Advanced Mechatronic Systems Group

ETH zürich

Environmental Compatibility – A New Key Performance Indicator of Multi-Objective Power Electronics Design

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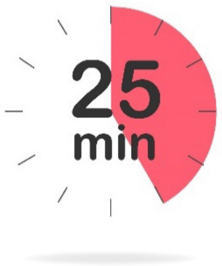


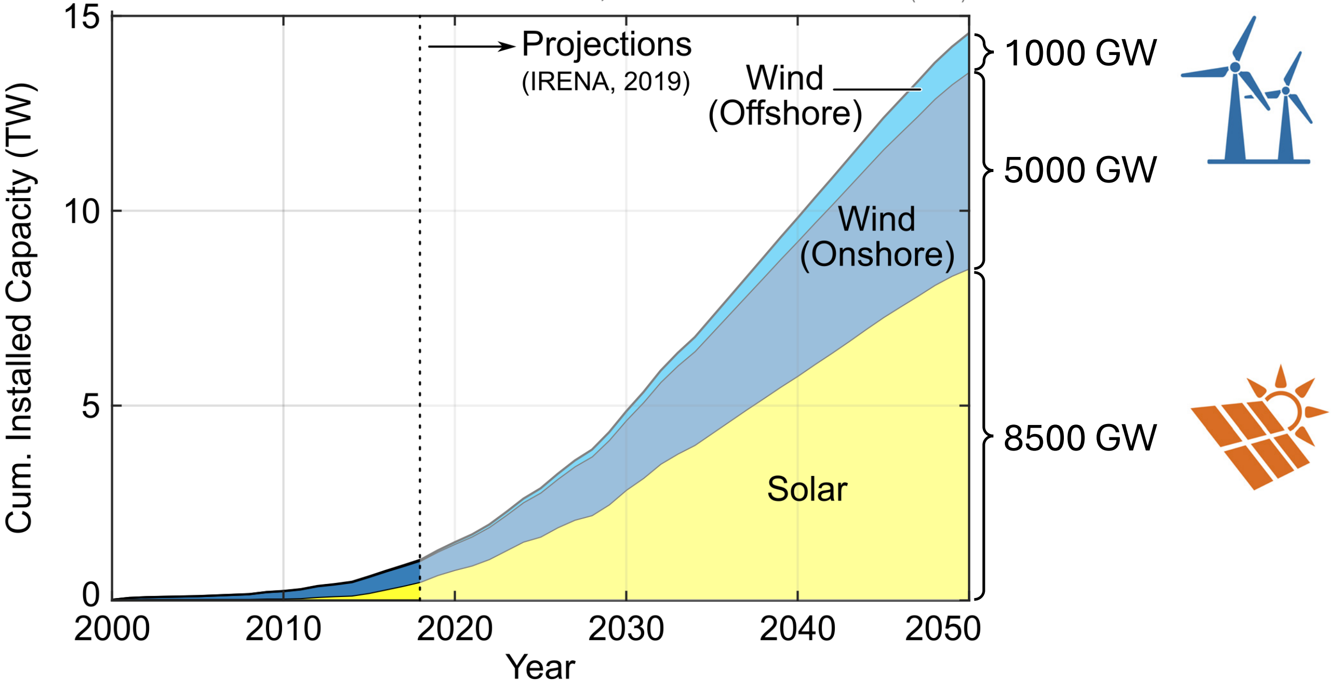
Outline

- Decarbonization
- The Elephant in the Room
- Multi-Objective Optimization
- Circular Economy Compatibility

Decarbonization

- Outlook of global cumulative installations until 2050
- In 2050 deployment of 370 GW/yr (PV) and 200 GW/yr (onshore wind) incl. replacements

