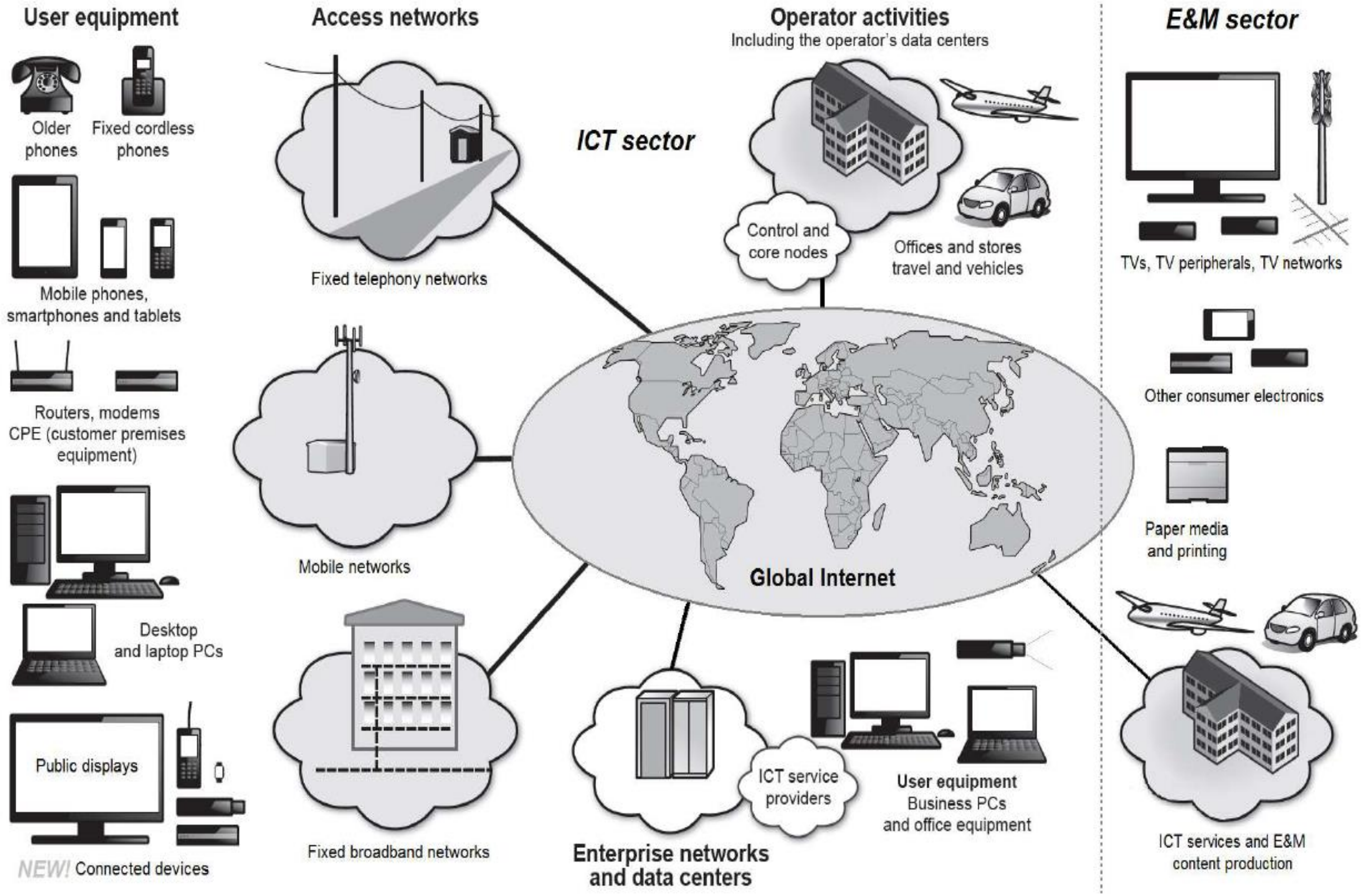
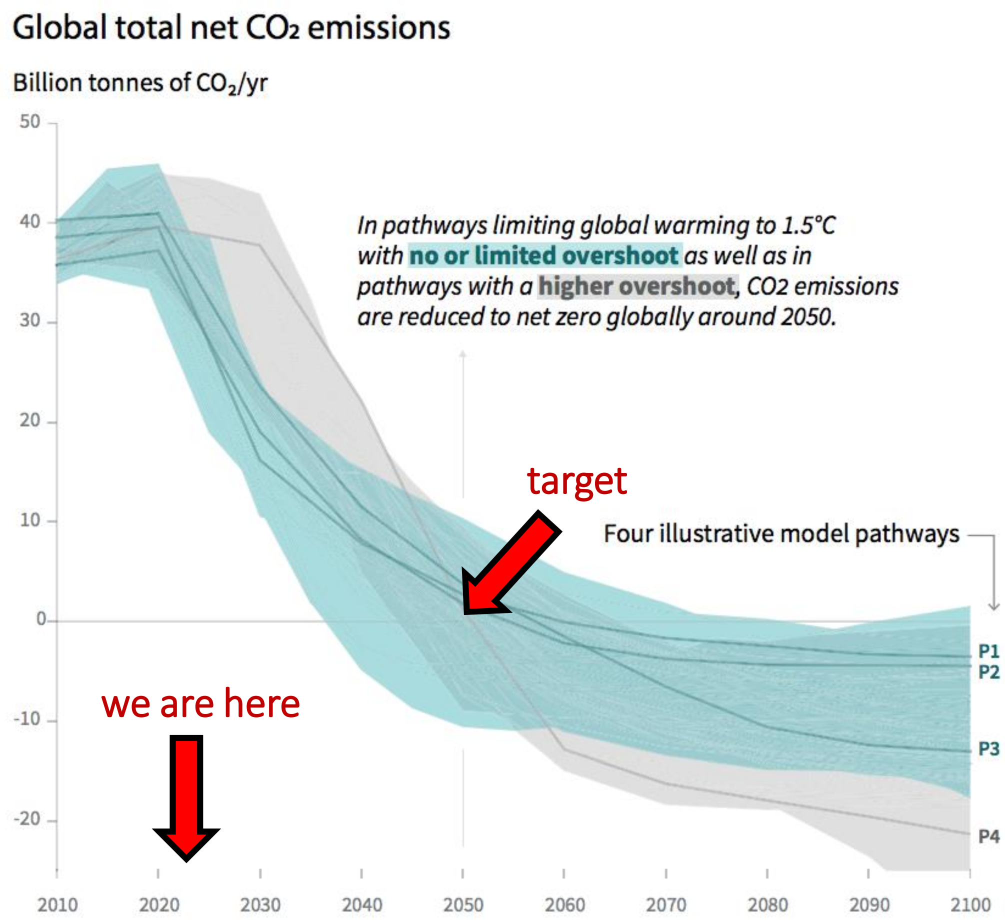
ICT helpful for many uses…



But, at the same time …



Source : IPCC 2018 report, SPM

Source : IPBES 2019

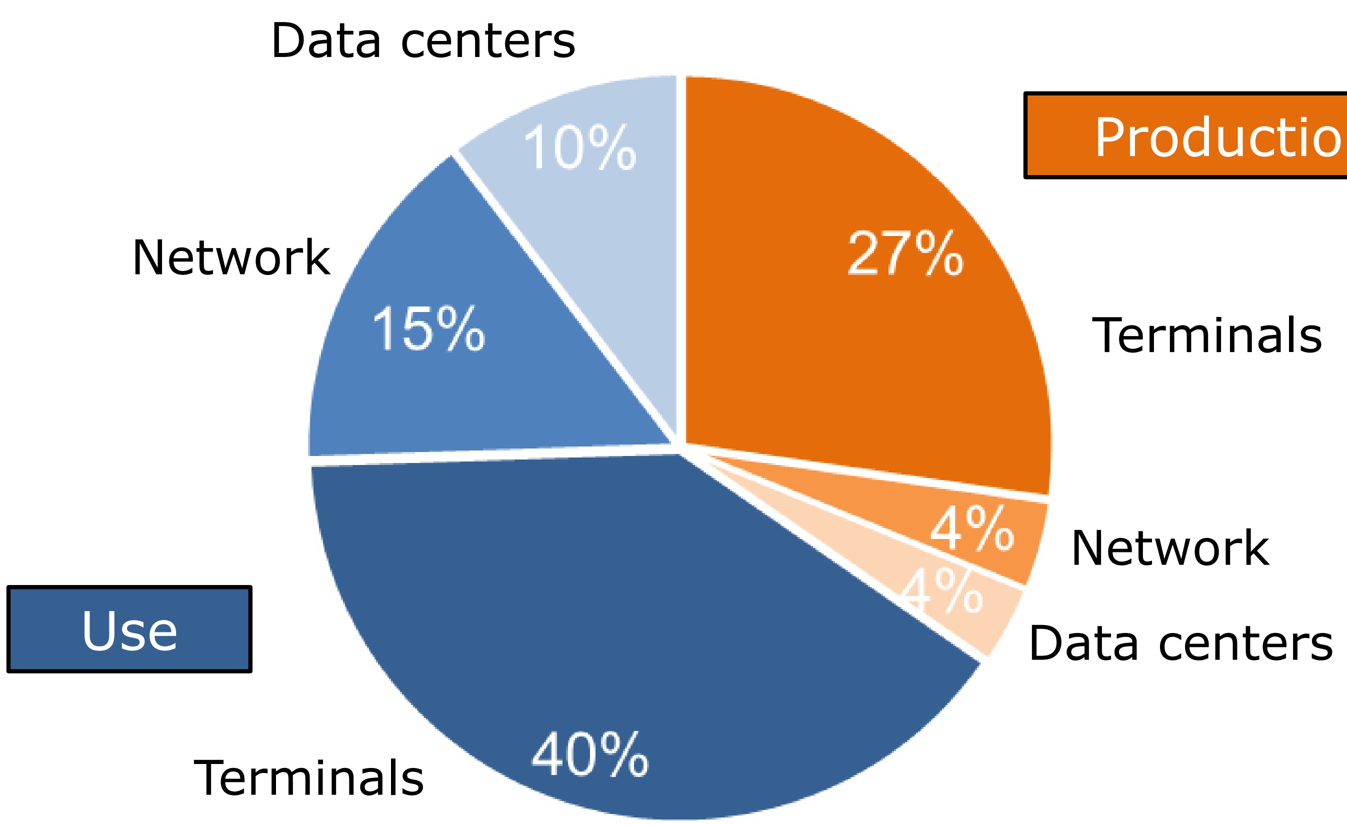
A1 Nature is essential for human existence and good quality of life. Most of nature's contributions to people are not fully replaceable, and some are irreplaceable. Nature plays a critical role in providing food

A4 Nature across most of the globe has now been significantly altered by multiple human drivers, with the great majority of indicators of ecosystems and biodiversity showing rapid decline. Seventy-five per

A8 Human-induced changes are creating conditions for fast biological evolution – so rapid that its effects can be seen in only a few years or even more quickly. The consequences can be positive or negative for biodiversity and ecosystems, but can create uncertainty about the sustainability of species, ecosystem functions and the delivery of nature's contributions to people.

