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Strategies and Life Cycle Analysis for Reducing E-Waste Generation and Environmental Impact of Printed Circuit Boards (PCBs)

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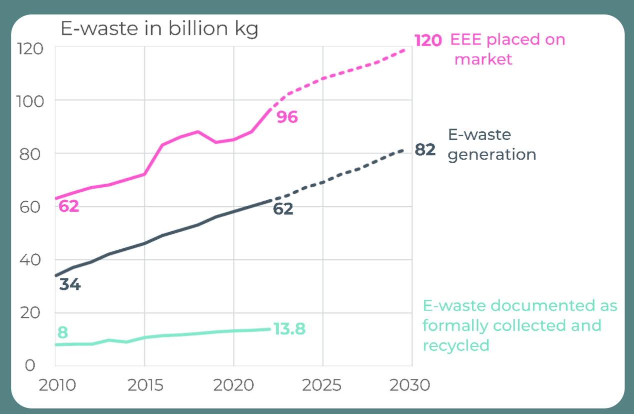
Motivation

As electronics have scaled exponentially in performance and efficiency (thanks to Moore's, Dennard's, and Koomey's laws), so too has the generation of electronic waste.

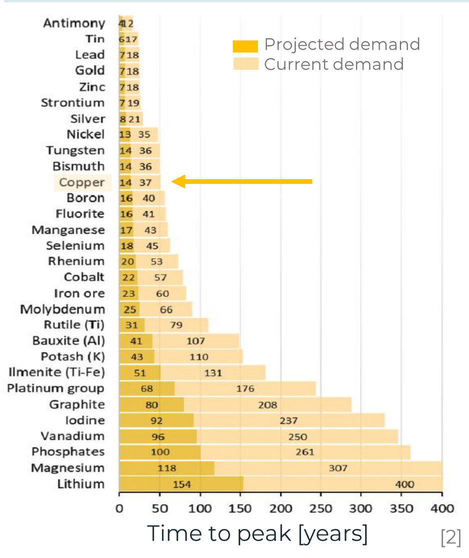


[1]

PCBs are a bottleneck of wasted electronics for recovering high value components (Integrated Circuits, copper,...)

Action strategies for disruption

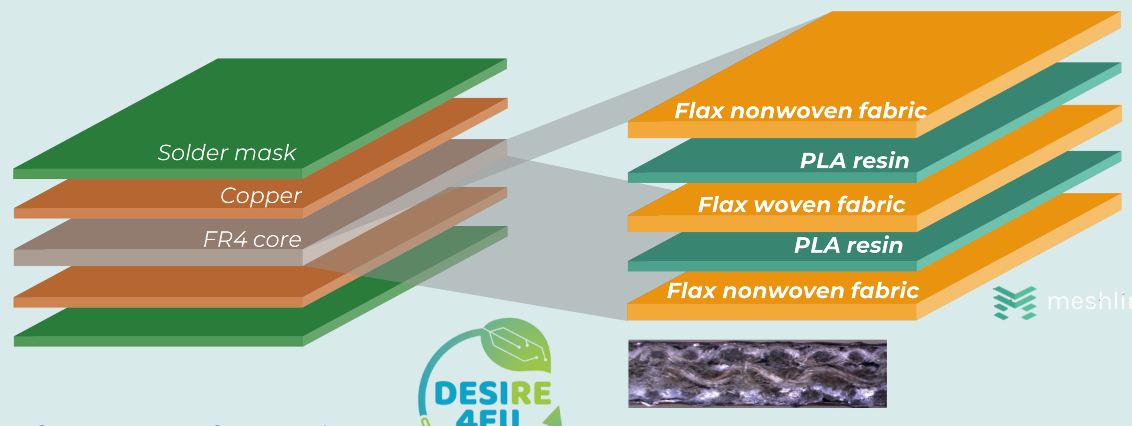
- Refuse
- **Rethink**
- **Reduce**
- Reuse
- **Repair**
- Refurbish
- Remanufacture
- Repurpose
- **Recycle**
- ~~Recover~~



DESIRE4EU project – Bio-based substrate for PCB

Replace FR4 substrate by **bio-sourced substrate** [2]

Target **two layers** PCB



Design for manufacturing

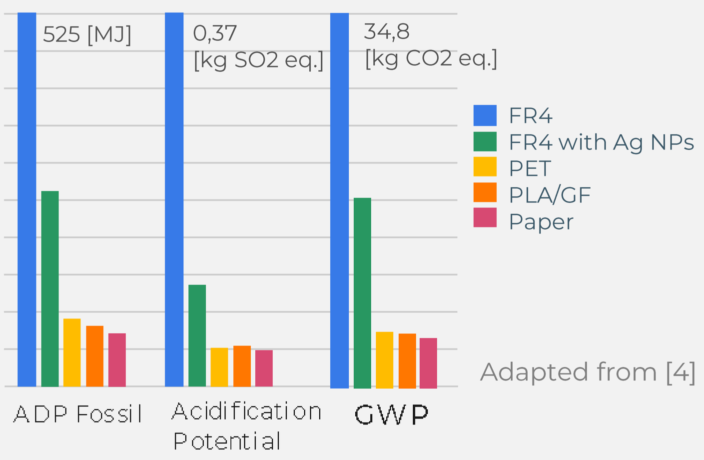
End-of-life through bioleaching for **copper recovery**

Treatment of PLA for **fire-retardancy**

Halogen-free (bio-resin)

Certifed UL94 V0 & EN 13501-1 rating

FR4* vs Bio-based



Adapted from [4]

A few studies have been conducted, and depending on authors, 30% or more of environmental footprint reduction can be achieved.
Use case dependency is not covered.

