Circular Economy Compatible Power Electronics

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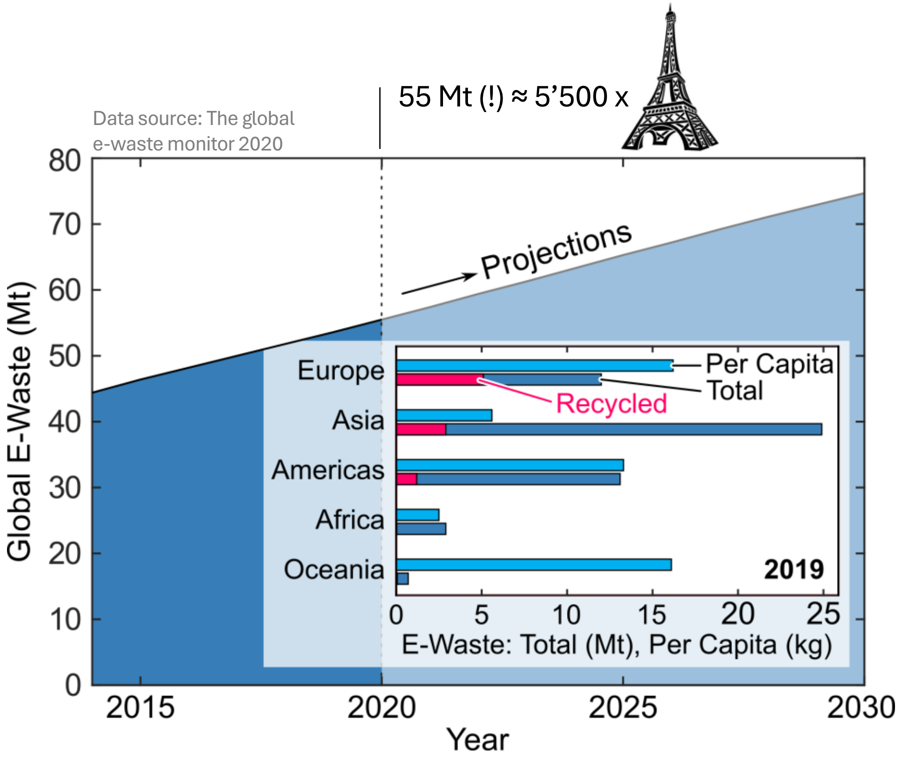
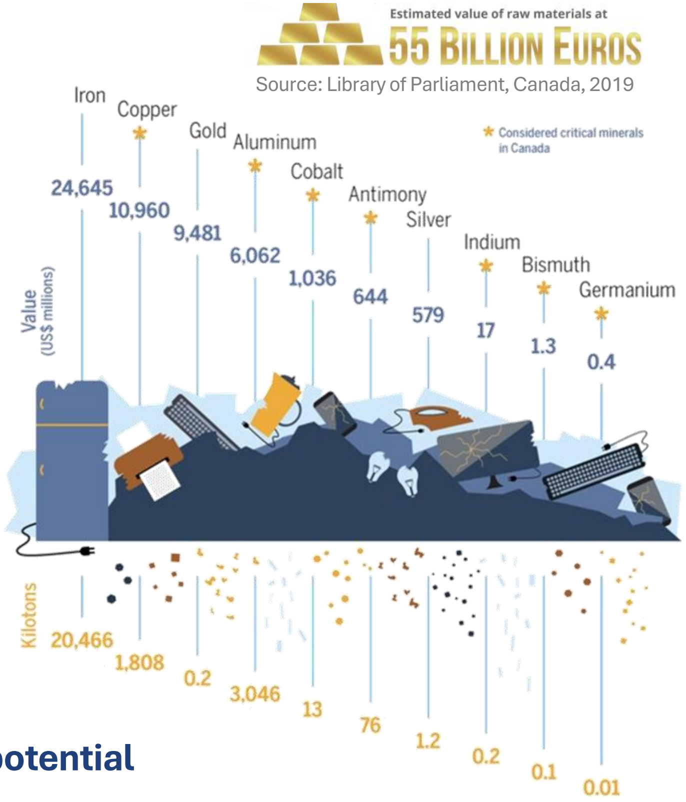
Outline

- Avoid and Reduce
- Paradigm Shift
- Multi-Objective Optimization
- Circular Economy Compatibility

Growth of Global E-Waste

- **Growing global e-waste streams: 120’000’000 tons of global e-waste in 2050 / < 20% recycling!**