Huge challenge : very few trials to get it right + short period of time (30 years) → **today's actions are critical**

ICT carbon footprint (2015)



Annual operational electrical energy [final TWh]	Total annual GHG emissions [MT CO_2e]
1390	**1200**
6-7% of world footprint	3-4% of world footprint

Source: [Ericsson] J. Malmodin and D. Lunden, MDPI Sustainability, 2018

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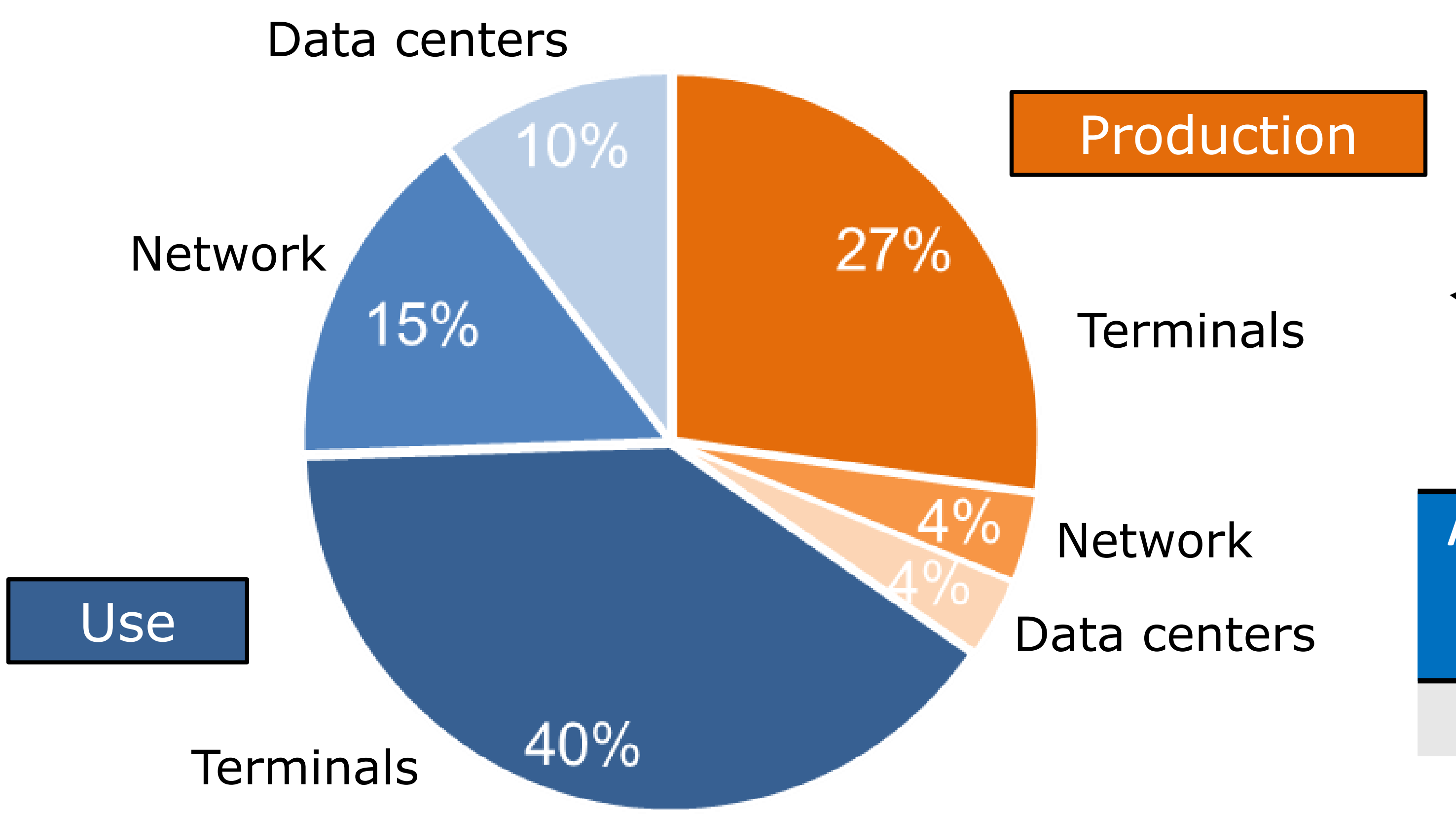

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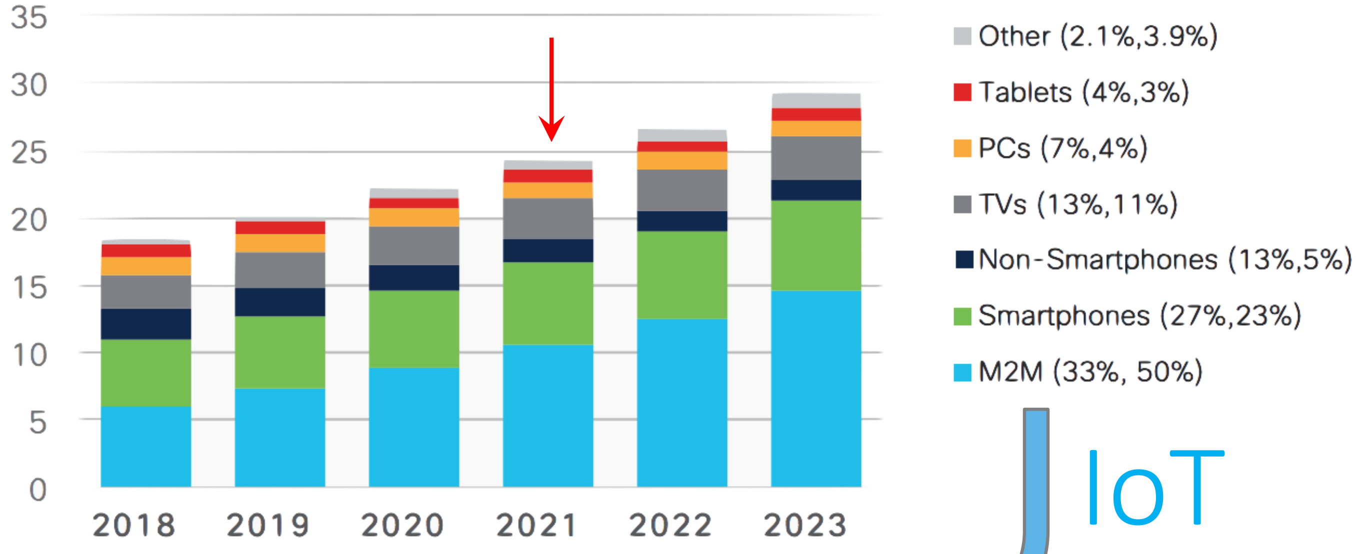
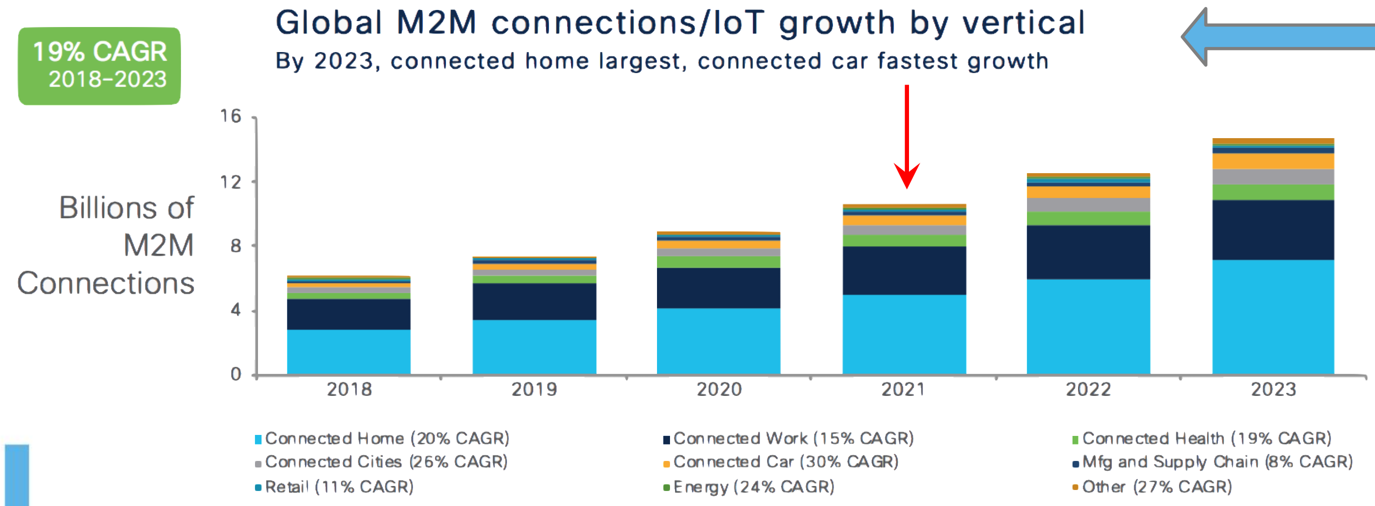
However, this DOES NOT include the carbon footprint of IoT !

What about IoT ?