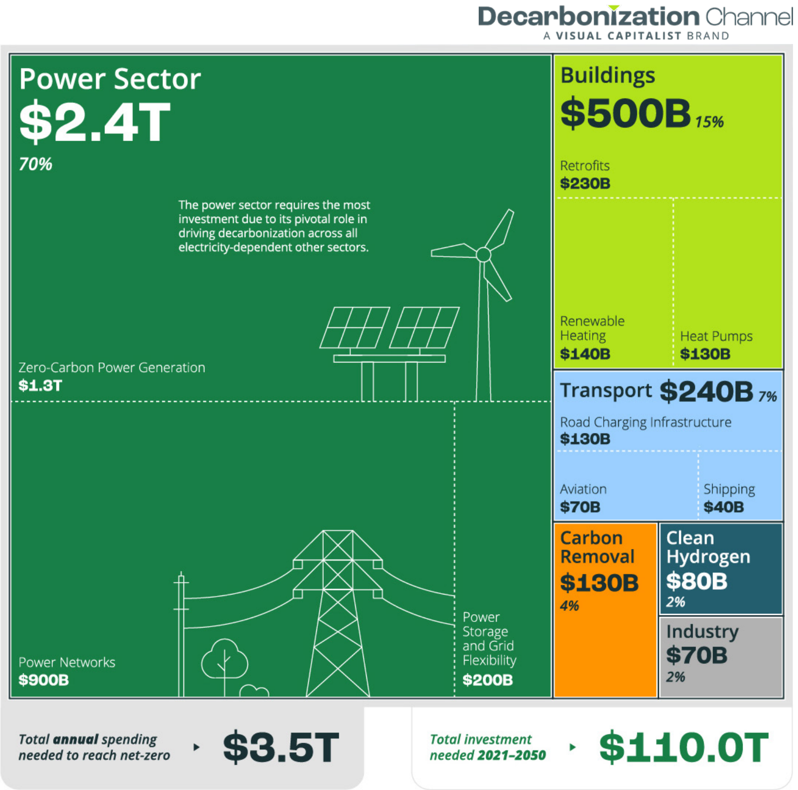
Source: IRENA, Future of Wind / Future of Solar PV (2019)



- Dominant share of electric energy — Power electronics as key enabling technology (!)

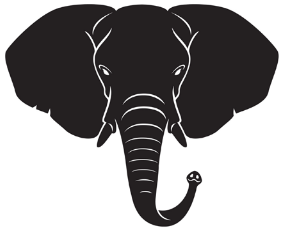
Remark: Cost of the Clean Energy Transition

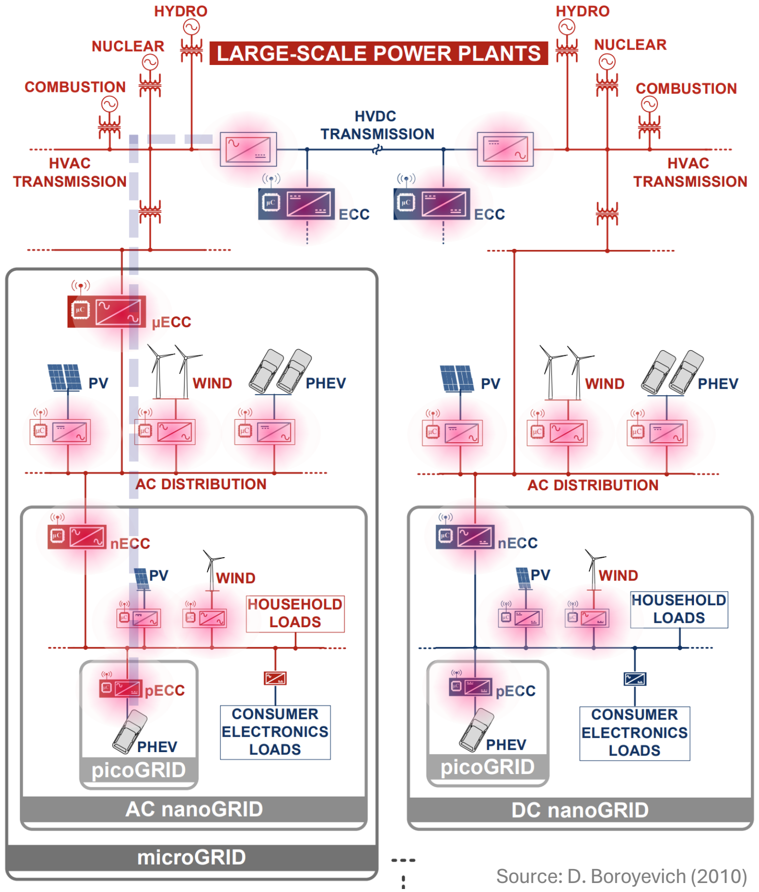
- Total annual spending for net-zero until 2050: 3.5 TUSD (3.5 $\cdot 10^{12}$ USD) / Total 110 TUSD until 2050



- **Perspectives:**
  - 3.5 TUSD are 12% of the U.S. GDP (2024) or 3% of the world GDP
  - World defense expenditures 2023 were 2.4 TUSD

Source: https://decarbonization.visualcapitalist.com/breaking-down-the-cost-of-clean-energy-transition/ based on data from the Energy Transition Commission.