* FR4 PCB: conventional Flame Retardant Class 4 epoxy-resin composite Printed Circuit Board

Life Cycle Analysis

Production
Bio-based materials

End-of-Life
Bio-leaching for copper recovery

Bio-leaching:
Take advantage of microbial communities to solubilize the metals of interest present in e-waste

Use phase

Reliability ?

Repairability ?

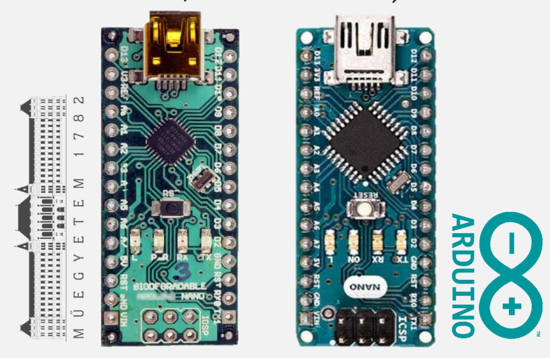
IC mounting at lower T°

	Glass Transition Temperature
PLA	60 °C
PLA High Tg	100 °C
FR4	125...140°C

The bio-sourced substrate calls for **alternative soldering techniques** (VPS) and Low Temperature Solder pastes (LTS) embedding more critical metals

→ Is there a risk of burden shifting ? [under investigation...]

PLA-flax $\varepsilon = 2,5$ FR4 $\varepsilon = 4,3$



The bio-based board also calls for design adaptations [5]

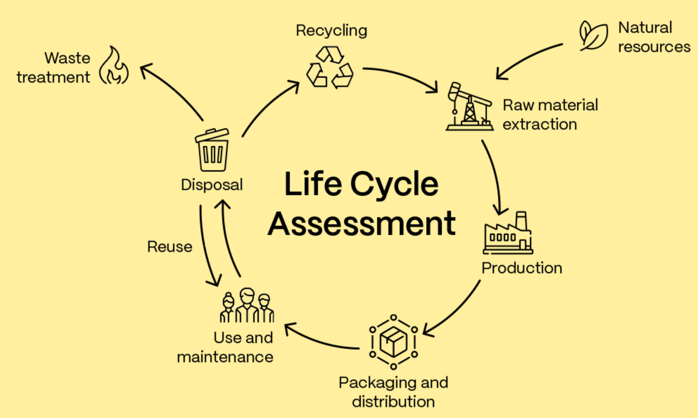
Wider tracks to preserve impedance matching, larger vias diameter, etc...