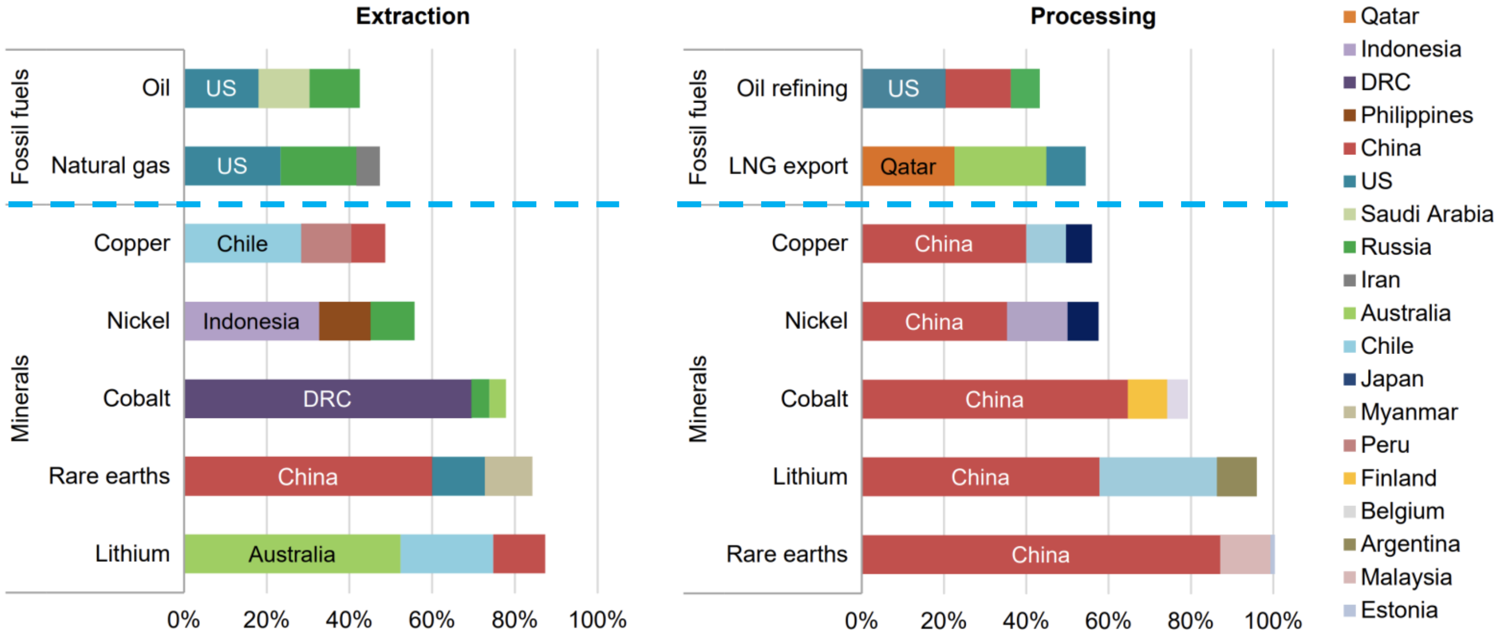


Global, 2019

- **E-waste represents an “urban mine” with great economic potential**

Critical Minerals

- Production of selected minerals critical for the clean energy transition
- Extraction & processing more geographically concentrated than for oil & gas (!)



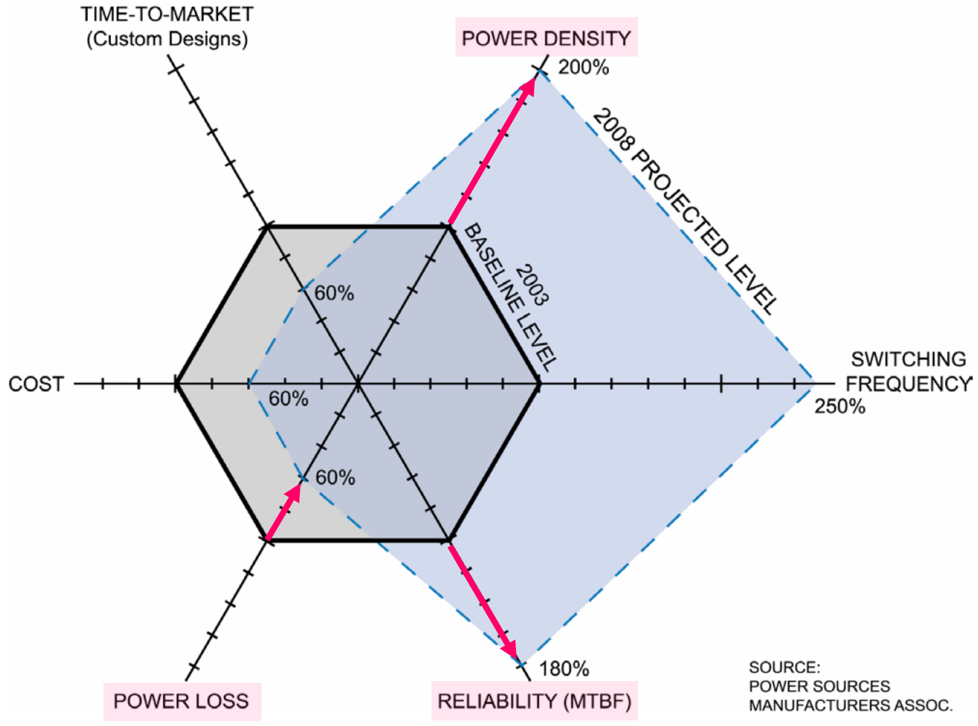
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

- EU Critical Raw Material (CRM) Act 2024 → Sustainability & circularity of CRMs on the EU Market

“Avoid and Reduce”

- **Today’s power electronics innovation basically contributes to lower environmental impact**

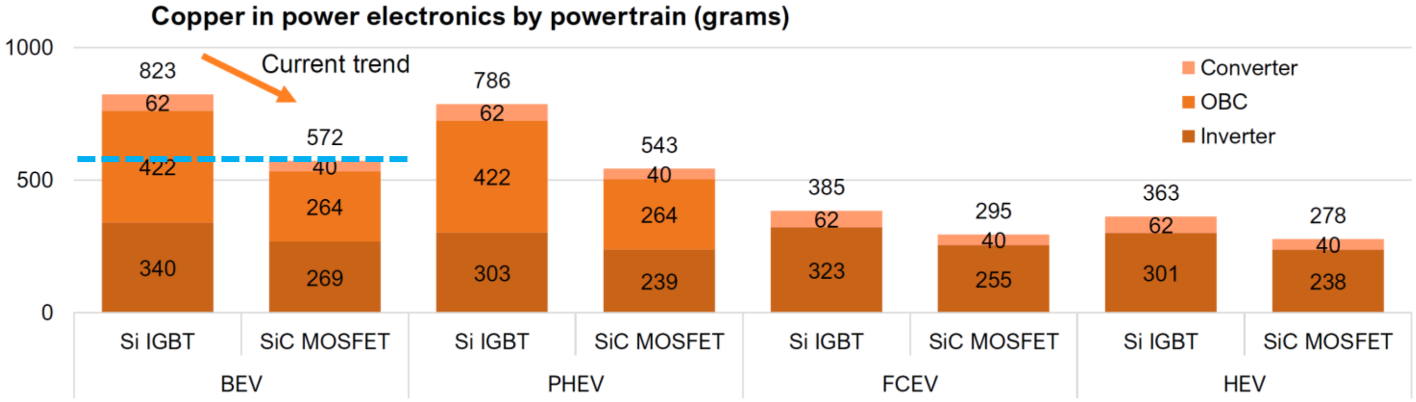
- Power Density → Red. of resources
- Efficiency → Red. of energy use
- Robustness → Increased lifetime



- **New set of KPIs mandatory to meet future environmental protection objectives**