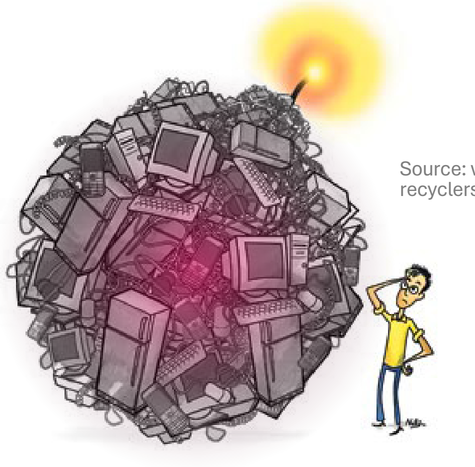
The  in the Room



Source: D. Boroyevich (2010)

- **25’000 GW** installed renewable generation in 2050
- **15’000 GWh** installed battery storage

- **4 x power electronic conversion** btw. generation & load
- **100’000 GW** of installed converter power
- **20 years** of useful life

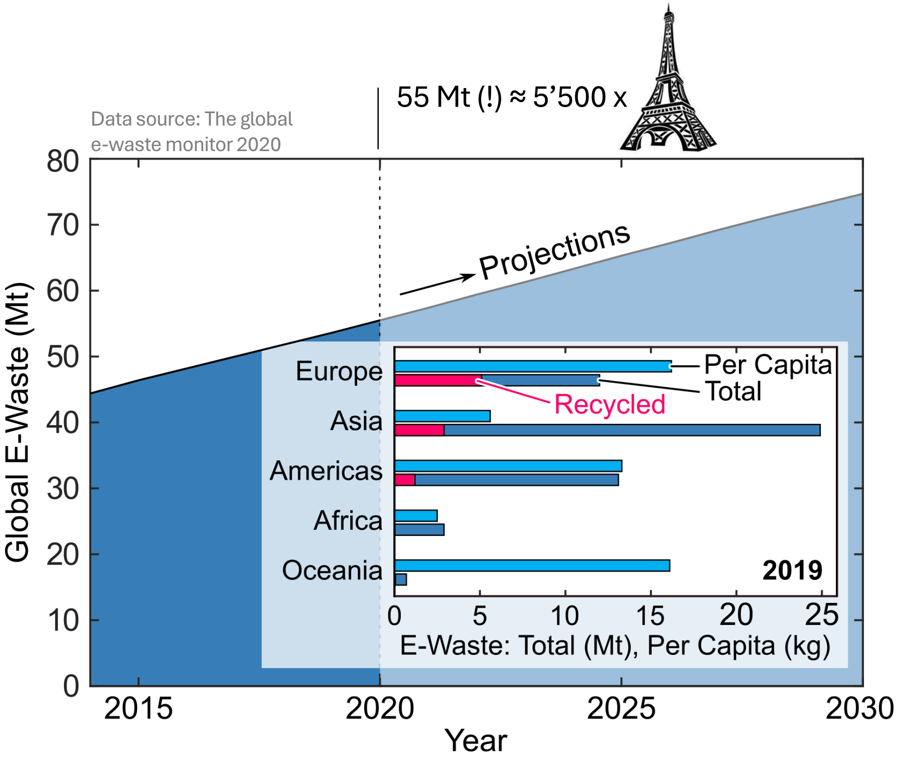


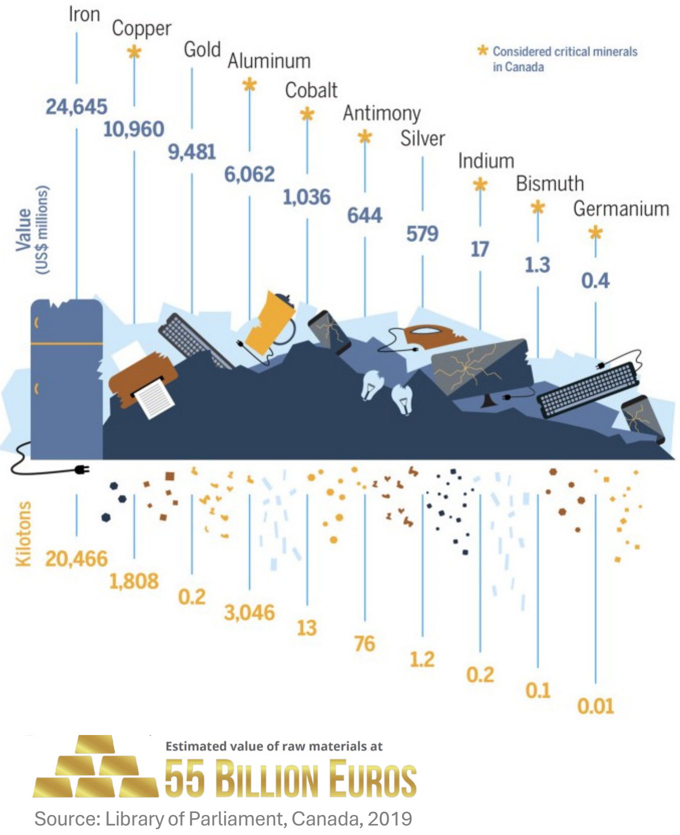
Source: www.e-waste-recyclers.co.in

- **5’000 GW$_{eq}$ = 5’000’000’000 kW$_{eq}$** of e-waste per year (!)
- **10’000’000’000 $** of potential value