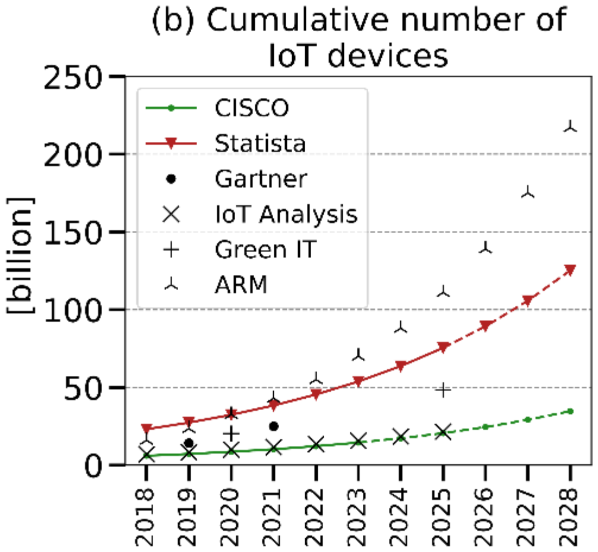
Global growth rate 2018-2023: + 10 % / year



Source: Cisco Annual Internet Report, 2018–2023



Source: Cisco Annual Internet Report, 2018–2023



Source: Pirson T., JCP, 2021

What are the

environmental impacts

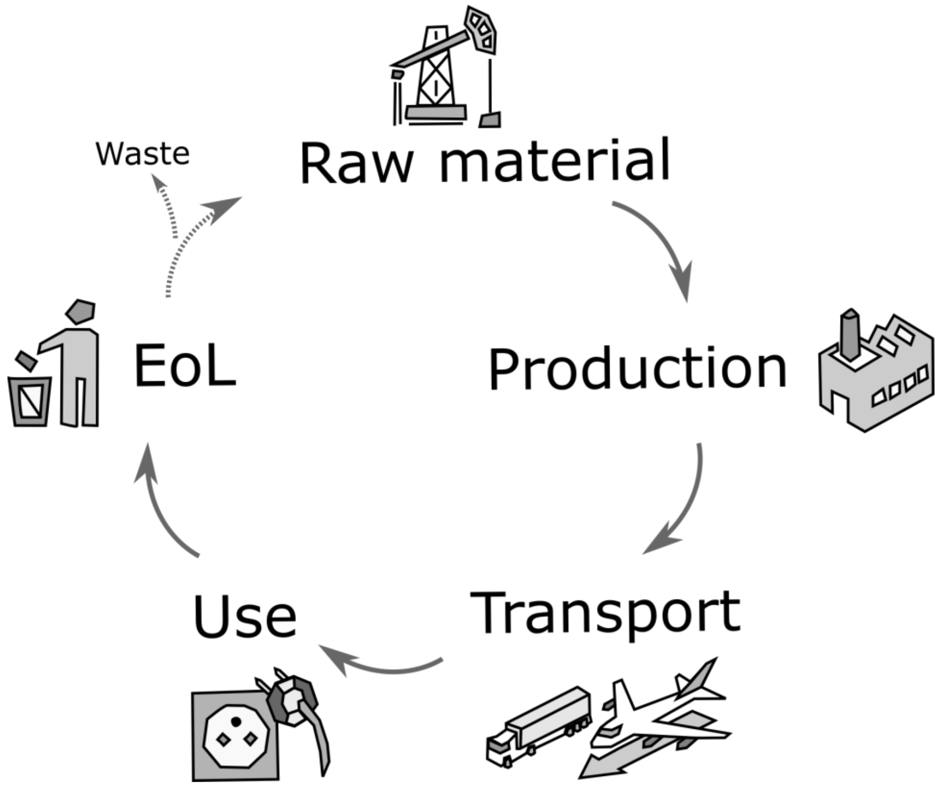
of a massive deployment of

IoT devices ?

Life Cycle Thinking

- **Life Cycle Thinking** aims at considering the (environmental) impacts of a device or service over its whole life cycle.

- **Life Cycle Assessment (LCA)** is a well-known methodology (ISO14040-4) supporting this goal in practice.



Why do we need

life cycle thinking

in the context of **IoT** ?

Outline

- ❑ Introduction & context

- ❑ **Modeling the environmental impacts of IoT devices**
  - The carbon footprint of IoT production *[JCP-2021]*
  - A multi-indicators cradle-to-grave LCA of wireless power transfer (WPT) *[In writing]*

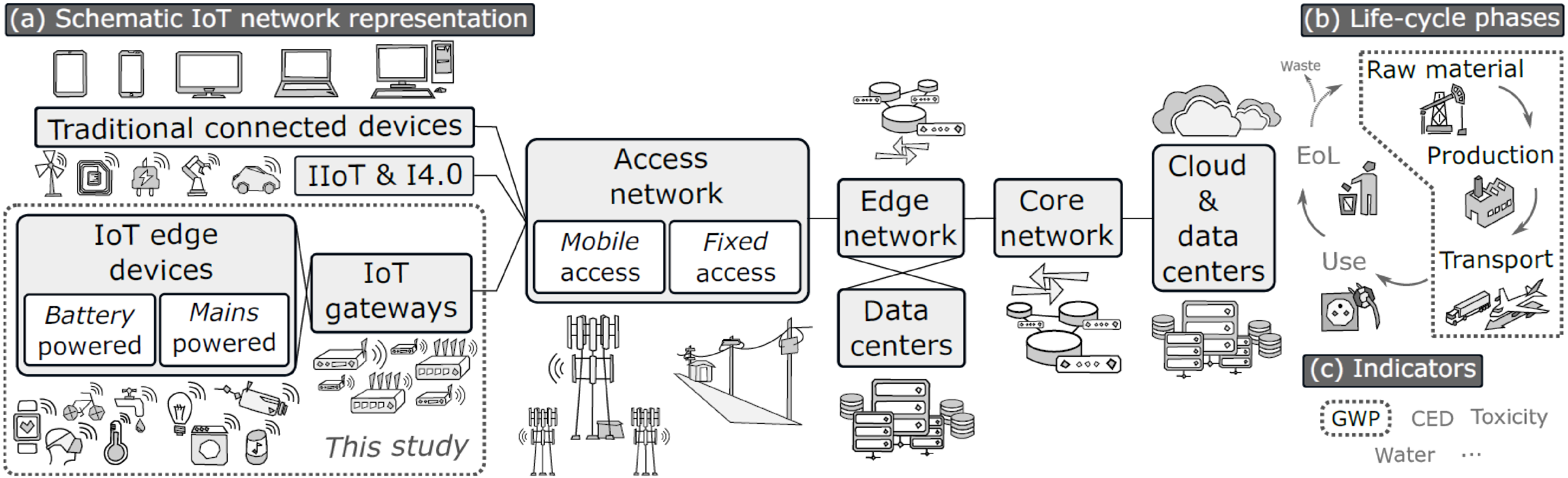
- ❑ Conclusions and perspectives

- ❑ Open discussions, Q&A

LCA of IoT

Carbon footprint of IoT edge devices

https://doi.org/10.1016/j.jclepro.2021.128966



Carbon footprint of IoT edge devices

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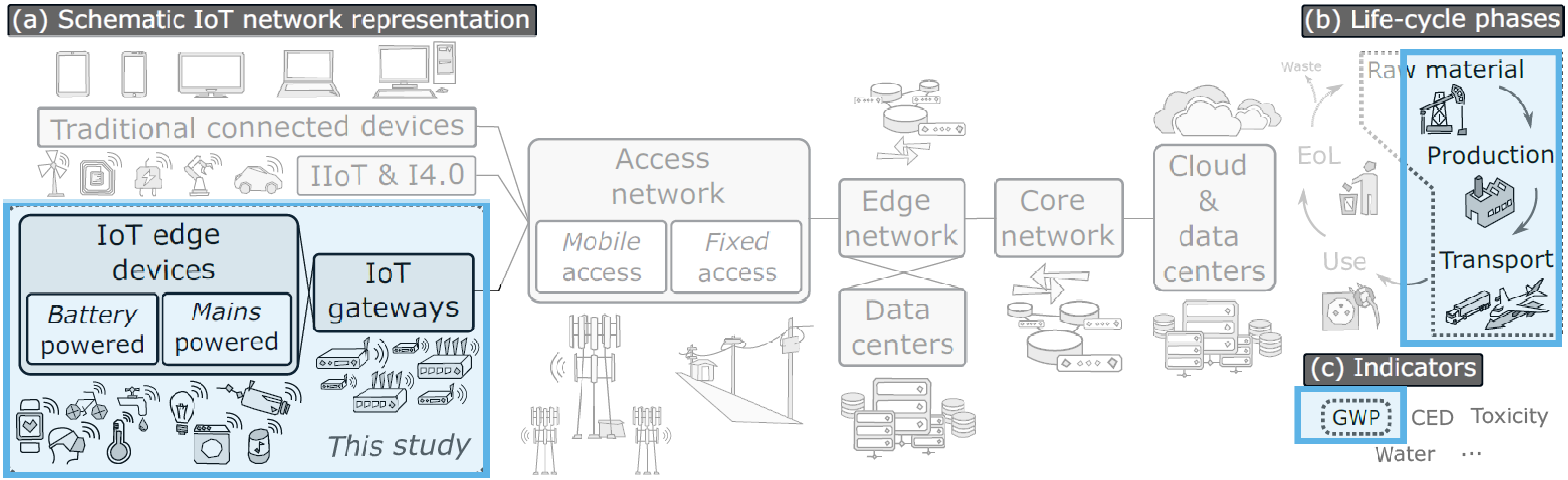


OUR CONTRIBUTION

Carbon footprint of IoT edge devices

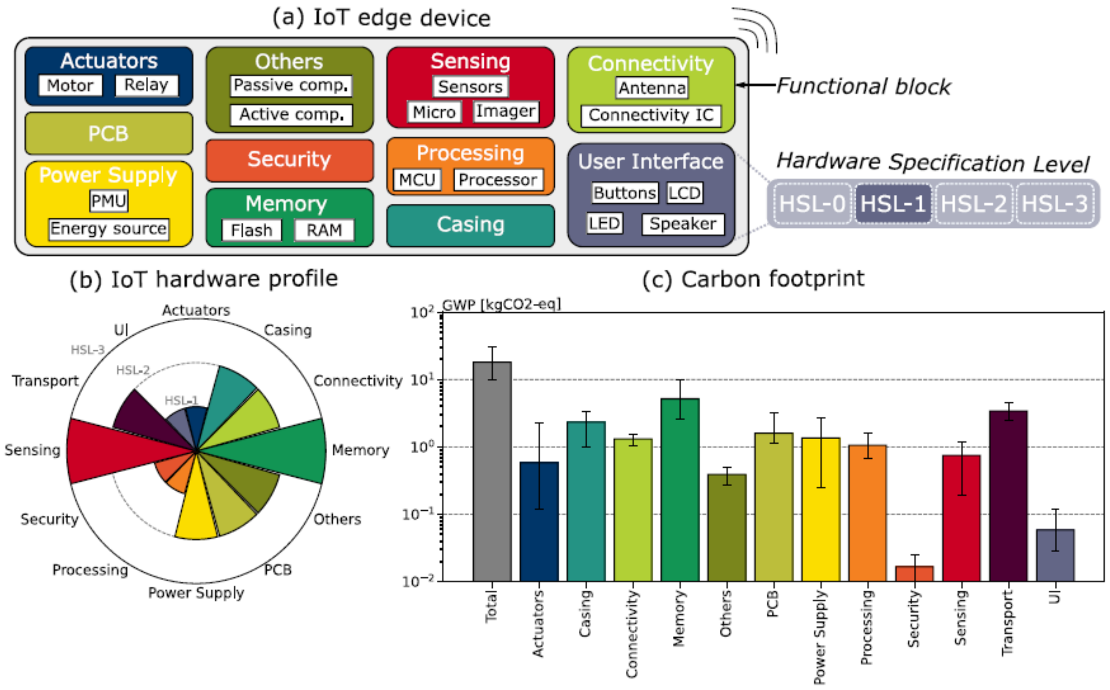
https://doi.org/10.1016/j.jclepro.2021.128966

Main question :

- How to model the embodied carbon footprint for a wide range of IoT edge devices while preserving precision ?