Example: Copper Use in EVs

- Cu used for traction motors, energy storage, power electronics, HV & LV, etc.
- ICE (2023) — 29.5 kg | BEV Robotaxi in 2034 — 73 kg (7.8 kg motor & power electronics)

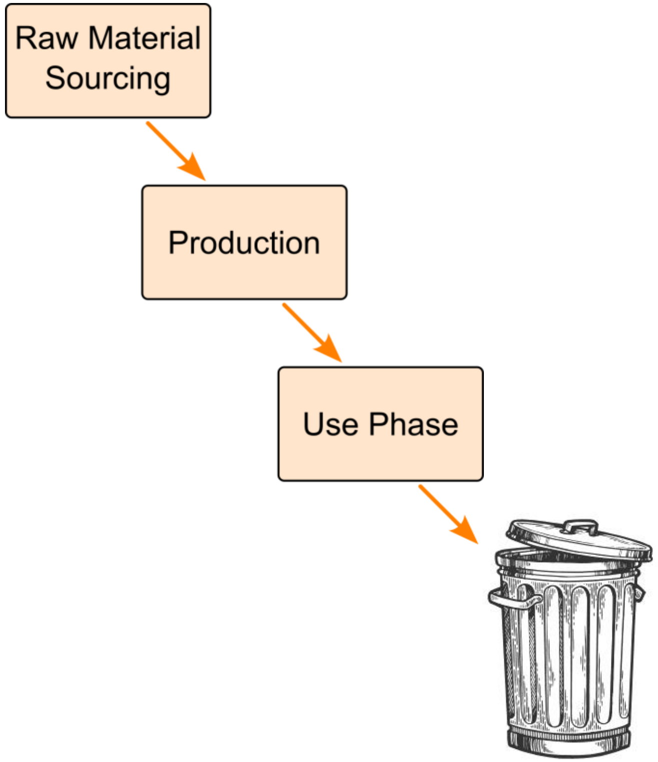


Source: IDTechEx

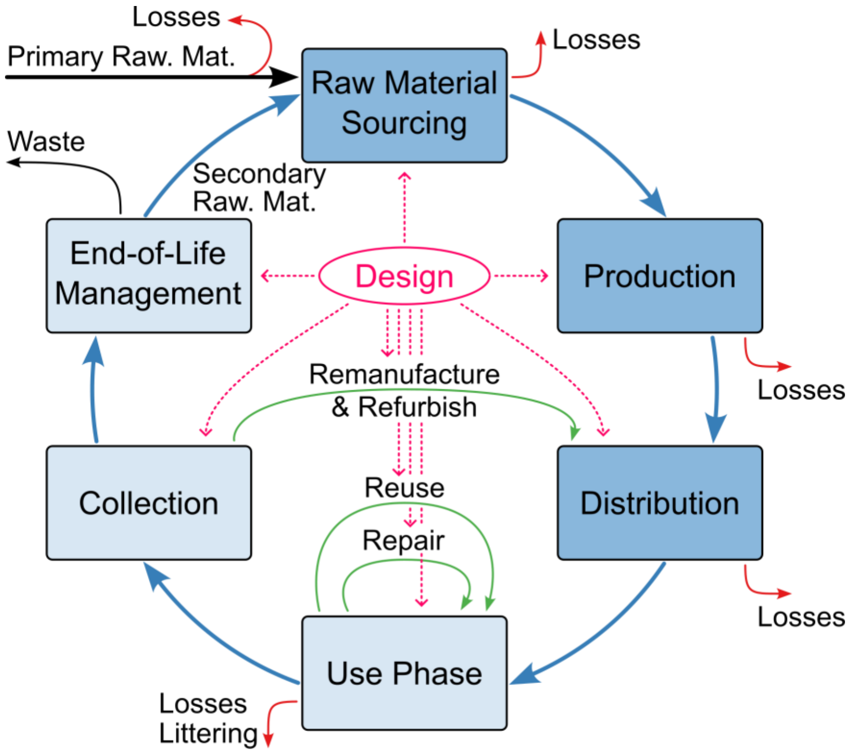
- Transition Si IGBTs → SiC MOSFETs — 25...30% Decrease of Cu intensity in the power electronics

The Paradigm Shift

- **Linear Economy**
  - Take – make – dispose



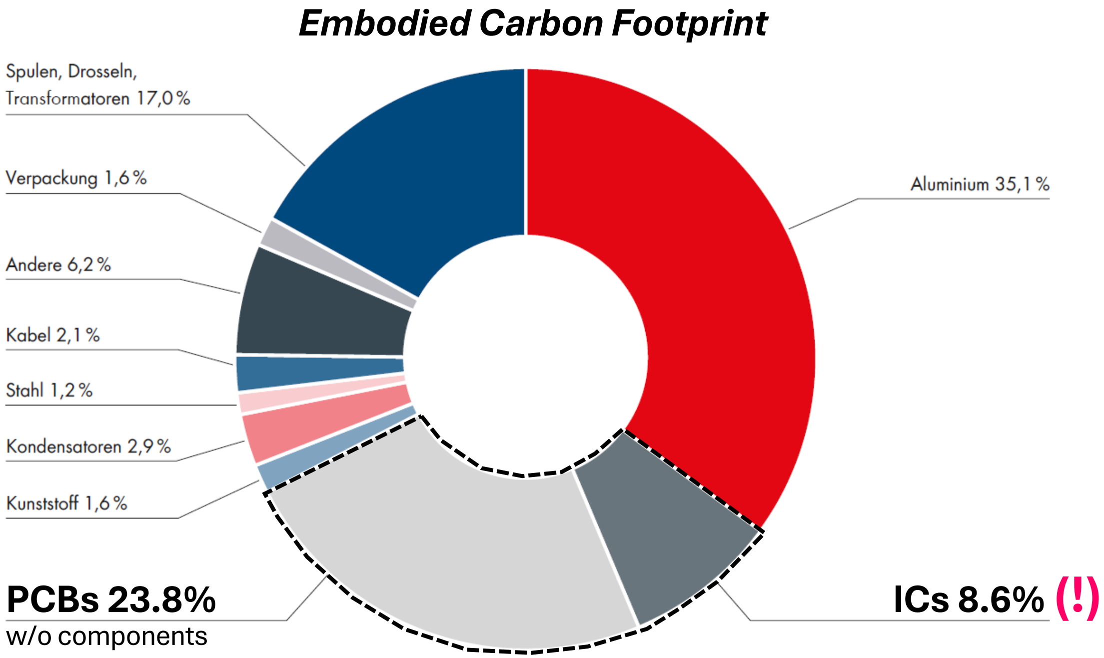
- **Circular Economy**
  - Perpetual flow of resources