Growth of Global E-Waste (1)

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



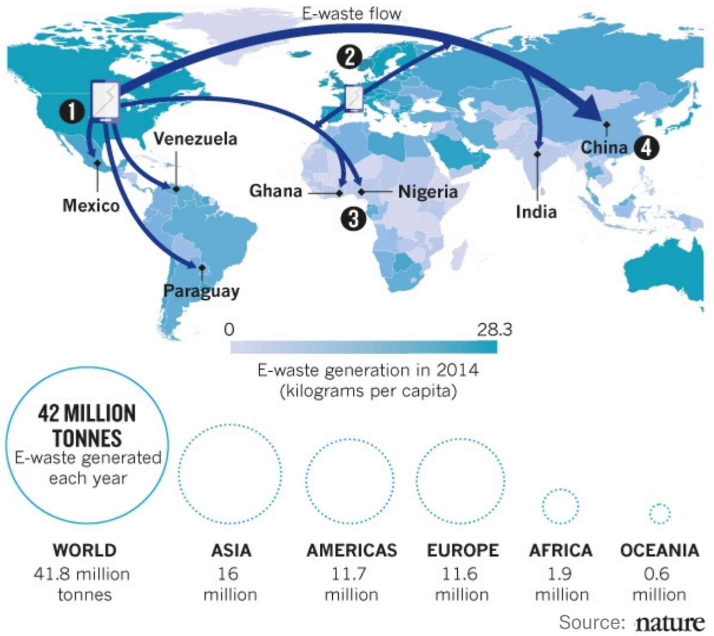


Global, 2019

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

Growth of Global E-Waste (2)

- Growing global e-waste streams → 120’000’000 tons of global e-waste in 2050
- Increasingly complex constructions → Little repair or recycling



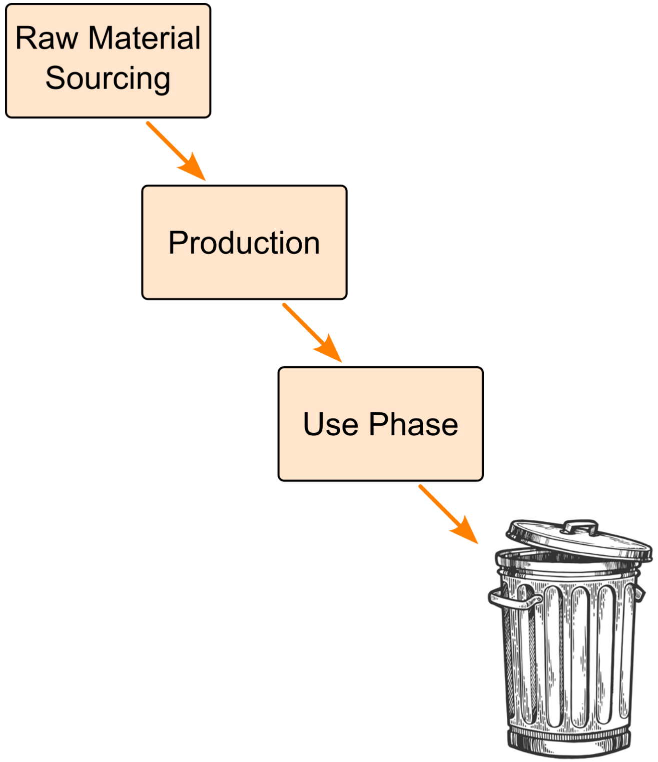
Source: Green IT Solution

- Growing global e-waste streams → Regulations mandatory (!)