Life Cycle Analysis to compare trade-offs

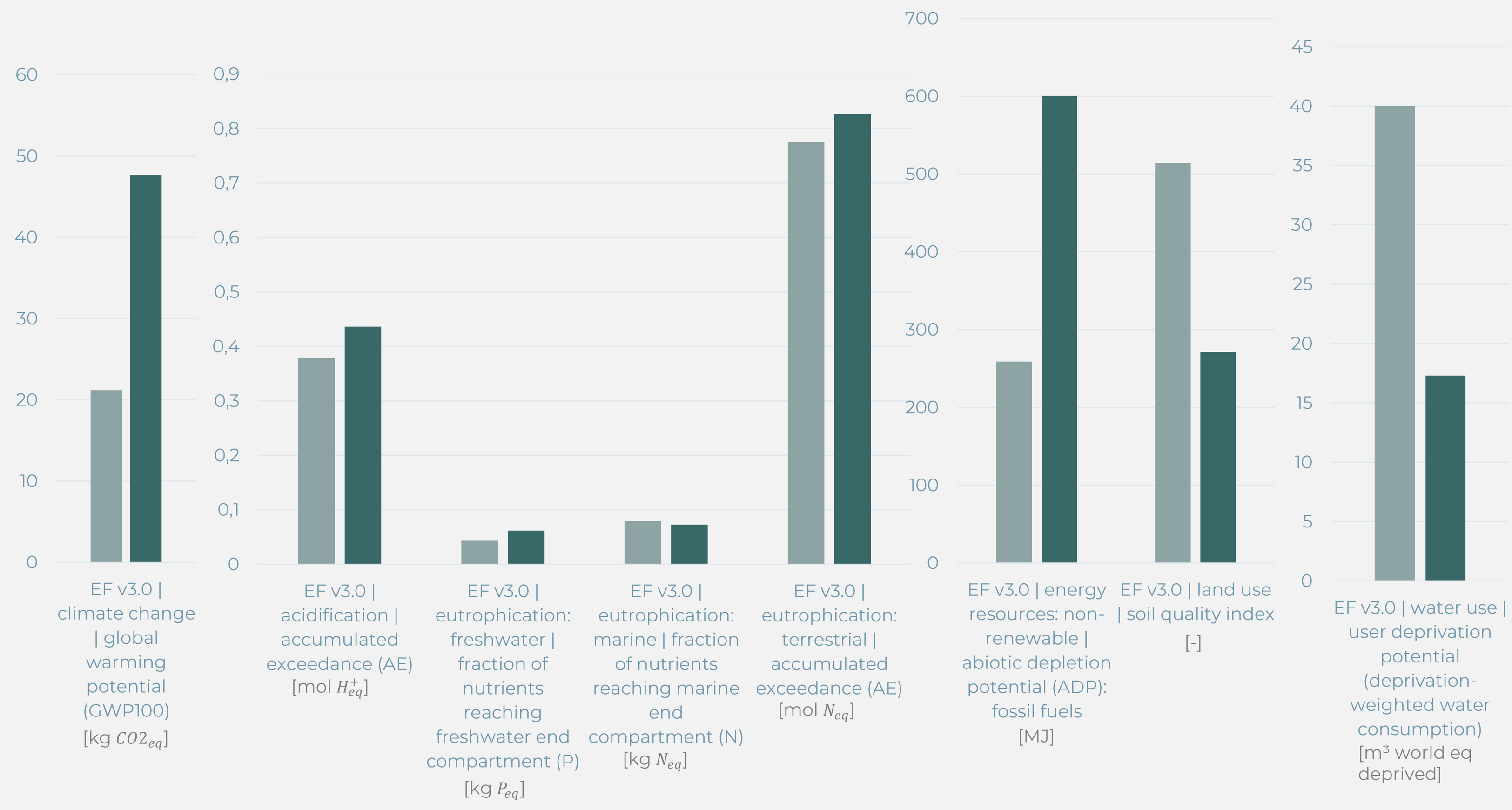
Baseline: A conventional FR4 PCB assembled with Sn95Ag3.9Cu0.6 solder paste (typically SAC396)
melting point: 217°C

Alternative: A bio-sourced PCB assembled with Sn42Bi57.6Ag0.4 solder paste (LTS)
melting point: 138°C

FUNCTIONAL UNIT : 1 m² PCB mounted, SMD, 2-layer, copper layer thickness 35 µm, thickness 1,5 mm



Preliminary results of simple model



Simplified cradle-to-gate study

Clear energy savings during PCB assembly when using Low Temperature Soldering (LTS).

However, the **switch to LTS**—necessary for bio-based substrates—**mitigates the environmental benefits** of replacing FR4 with PLA–flax.

Future LCA should:

Include **uncertainty analysis** to reflect data limitations

Better model **supply chain of bismuth**, key element in LTS alloys, with system expansion (90–95% of bismuth is derived as a by-product of lead smelting)

Integrate **End-of-Life** phases, especially exploring **bioleaching** for the PLA-flax substrate and **copper recovery** benefits

Perspectives

'Circular-by-design' methodology needs **iterative LCA** to drive efficient design choices

Anticipate **assembly adaptations required by bio-based substrates** — low glass transition temperature (Tg) necessitates low-temperature solders (LTS) instead of traditional SAC alloys.
→ What are the implications on LCA results and critical metals supply chains (e.g., bismuth)?

Expand PCB Life Cycle Inventories (LCIs) to incorporate **design-level parameters** such as copper layers thickness, via redundandy impacts, modularity impacts,... [3]

Improve the **industrial process modeling** for current conventional PCB manufacturing chains (lab-scale vs. Fab-scale) and for the emerging bio-based PCB processes, (once development is stable).

Integrate **End-of-Life** phases, to explore benefits of **bioleaching** for the PLA substrate
Coupling with real-time process LCA

LCA on different **use cases**

References

[1] E-Waste Monitor, « The Global E-Waste Monitor 2024 - E-Waste Monitor » , E-Waste Monitor, 12 décembre 2024. https://ewastemonitor.info/the-global-e-waste-monitor-2024/
[2] B. Duchemin, « The sustainability of phytomass-derived materials : thermodynamical aspects, life cycle analysis and research perspectives » , Green Chemistry, vol. 24, no 7, p. 2653-2679, janv. 2022, doi : 10.1039/d1gc03262c.
[3] C. Farkas *et al.*, « Sustainable printed circuit board substrates based on flame-retarded PLA/flax composites to reduce environmental load of electronics : Quality, reliability, degradation and application tests » , *Sustainable Materials And Technologies*, vol. 40, p. e00902, mars 2024, doi : 10.1016/j.susmat.2024.e00902.
[4] Nassajfar, M. N., Deviatkin, I., Leminen, V., & Horttanainen, M. (2021). Alternative Materials for Printed Circuit Board Production: An Environmental Perspective. Sustainability, 13(21), 12126. https://doi.org/10.3390/su132112126
[5] V. Grennerat *et* al., « Power Electronics Solar Inverter on a Biosourced and Biodegradable Substrate – Thermal Study », ISSE2025 Proceedings.

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