  - Resources returned into the product cycle at end of life

LCA Example: Carbon Footprint of a 150-kW PV Inverter

- **Production phase / embodied carbon footprint of 903 kg CO_2eq (15...20% of life-cycle carbon footprint)**
- **Use phase contributes >80% to life-cycle carbon footprint (conversion losses & standby/night consumption)**

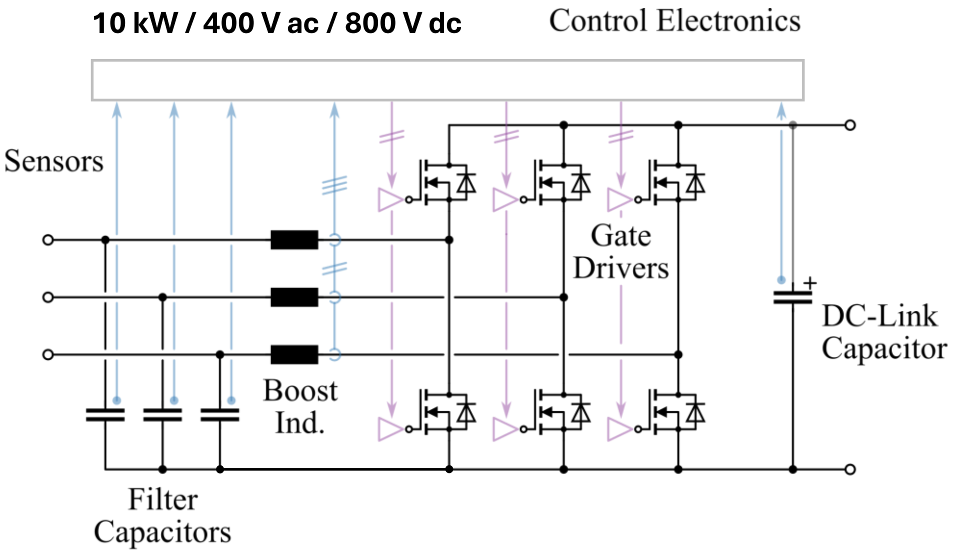


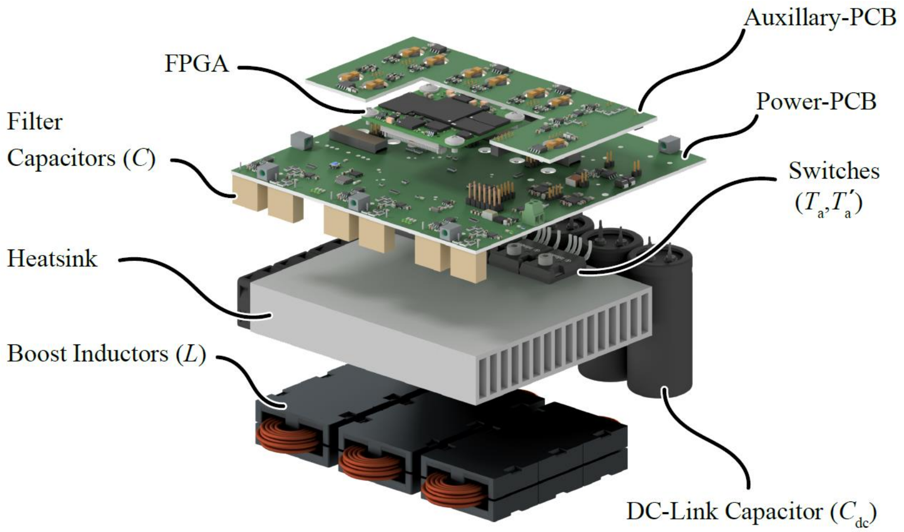
- **150 kW rated power for typ. 225 kW_p PV system**

Source: SMA Solar Technology AG, "Sunny Highpower PEAK3 life cycle assessmnet (LCA)," 2023. https://files.sma.de/assets/280662.pdf

A Priori LCA Example: 10-kW Three-Phase AC-DC PEBB

- Key power electronic building block (PEBB) for three-phase PFC rectifiers & inverters