The Paradigm Shift

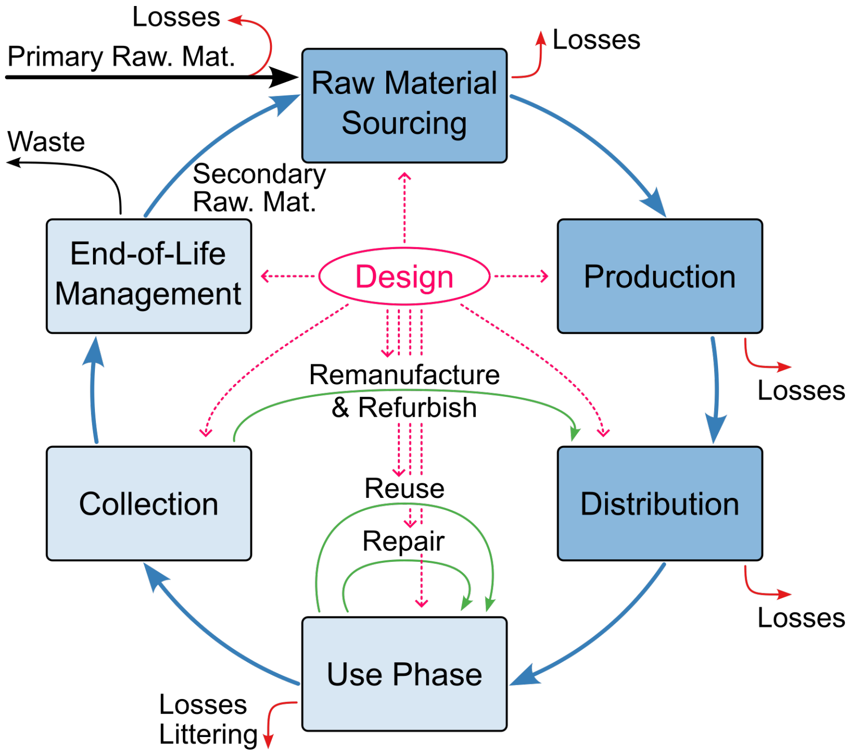
Linear Economy

- Take – make – dispose



Circular Economy

- Perpetual flow of resources

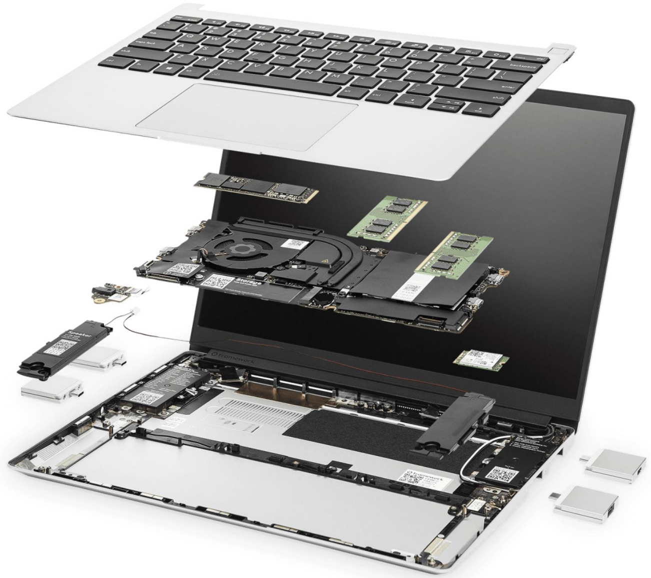


- Resources returned into the product cycle at end of life

Design for Repairability & Circularity

- Eco-design — Reduce environmental impact of products, incl. life-cycle energy consumption
- Re-pair / Re-use / Re-cycle / disassembly / sorting & max. material recovery, etc. considered
- EU eco-design directive (!)

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



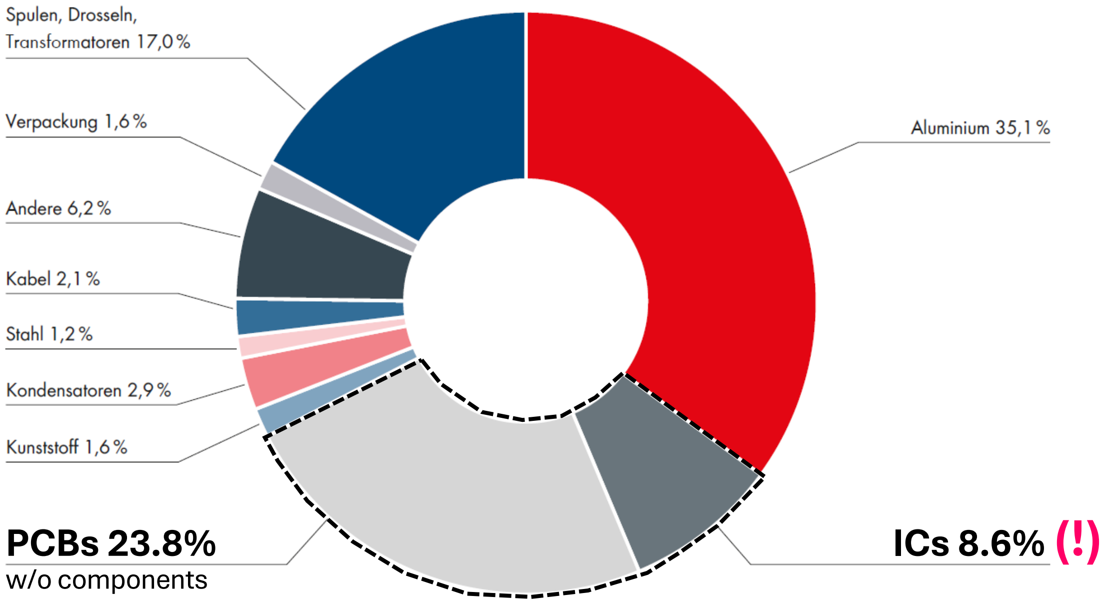
Source: Life Cycle Assessment of the Framework Laptop 2022, Fraunhofer IZM