Our contribution :

- **Framework (quantitative)** to streamline the carbon footprint of IoT edge devices production
- Addresses directly the **heterogeneity** of the IoT and the **lack of work** in this field
- **Transparency** to foster the use of the framework
- Benchmarked with existing results (sparse)
- Applied on **4 use-cases**



Carbon footprint of IoT edge devices

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IoT hardware profiles :

- High level of details for each hardware specification level.
- Based on data sheets, review of literature and reports, teardowns and expertise.
- Not exhaustive but covers already a wide range of IoT hardware.
- *Main gaps:* sensing and actuation could be improved, energy harvesting was not considered

Table 1
Detailed life-cycle inventory (LCI) for IoT hardware profiles. For each *hardware specification level*, lower/typical/upper parameters considered are given. If not mentioned explicitly, all data is taken from GaBi professional and GaBi Extension XI (Electronics) databases. All the modeling is carried out in the GaBi LCA software. Additional details are provided in the supplementary material.

Functional block	Definition	Hardware specification level (HSL)			
		HSL-0	HSL-1	HSL-2	HSL-3
Actuators	Components that physically act on the environment	No actuator	Vibration motor (1g) 1/2/4	Relay (SSR) 1/2/4	DC motor (50g) 1/4/6 Motor driver[b] 1/2/5 mm^2 Motor driver transistor 1/4/6
Casing	Structural components of the IoT edge device whose primary function is to protect the electronic components	No casing	ABS plastic granulate 10/50/100 g Aluminum 1/10/30 g Steel 1/10/30 g	ABS plastic granulate 200/400/500 g Aluminum 20/80/150 g Steel 20/80/150 g	ABS plastic granulate 700/800/900 g Steel 70/160/300 g
Connectivity	Components which are involved in data transmission	Embedded in *Processing* (share of the die area) Printed antenna (embedded in *PCB*)	Connectivity IC[c] 5/10/20 mm^2 Printed antenna (embedded in *PCB*)	Connectivity IC[d] 20/30/45 mm^2 External whip-like antenna 10/15/30 g	Connectivity IC[d] 45/50/60 mm^2 External whip-like antenna 10/15/30 g
Memory	Components involved in the data storage on the IoT edge device	Embedded in *Processing*, Flash + RAM (≃ kB)	DRAM[g] (32/128/512 MB) 2/7.9/31.5 mm^2 Flash[f] (32/128/512 MB) 0.2/0.8/3.2 mm^2	DRAM[g] (0.5/1/2 GB) 31.5/61.5/123.1 mm^2 Flash[f] (1/4/8 GB) 6.3/25/50 mm^2	DRAM[g] (0.5/1/2 GB) 31.5/61.5/123.1 mm^2 Flash[f] (8/16/32 GB) 50/100/200 mm^2
Others	The rest of the components which do not fit another *functional block*	Capacitors and resistors 5/10/15 Diodes 2/2/2, transistors 1/2/3 Tantalum capacitors 0/0/2, crystals 0/1/1	Capacitors and resistors 15/20/25 Diodes 2/4/6, transistors 2/4/6 Tantalum capacitors 0/0/3 Crystals 1/1/2 Steel metal shield 0.5/1/2 g Cables 1/2/5 cm	Capacitors and resistors 40/50/60 Diodes 2/4/6, transistors 4/7/9 Tantalum capacitors 0/0/4 Crystals 1/2/4 Steel metal shield 0.5/1/2 g Cables 1/2/5 cm	Capacitors and resistors 75/85/100 Diodes 2/6/10, transistors 7/10/15 Tantalum capacitors 0/2/4 Crystals 1/2/4 Steel metal shield 0.5/1/2 g Cables 1/2/5 cm
PCB	Components responsible for the electro-mechanical support and electrical connections between electronic components of the IoT edge device	FR4 (4 layers) 8/10/15 cm^2 Solder Paste (SAC305) 4/8/13 mg	FR4 (4 layers) 15/35/50 cm^2 Solder Paste (SAC305) 28/53/98 mg	[illegible] Solder Paste (SAC305) 99/155/249 mg	FR4 (8 layers) 80/120/150 cm^2 Solder Paste (SAC305) 178/265/454 mg
Power supply	Components involved in the energy source and energy management of the IoT edge device, which could be battery-powered or main-powered	Mains powered Power transistor 2/3/4 Diodes power 0/1/2 Radial capacitor 2/3/4 Miniature coil 2/3/4 Ring core coil 0/1/1 Power cable 0.5/1/1.5 m CEE 7/4 Schuko plug 0/1/1	1 Coin cell Li-Po/2 AAA alkaline/2 AA alkaline	Li-ion battery[i] 10/50/100 g Power transistor 0/1/2 Diodes power 0/1/2 Radial capacitor 0/1/2 Miniature coil 0/1/2	Li-ion battery[i] 10/50/100 g Power transistor 0/1/2 Diodes power 0/1/2 Radial capacitor 0/1/2 Miniature coil 0/1/2 External IC[c] 5/15/25 mm^2
Processing	Components involved in the data processing and control tasks on the IoT edge device	MCU[c] 5/10/17 mm^2	Application processor[e] 20/30/45 mm^2 Auxiliary MCU[c] 5/10/17 mm^2	Application processor[e] 50/60/75 mm^2 Auxiliary MCU[c] 5/10/17 mm^2	Application processor[e] 75/100/125 mm^2 Auxiliary MCU[c] 5/10/17 mm^2
Security	Components related to cryptography and protection of sensitive data	Embedded in *Processing* or non-existent	External IC[b] 1/2/3 mm^2	N/A	N/A
Sensing	Components involved in measuring physical quantities of the environment	No sensor	Electre[illegible]	[illegible]	[illegible] mm^2 [illegible]") 8/30/58 mm^2
Transport	Related to the shipping of the assembled IoT edge device from the factory to the consumer	No transport	Transp[illegible] Truck [illegible] Plane [illegible] Total [illegible]	[illegible]	[illegible] [illegible] km [illegible] km [illegible] g
User interface	Components allowing interactions between external users and the IoT edge device	No user interface	Switch[illegible] LED 1[illegible]	[illegible]	[illegible] mm^2

[a] CMOS 0.25 µm; [b] CMOS 0.13 µm; [c] CMOS 90 nm; [d] CMOS 22 nm; [e] CMOS 14 nm; [f] Flash 45 nm; [g] DRAM 57 nm; [h] Data from AUO (20[illegible]

Capacitors and resistors 40/50/60
Diodes 2/4/6, transistors 4/7/9
Tantalum capacitors 0/0/4
Crystals 1/2/4
Steel metal shield 0.5/1/2 g
Cables 1/2/5 cm

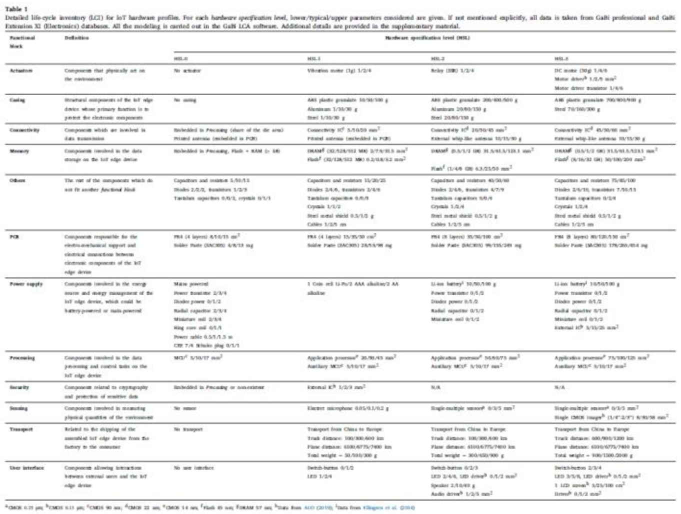
Carbon footprint of IoT edge devices

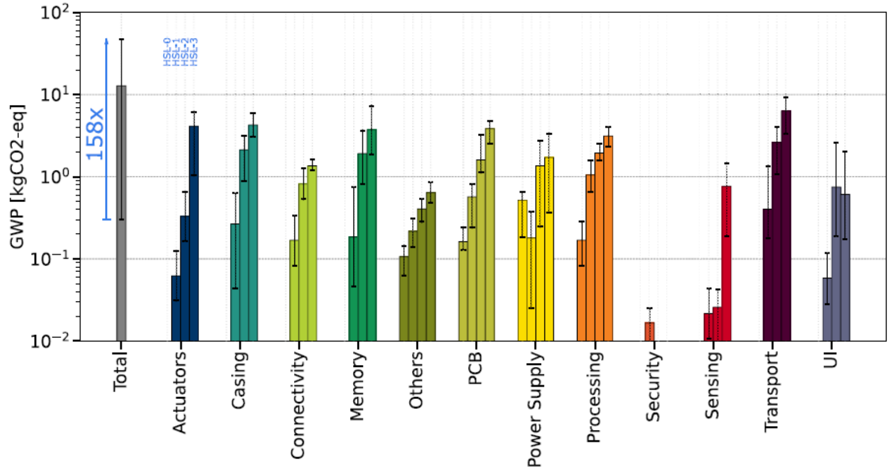
https://doi.org/10.1016/j.jclepro.2021.128966