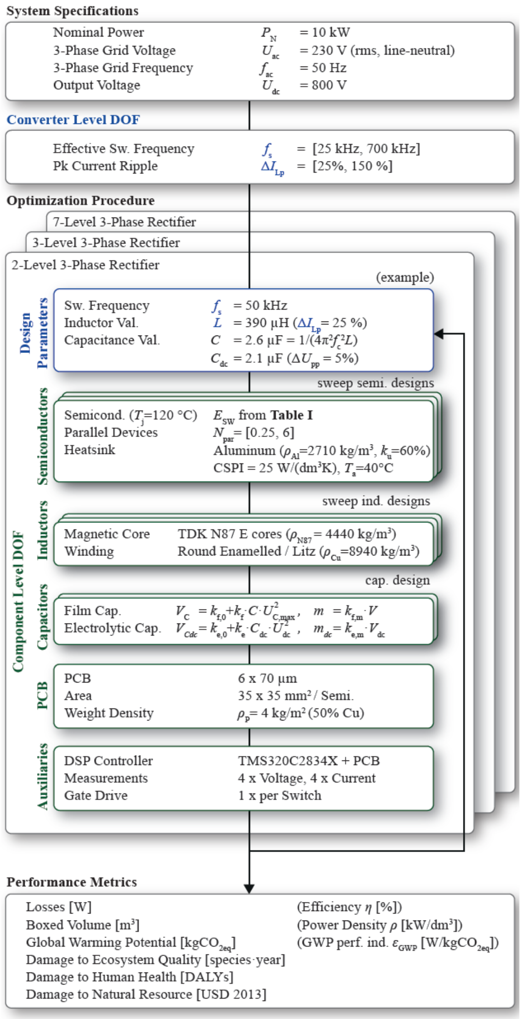


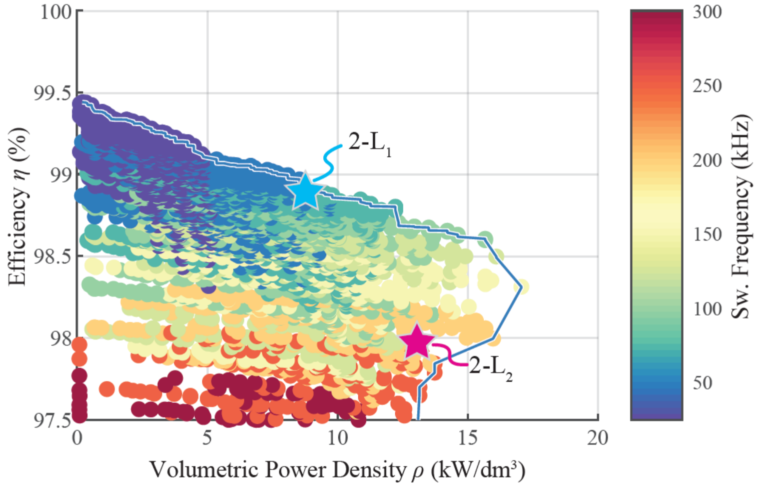


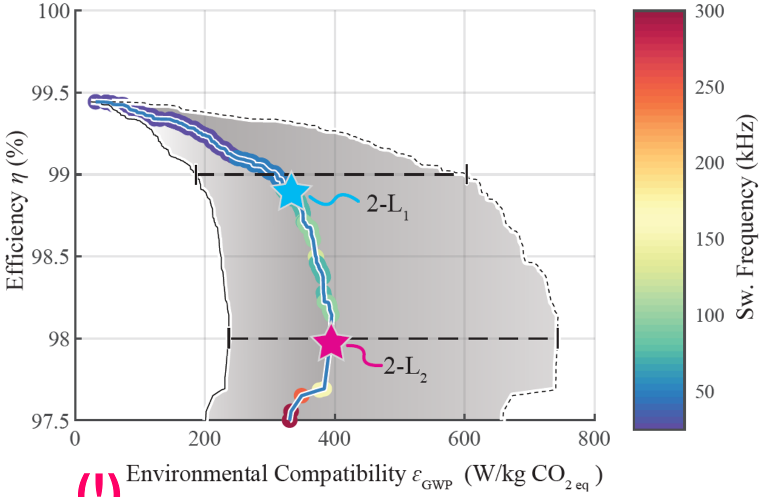
- **Degrees of freedom:**
  - Switching freq. [25…700 kHz]
  - Rel. Ind. Peak cur. ripple [0.25…1.5]
  - Var. transistor chip area
  - Variable ind. size (N87; solid/litz)

- **Assumptions:**
  - Junction temp. @ 120 °C
  - Ambient temp. 40 °C
  - Necessary heat sink vol. via CSPI = 25 W/(K dm^3)

Multi-Objective Optimization Including Env. Impacts

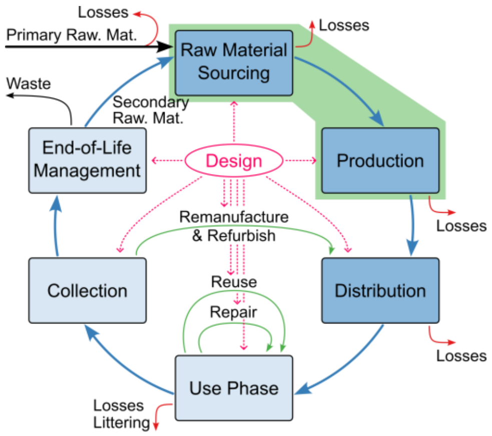






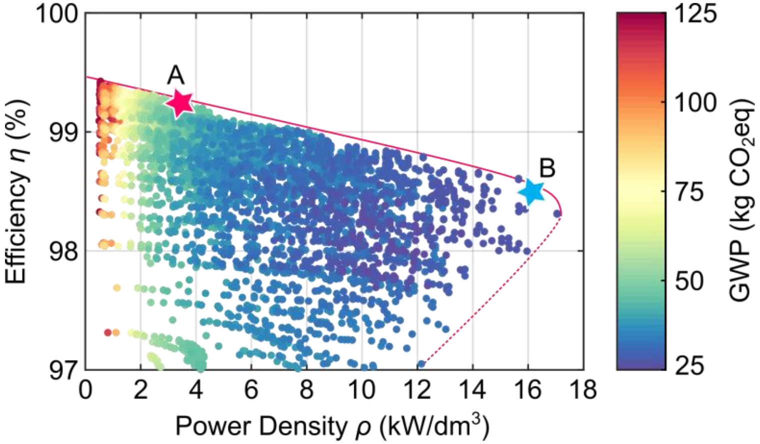
(!)

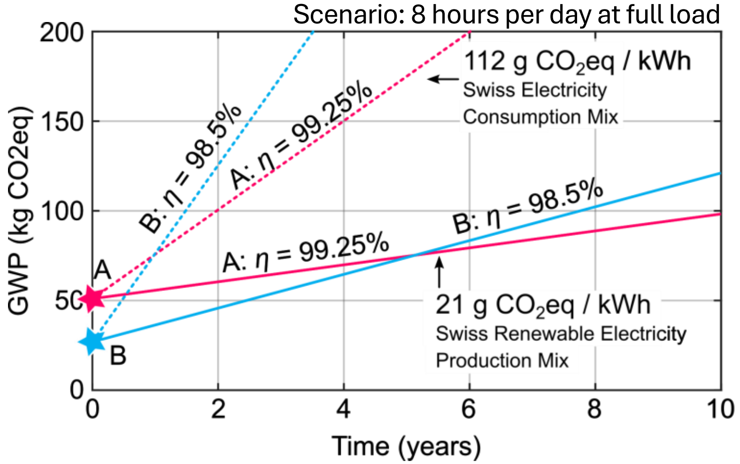
- **Trade-Offs**
  - Efficiency vs. power density
  - Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)
- **Env. Impacts with high uncertainties due to data availability/quality**