- FAIRPHONE — Modular design / man. replaceable parts / 100% recycl. of sold products / fairtrade materials
- Framework laptop "You should be able to fix your stuff." — Modular design / man. replaceable parts
- "80% of environmental impact of products are locked-in at the design stage" — J. Thackara, *In the bubble: Designing in a complex world.* Cambridge, MA, USA: The MIT Press, 2006.

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)**

Embodied Carbon Footprint



- **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

New Holistic Design Procedure

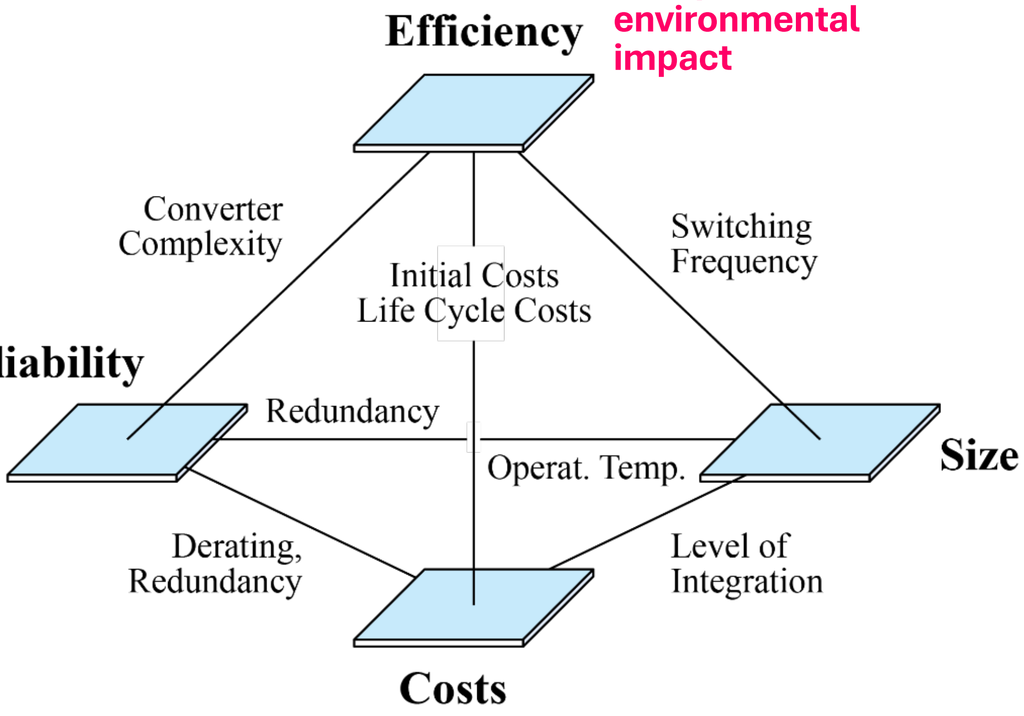
Multi-Objective Optimization with Environmental Impacts as New Performance Indicators

System Design Challenge

- Mutual coupling of performance indicators → Trade-off analysis!