LCI

LCA modeling in GaBi

LCA Results





Carbon footprint of IoT edge devices

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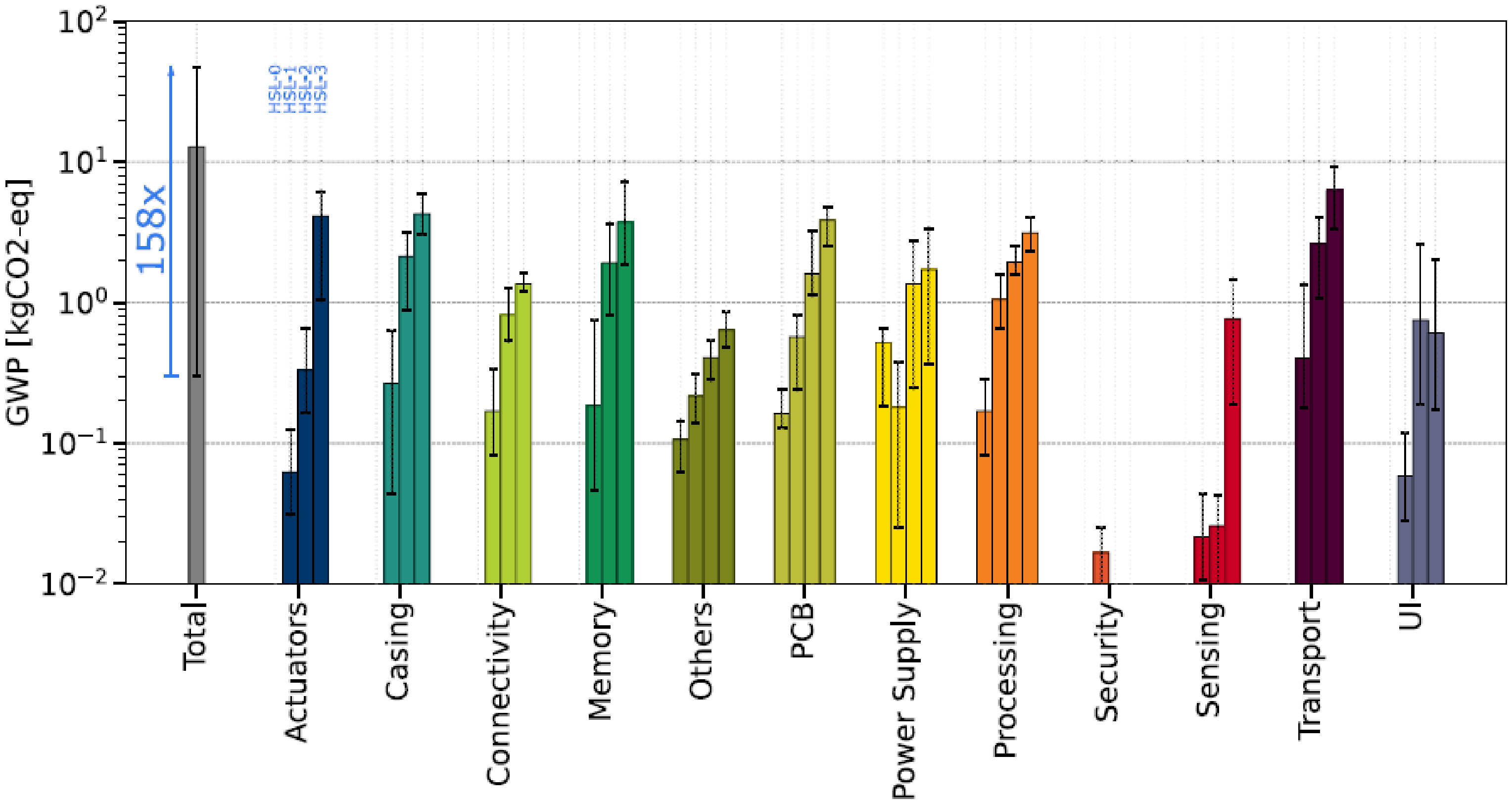
Results :

- Values are given for each hardware specification level.
- The framework can be easily used to streamline the carbon footprint of other IoT edge devices thanks to the **hardware profiles**.
- The carbon footprint of **simple and complex devices** can vary by a factor more than **150×** according to our framework

used



Carbon footprint of IoT edge devices

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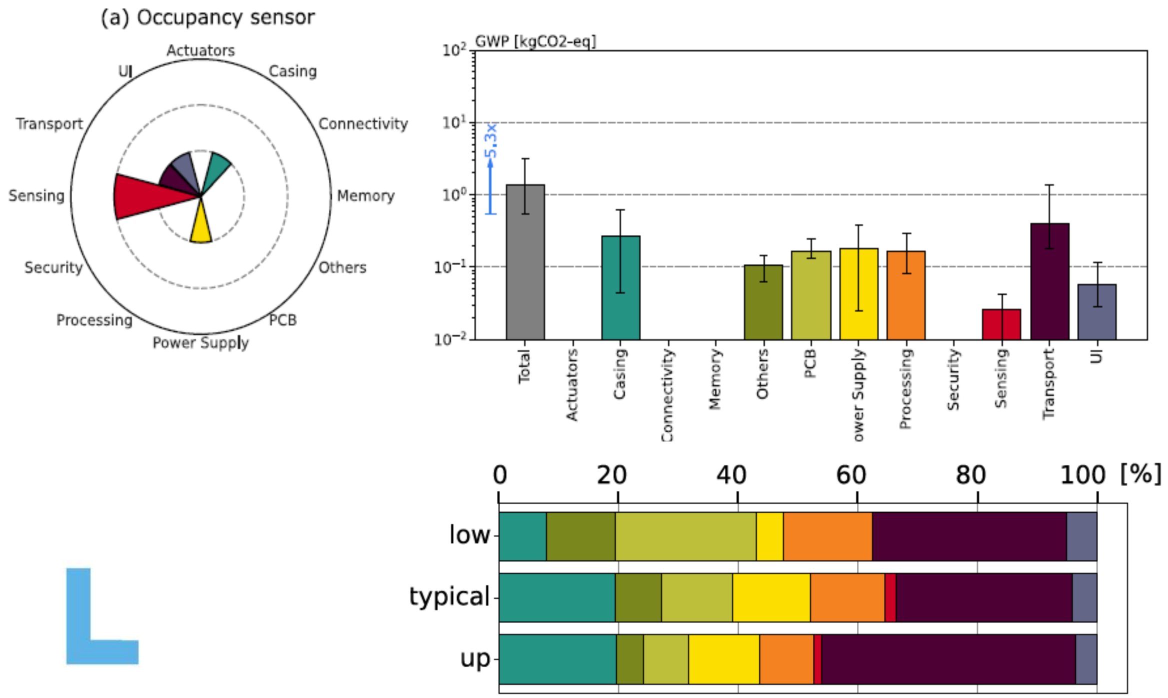
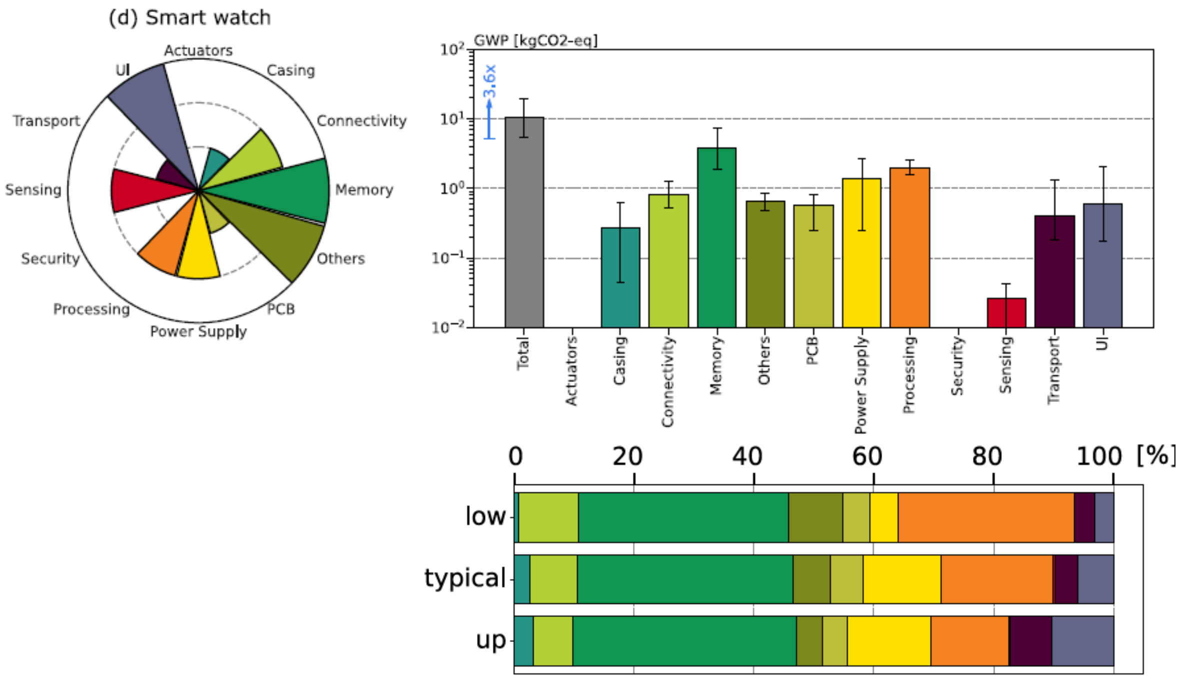
Applying the framework on 4 use-cases :

- (1) an occupancy sensor; (2) a smart watch; (3) a home-connected assistant (Google Home MINI); and (4) a drone (Mavick MINI)
- Less specific than a dedicated LCA but already provides a detailed modeling
- Different hot-spots depending on the hardware profile : **all IoT devices are not equal** !





Carbon footprint of IoT edge devices

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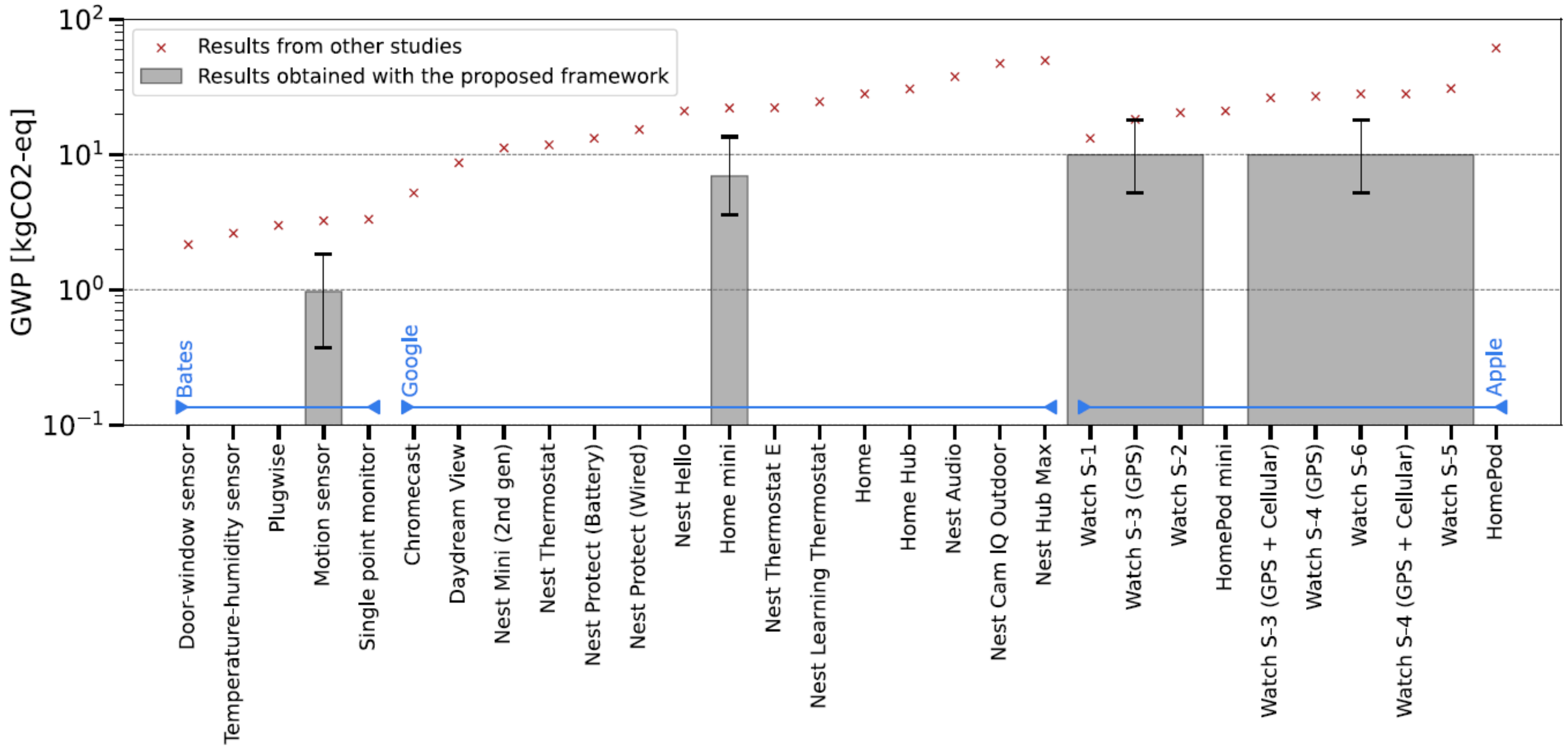
Limitations