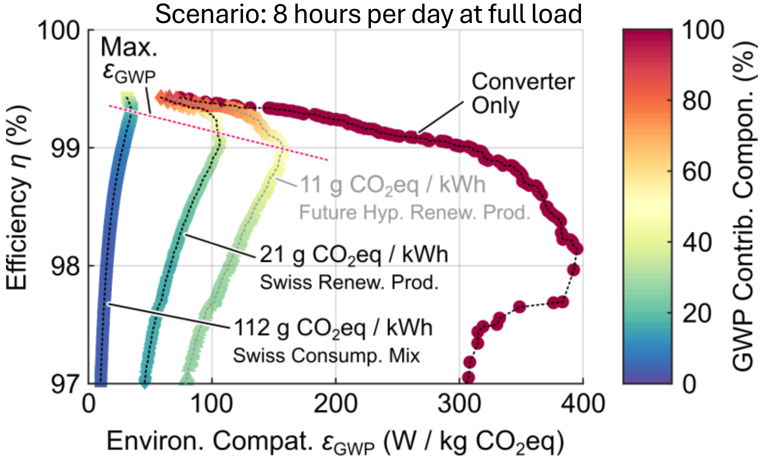
Multi-Objective Optimization Including the Use Phase

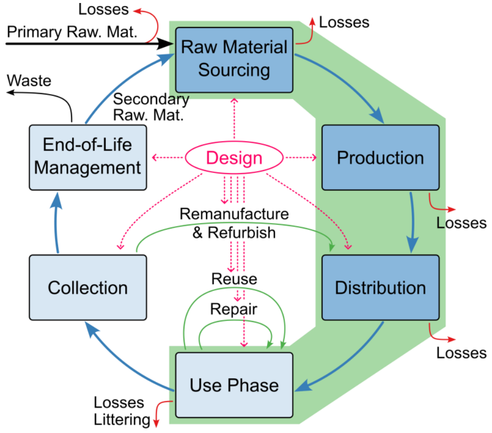
- **Life-cycle carbon footprint strongly depends on electricity mix and mission profile / usage intensity**





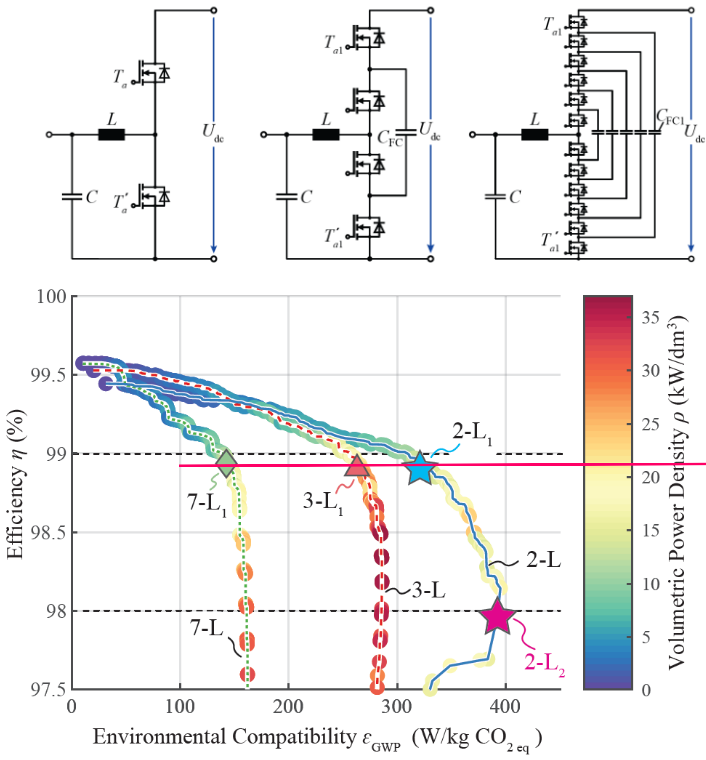
- Design should consider use phase for best life-cycle performance
- Analogy to total cost of ownership (TCO) perspective



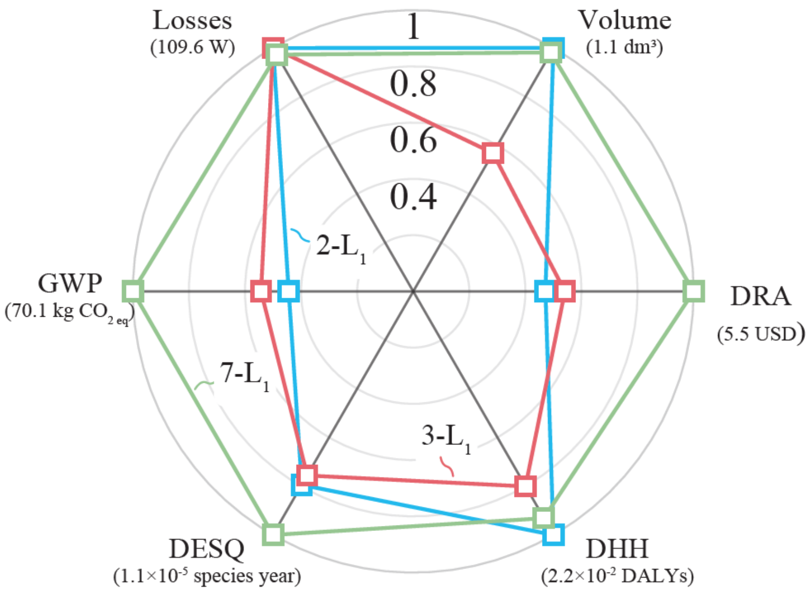


Comprehensive Environmental Impact Profiles

- Different bridge-leg topologies — 2-Level (1200-V SiC) | 3-Level (650-V SiC) | 7-Level (200-V Si)