Use-phase environmental impact

Lifetime / Replacements

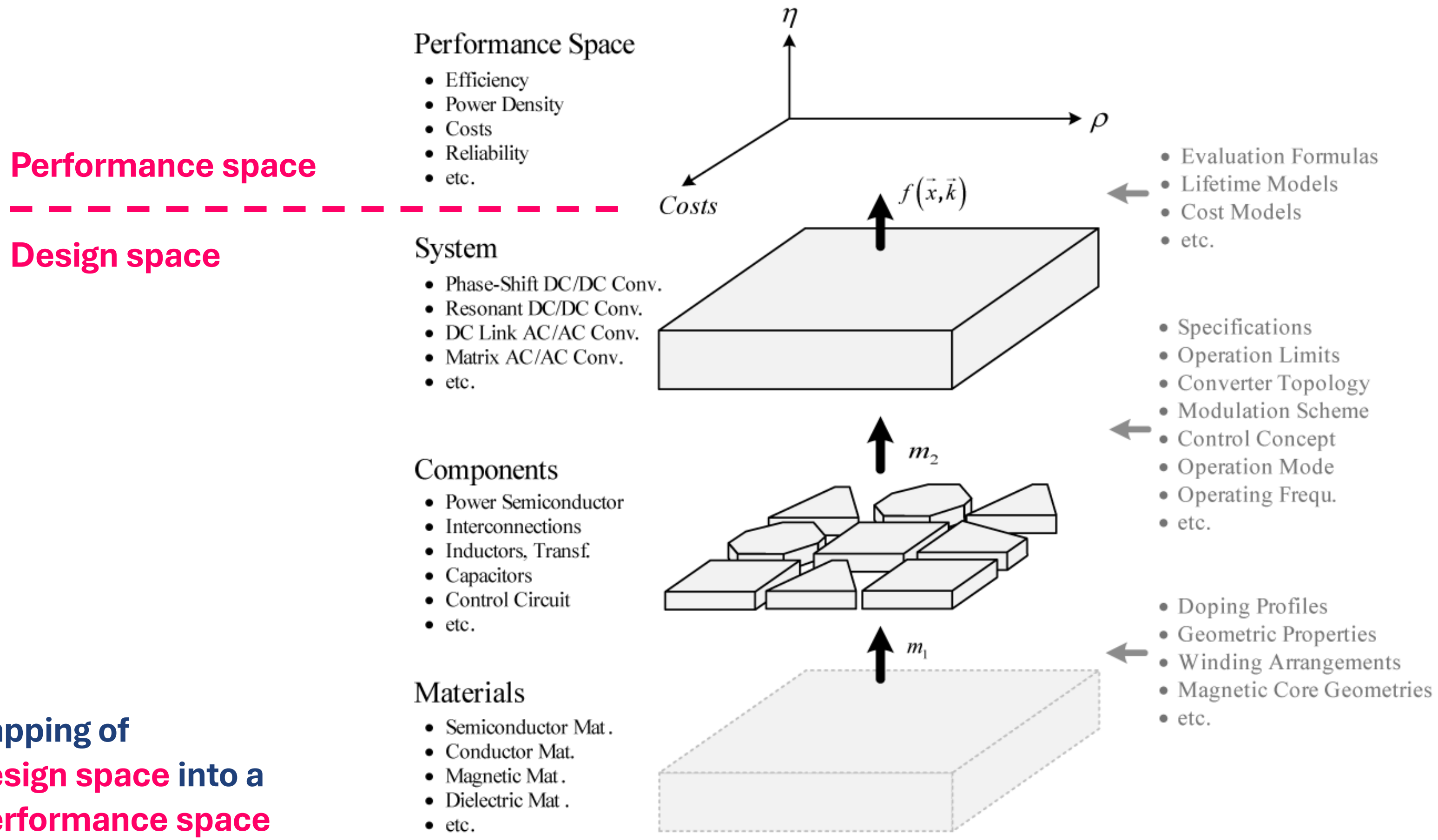


Embodied environmental impact

- For optimized systems, it is not possible to improve several performance indicators *simultaneously*

Source: J. W. Kolar, F. Krismer, H. P. Nee, "What are the "Big CHALLENGES" in Power Electronics?," *Presentation at the 8th Int. Conf. Integr. Power Electron. Syst. (CIPS),* Nuremberg, Germany, Feb. 2014. .

Abstraction of Power Converter Design

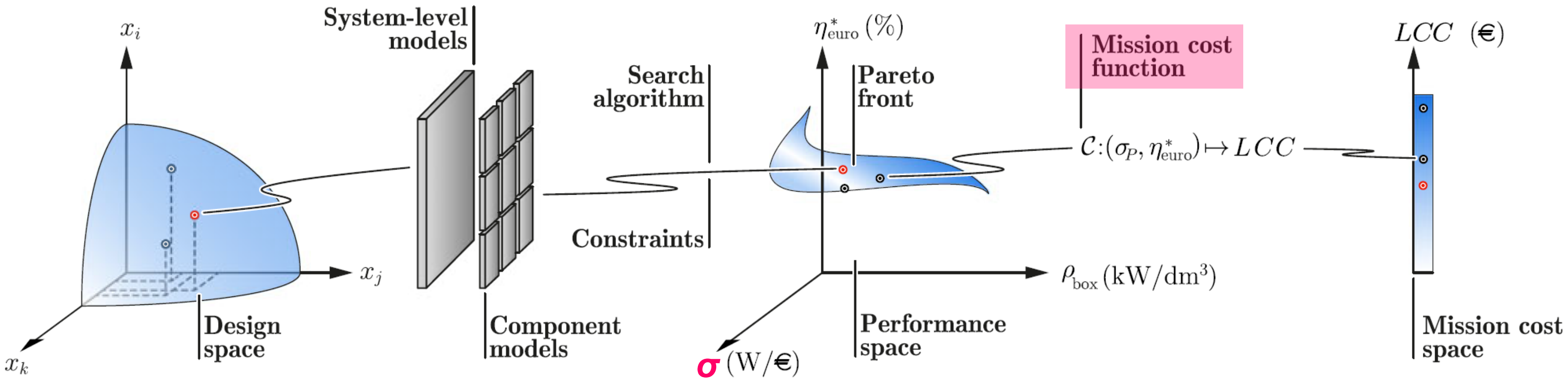


- **Converter Design: Mapping of multi-dimensional design space into a multi-dimensional performance space**