- Truncation error due to the bottom-up approach (well-known issue)
- Strong lack of details in other studies to enable a fair and detailed comparison
- Focuses only on the production + a single indicator (GWP) → **not sufficient**
- GaBi (Sphera) databases are **not open source**

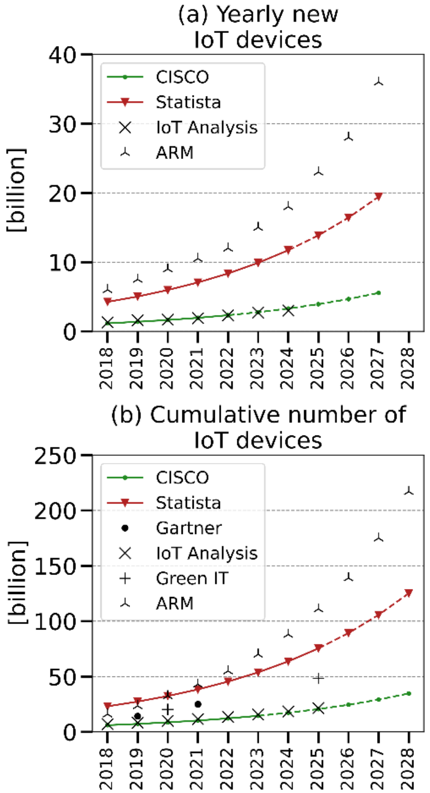


Carbon footprint of IoT edge devices

https://doi.org/10.1016/j.jclepro.2021.128966

Second question :

- How coherent is the massive deployment of devices with the Paris Agreement (PA) objectives ?



Carbon footprint of IoT edge devices

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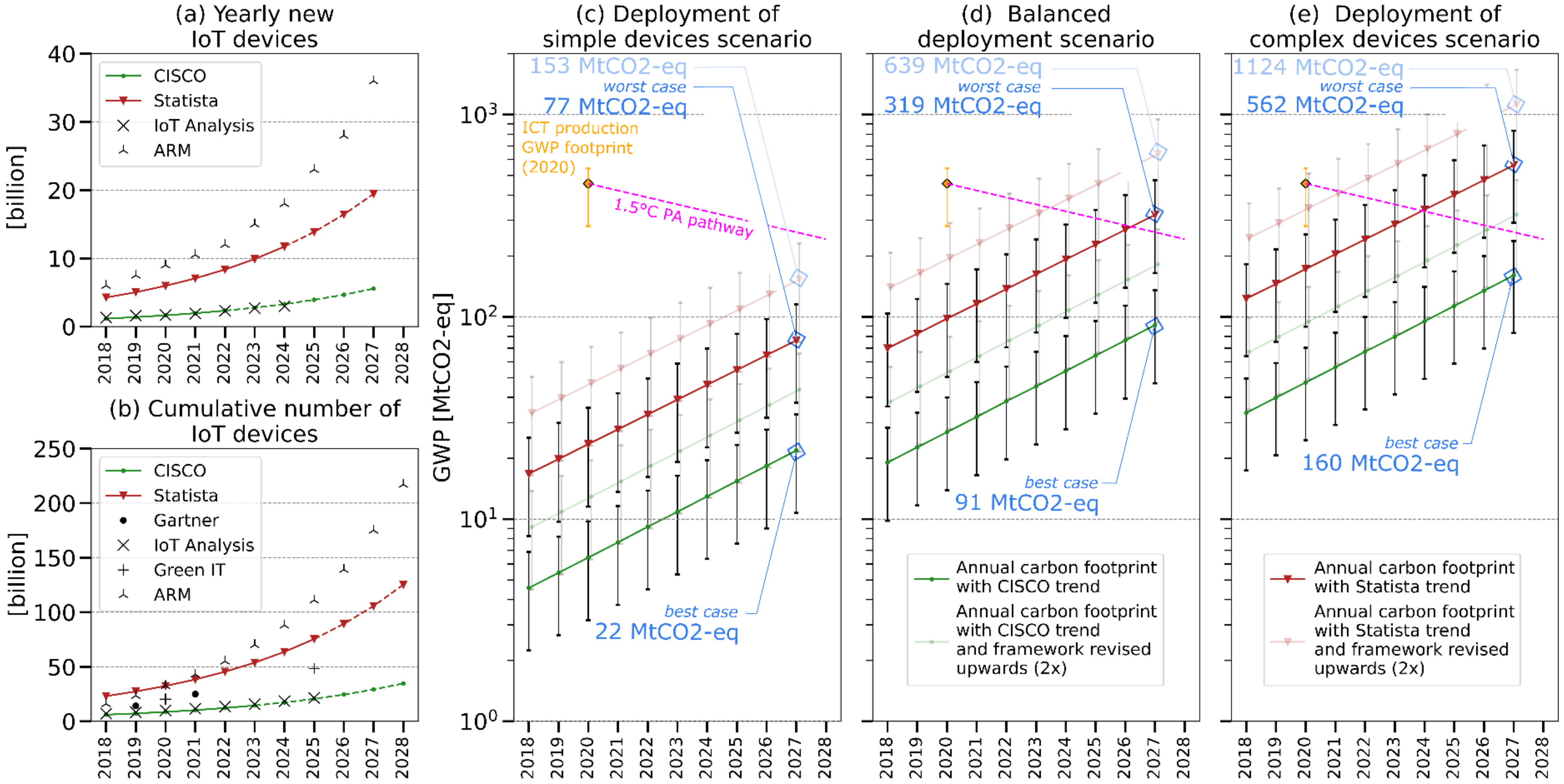
Results :

- **Conflicting paths** with PA (scenarios) → critical need to integrate LCA for IoT: trade-off between the type of profile and the number of devices



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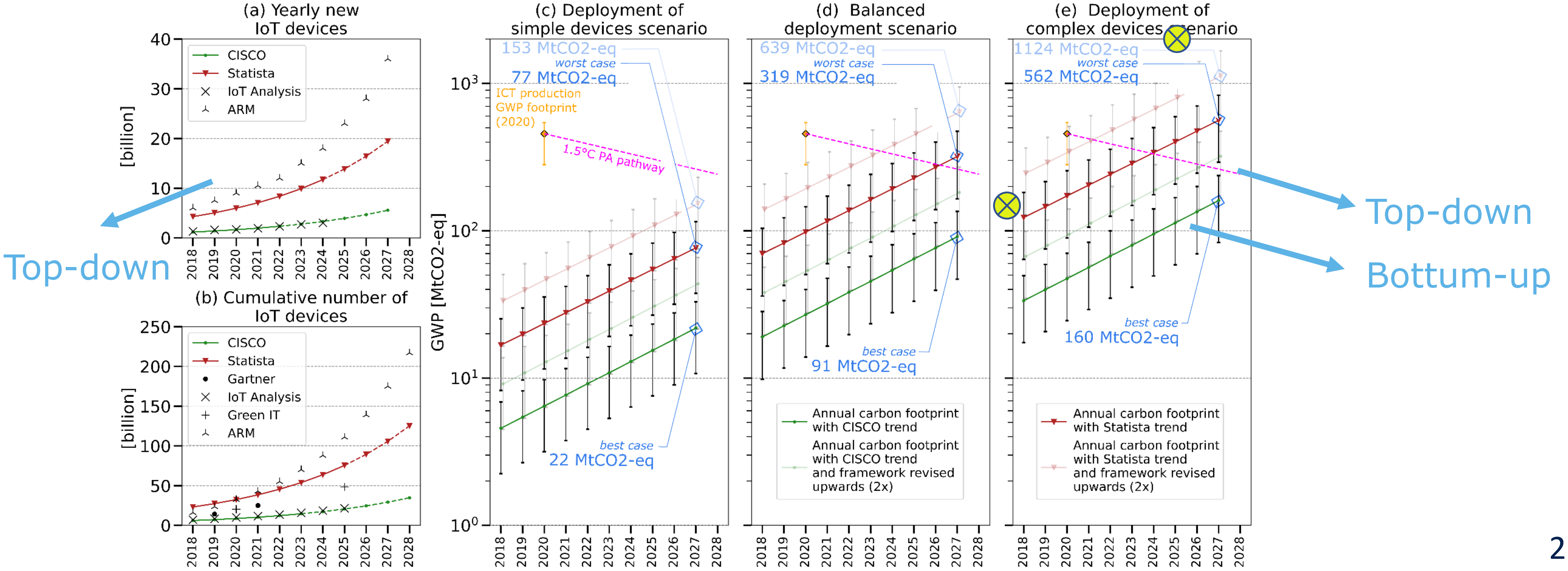
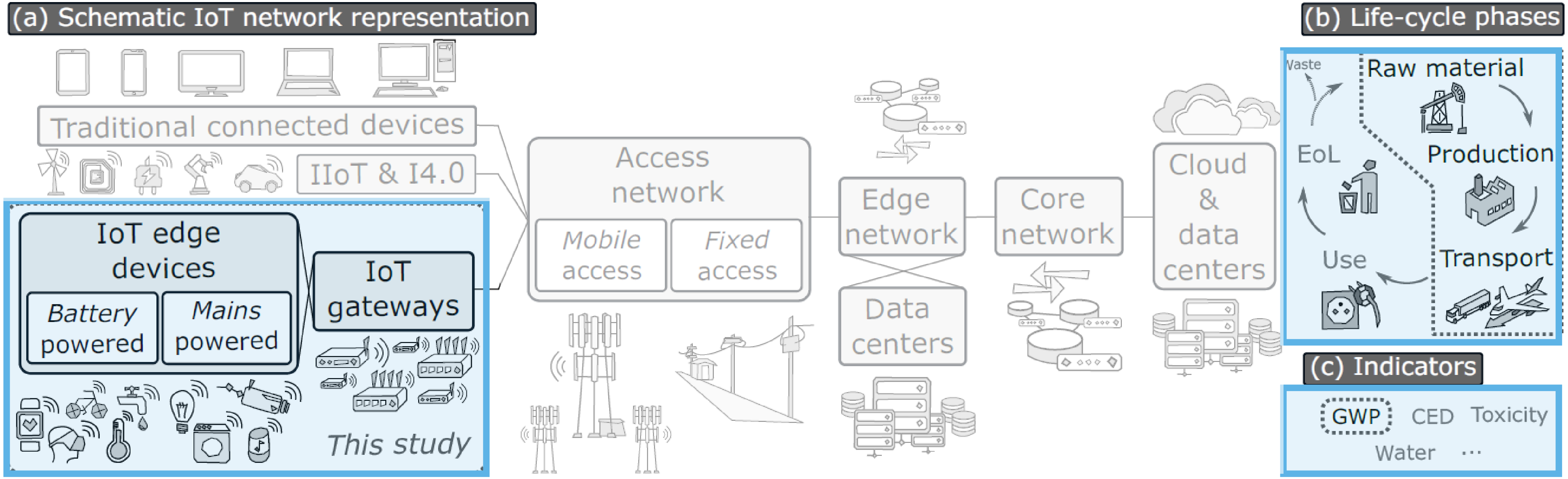