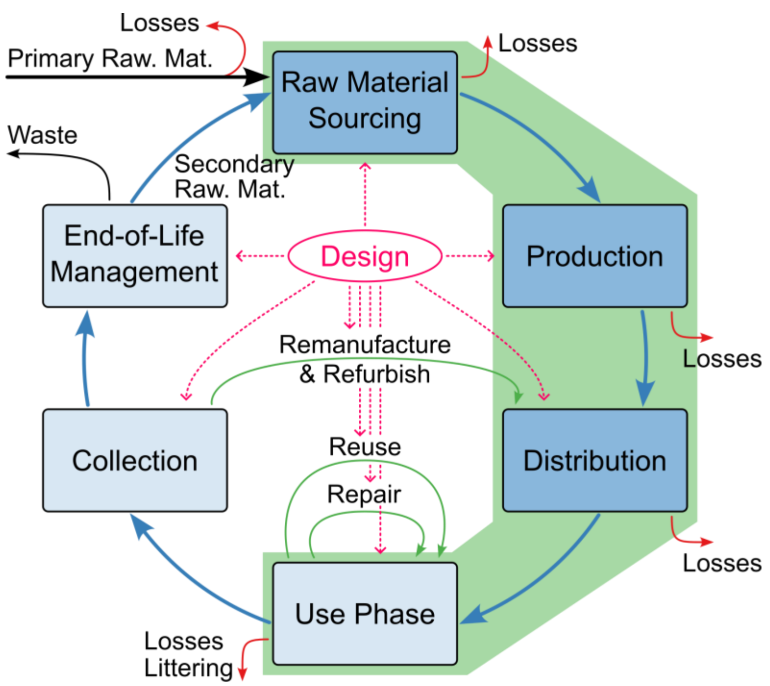
(!) ReCiPe 2016:
DESQ: Damage to ecosystems
DHH: Damage to human health
DRA: Damage to resource availability

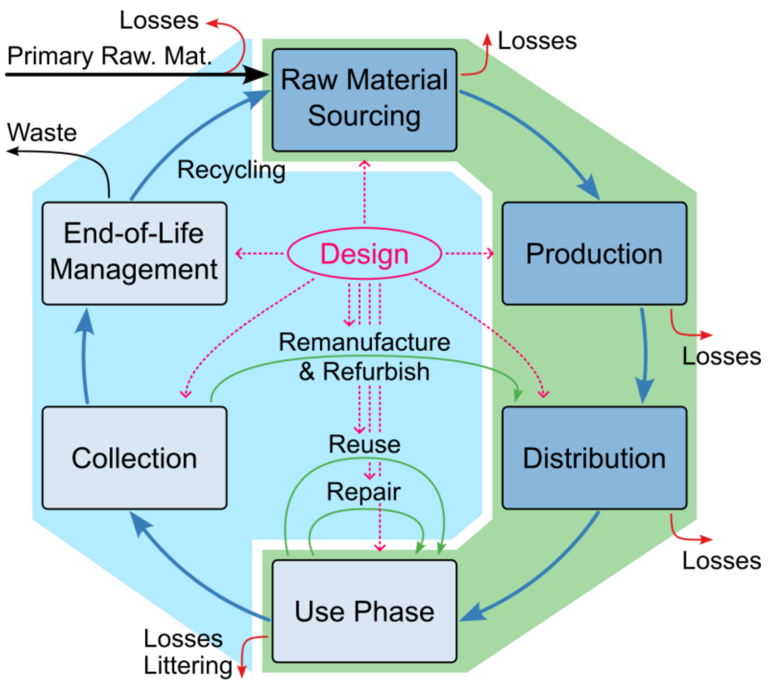


- Embod. env. footprint of 2L/3L/7L-designs with $\eta \approx 99\%$ and max. env. compat. ε_{GWP} in W / kg CO_2eq
- Same efficiency via different usage of act./pass. components — Different environmental impact profile!

"Closing the Loop"

- **Including 4R into the design process — Repair / Reuse / Refurbish / Recycle**





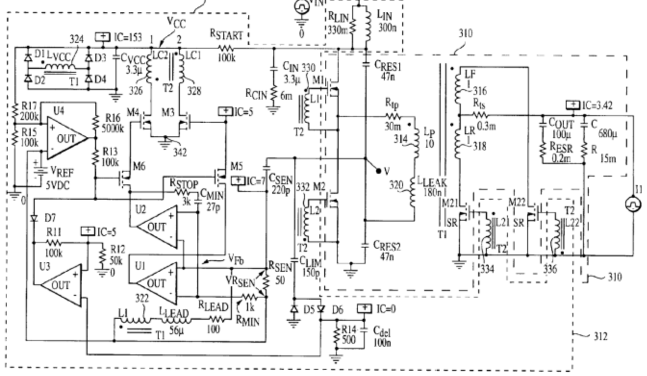
- **How to quantify repairability / reusability / ...?**
- **Value proposition through life-cycle cost perspective (suppliers *and* customers)?**

Integration: Minimize Size / Initial Resource Usage

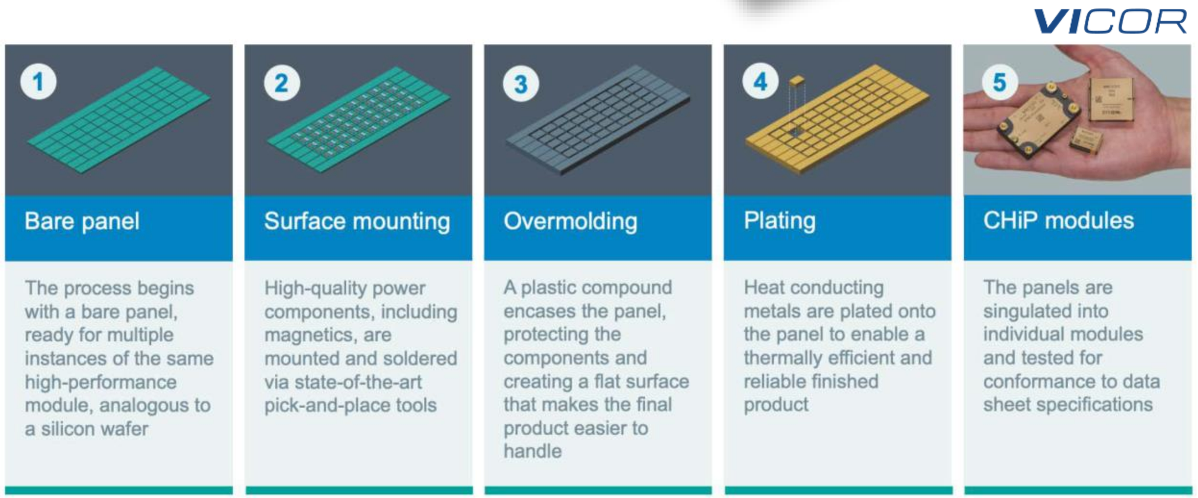
- **Maximum integration facilitates extreme power densities (10…100 x conv.)**
  - Example: 30 kW non-isolated fixed-ratio conversion (400 V to 800 V) in 92 x 80 x 7.4 mm^3 — 550 kW/dm^3 and 130 kW/kg