LCA of WPT

(wireless power transfer)

LCA of wireless power transfer (WPT)
In writing



OUR CONTRIBUTION

LCA of wireless power transfer (WPT)
In writing

Main question :

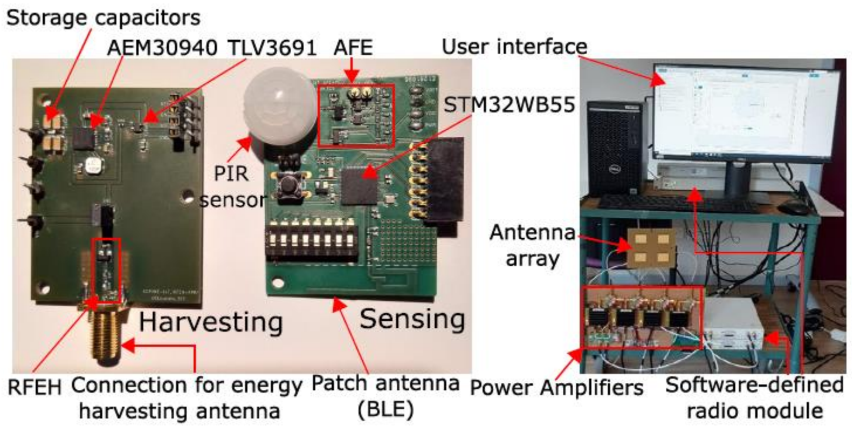
- How does a state-of-the-art WPT system compare to a battery-powered system in terms of environmental impacts ?

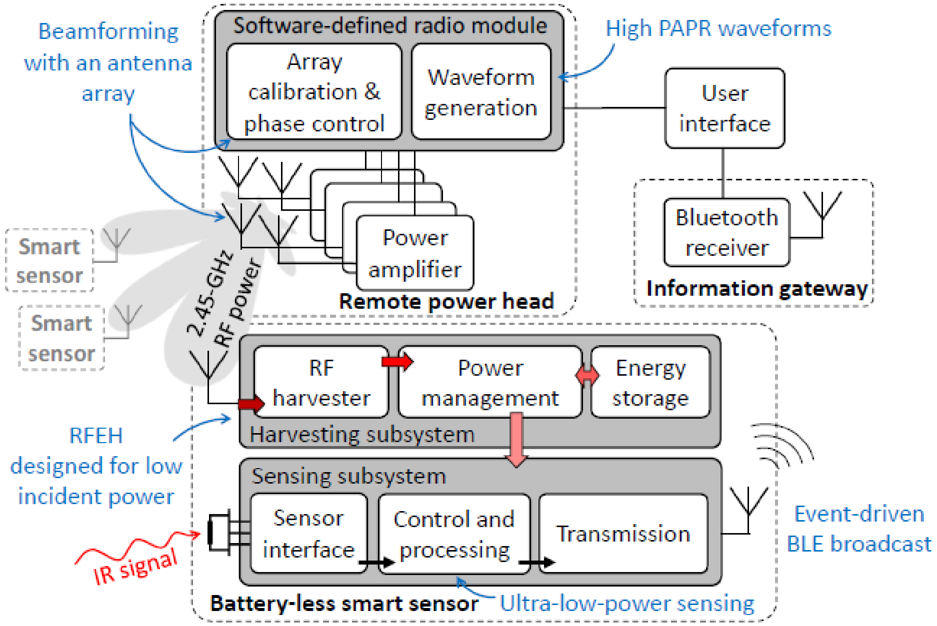
Our contribution :

- Comparative LCA (cradle-to-grave). Specific modeling of the two setups.
- LCA needed for 4 indicators : PED, GWP, EcoTox, Water.

[core of the paper: Marco Gonzalez et al.]

- PIR sensor for room occupancy monitoring consuming 4 µW
- Sensor supplied with 2.45-GHz WPT at 3.5m from the RPH (cold-start)





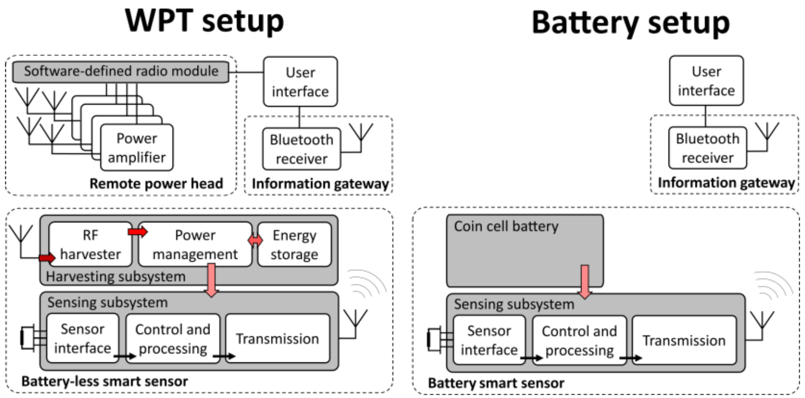
LCA of wireless power transfer (WPT)

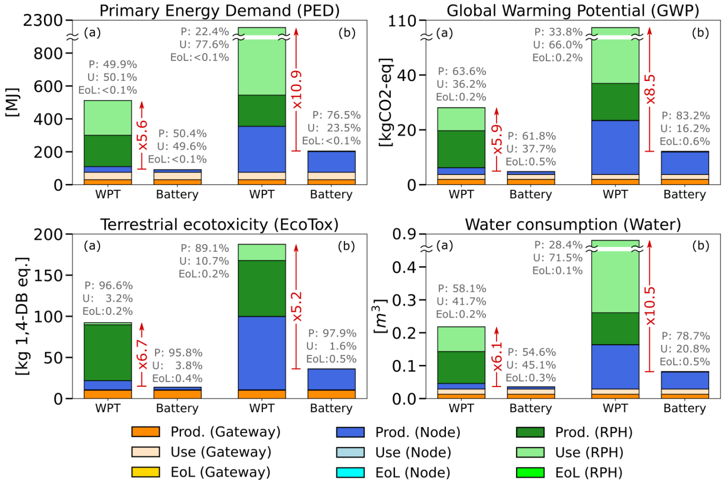
In writing

LCI

LCA modeling in GaBi

LCA Results



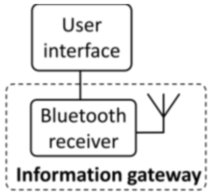


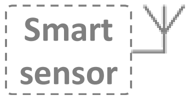
LCA of wireless power transfer (WPT)

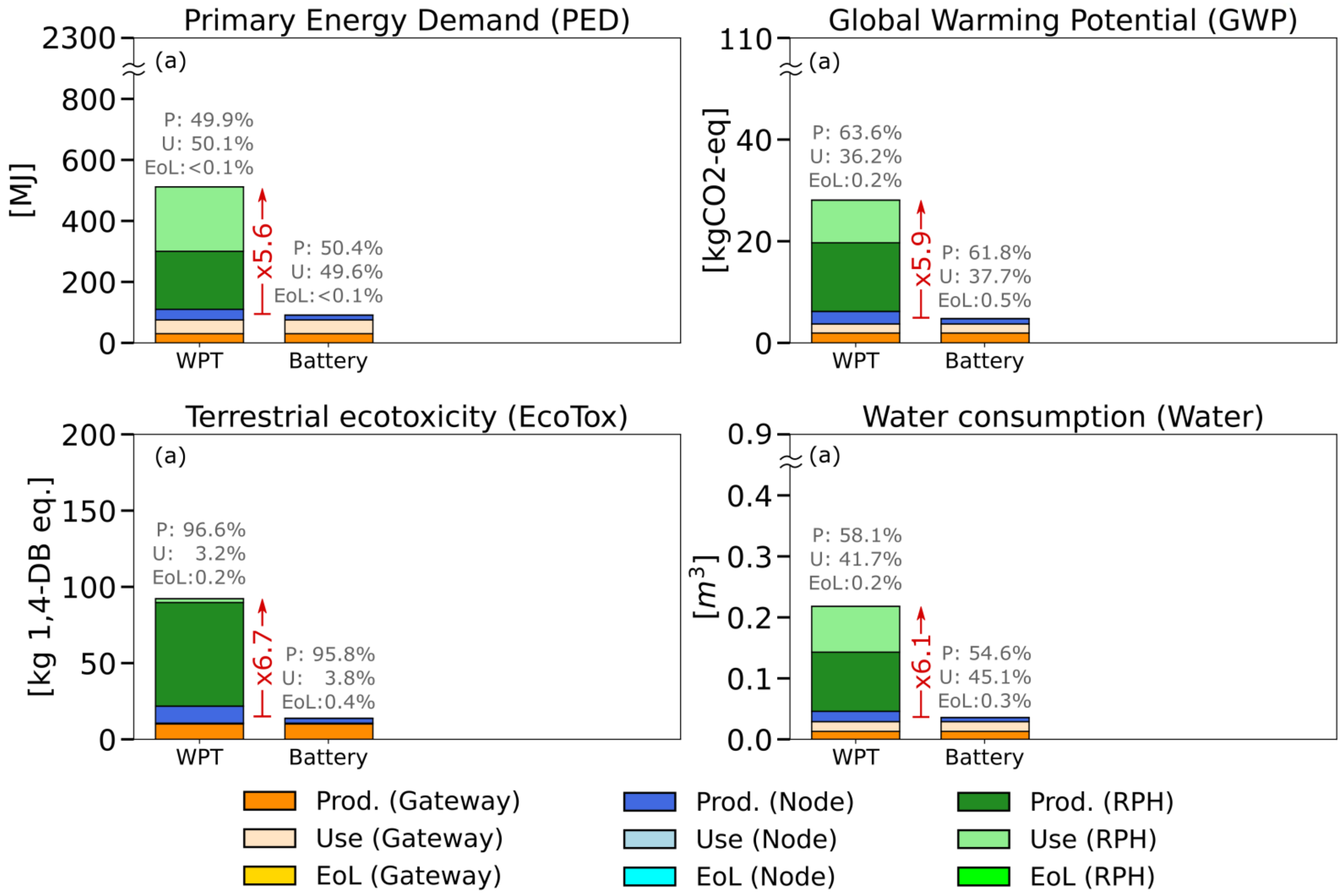
In writing

Results :