- **Opposite of CEC (?)**
  Low initial material usage ↔ Difficult material separation

FIG. 35



Example: Isolated dc-dc



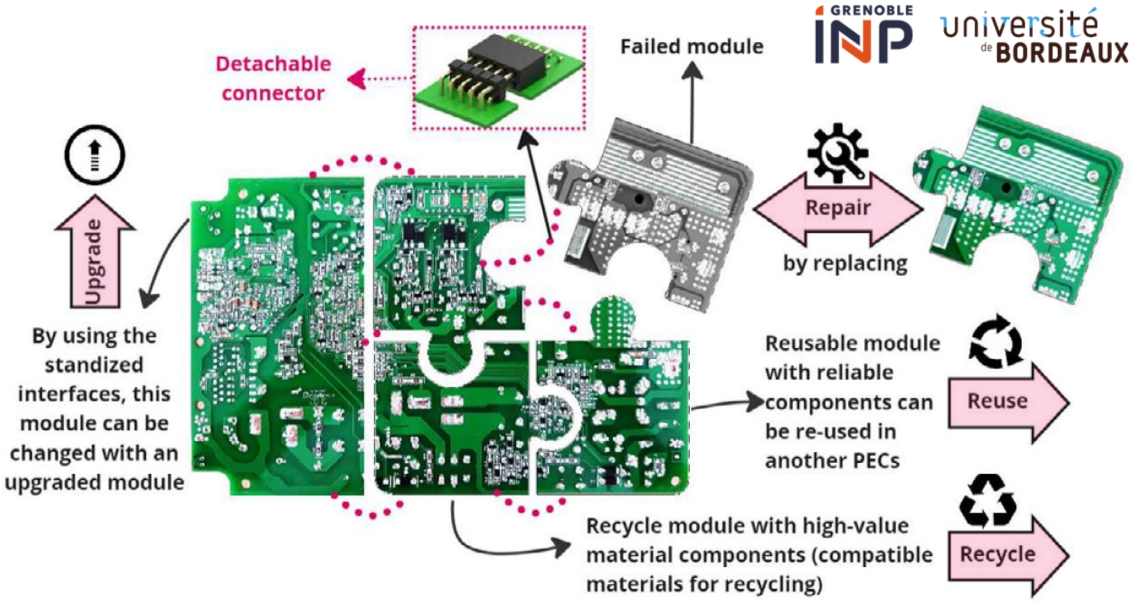
Sources: vicorpower.com, US6930893B2

Modularity Facilitates Upgrade, Reuse, Repair, …

- Modular design for ease of disassembly: Maintainability, upgradability, repairability, reusability, recyclability
- FAIRPHONE — Modular design / man. replaceable parts / 100% recycl. of sold products / fairtrade materials

Source: www.ligman.com/

Source: https://de.ifixit.com/



- Grouping of components determined by reliability level & expected lifetime / level of reusability or recyclability
- Standardized interfaces / Mechanically loose connections ↔ Electrical characteristics
- Potential for leveraging economies of scale to compensate interface costs (?)

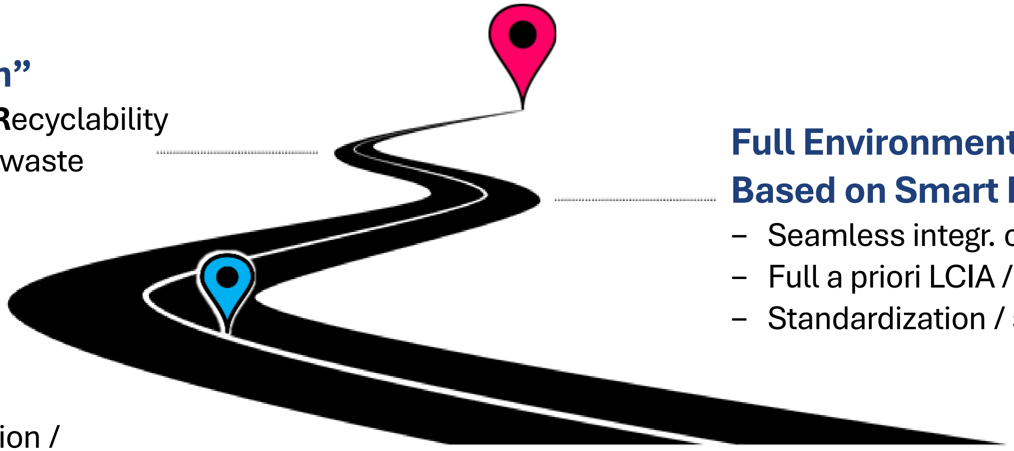
Source: T. T. Romano, T. Alix, Y. Lembeye, N. Perry, and J.-C. Crebier, "Towards circular power electronics in the perspective of modularity," *Procedia CIRP,* vol. 116, pp. 588–593, Jan. 2023, doi: 10.1016/j.procir.2023.02.099.

CEC Power Electronics Roadmap

- **Environmental awareness as integral part of environmentally conscious power electronics design**

Circular-Economy-Compatible (CEC) Power Electronics

"Net-Zero CO_2 is NOT Enough"
- Max. **R**epairability | **R**eusability | **R**ecyclability
- Min. scarce materials, min. toxic waste



Full Environmental Footprint Based on Smart Datasheets
- Seamless integr. of comp. models in multi-obj. opt.
- Full a priori LCIA / environmental footprint
- Standardization / single source of truth

Generic Life-Cycle Impact Analysis (LCIA)
- New KPIs in multi-obj. opt.
- Data sources / quality / abstraction / generalization as key challenges

Classical *ηρ*-Pareto Optimization / Design
- Manual a posteriori LCA of complete converters

- **Automated design | On-line monitoring | Preventive maintenance | Digital product passport**

Thank You!