- Environmental impacts of WPT are significantly higher compared to the equivalent setup using a battery (coin cell). Lifetime is assumed to be 10 years.
- WPT system yields higher absolute impacts, i.e. from **5.6× to 6.7×.**

1x 

1x 

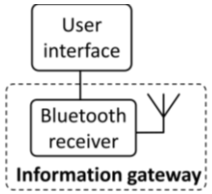


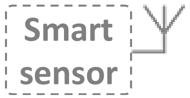
LCA of wireless power transfer (WPT)

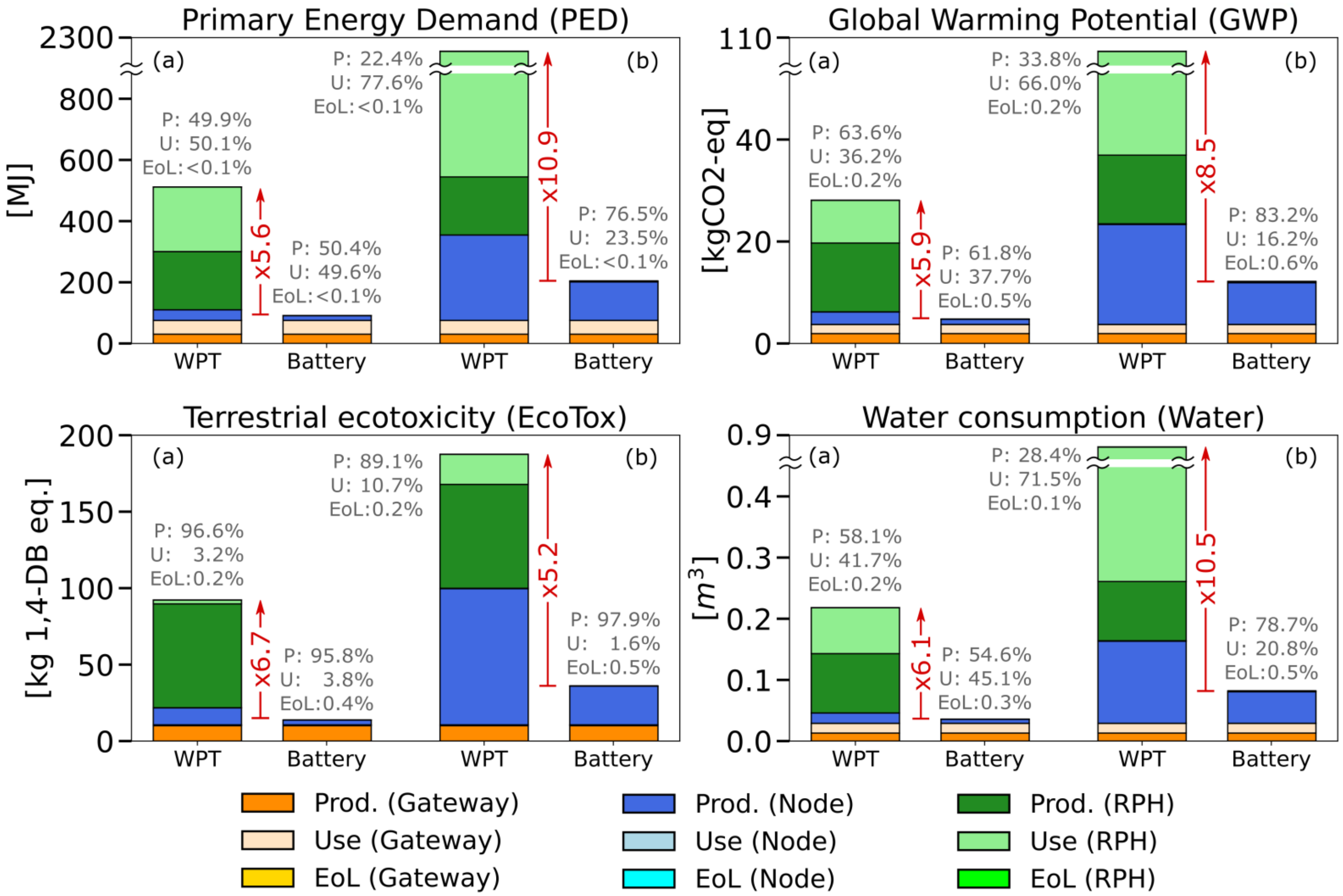
In writing

Results :

- Environmental impacts of WPT are significantly higher compared to the equivalent setup using a battery (coin cell). Lifetime is assumed to be 10 years.
- WPT system yields higher absolute impacts, i.e. from 5.6× to 6.7×.
- Increasing the number of smart sensors (up to 8) generally strengthen the previous conclusions, with impacts up to **10.9×** higher.

1x 

8x 



Conclusions

Conclusions

Why do we need **life cycle thinking** in the context of **IoT** ?

- IoT is a **fast growing** subpart of ICT and implies a massive deployment of electronics: the environmental impacts generated **must be better understood**.
- There is a high degree of heterogeneity in IoT devices: **all IoT devices are not equal**.
- LCA for electronics also embeds **limitations** and **blind spots**: current modeling only provides a downgraded picture of the reality. More expertise and research is needed in this field. **Carbon footprint is only one** (dark) **side** of environmental impacts (e.g. the total amount of **WEEE** keeps increasing every year (>10 Mt in 2019 for IT [GEM, 2020]))
- **Take home message for IoT designers:** include environmental considerations during the development of your technical solution and investigate further than the use phase.

Conclusions

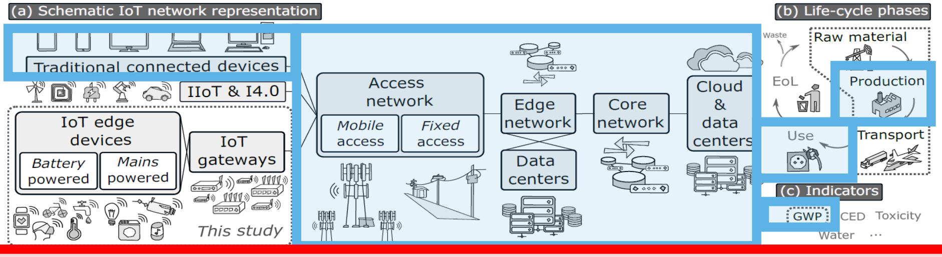
What LCA also looks like in practice:

- **Teardowns** (including IC desoldering)
- In-house **die inspection** (destructive + microscopes) for very specific LCA (while low latency/cost)
- **PCB** design on EAGLE
- **Power measurements** in **WELCOME** (AC and DC)

Perspectives: one step at a time …

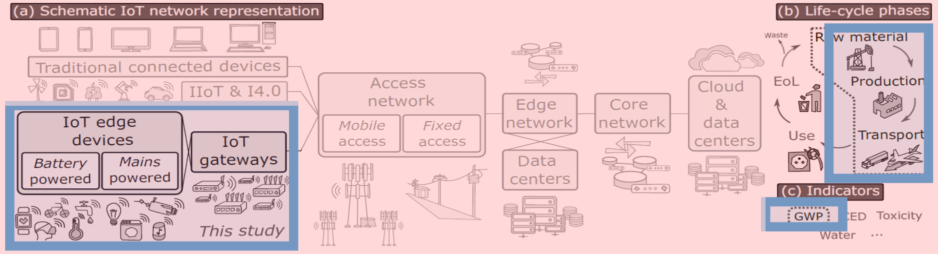
ICT

PAPER
Moore's law



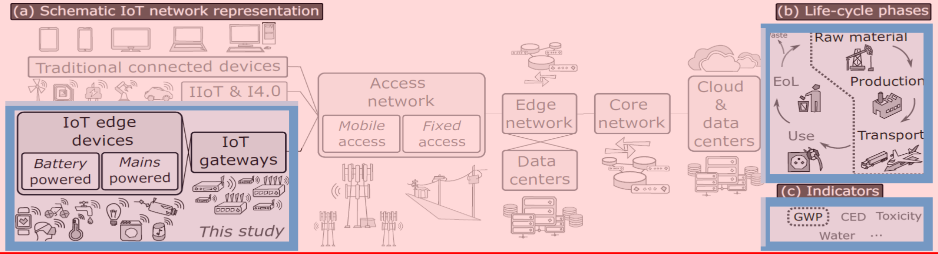
IoT

PAPER
IoT CF



IoT

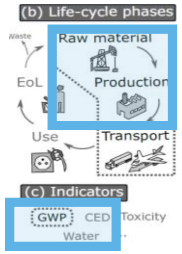
PAPER
LCA RFEH



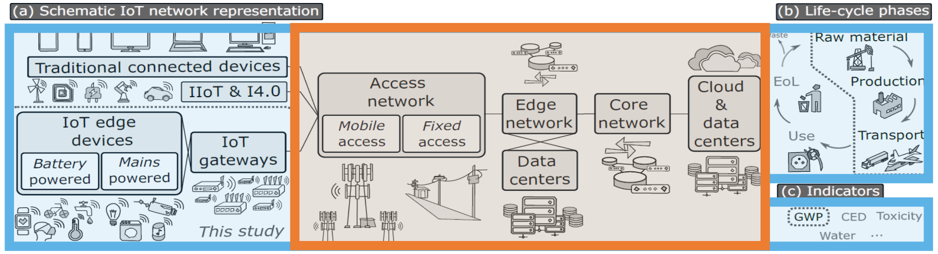
Electronics

PAPER
Footprint of IC prod.

DATA



Last step (TO DO)



TO BE INCLUDED

This talk

Perspectives

- How to integrate LCA during the design of IoT systems ? What about eco-design ? Could we imagine the IoT to be fully designed-for-reuse or designed-for-X ?
- What about the end-of-life of IoT devices ? What will be the impact on WEEE management ?
- There is a trend towards edge-computing: what will be the impacts from a life cycle thinking analysis ?
- Technology development and rebound effects : how do they interact ?
- …

Thank you

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