Source: J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner, "Performance trends and limitations of power electronic systems," in *Proc. 6th Int. Integr. Power Electron. Systems Conf. (CIPS)*, Nuremberg, Mar. 2010.

Multi-Objective Optimization of Converter Designs

- **Pareto front: Boundary of the feasible performance space**
- **Mission profiles: Power loss → Energy loss / Life-cycle *cost* (!)**



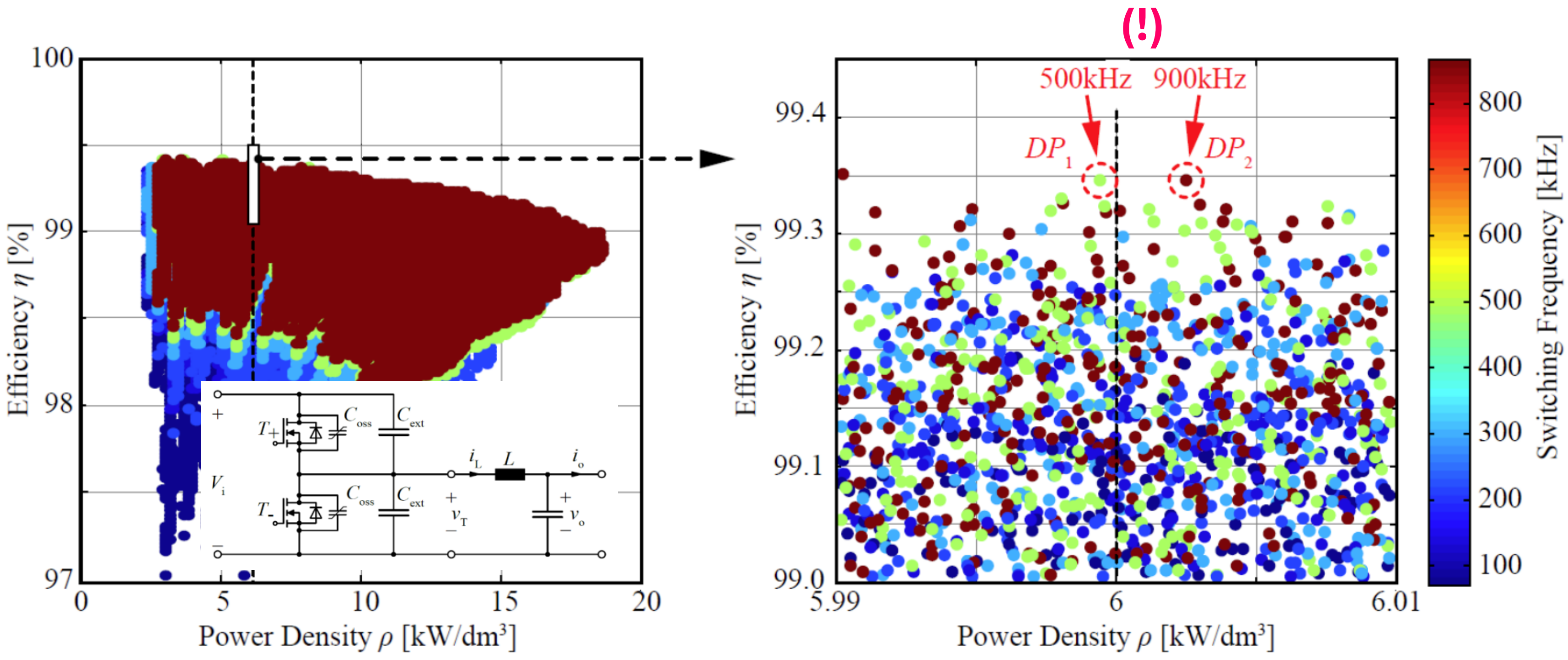
- **Typically considered performance indices:**

η Efficiency in %
ρ Volumetric power density in kW/dm^3
γ Gravimetric power density in kW/kg
σ **Cost density in W/€**

Source: R. M. Burkart and J. W. Kolar, "Comparative life cycle cost analysis of Si and SiC PV converter systems based on advanced η-ρ-σ multiobjective optimization techniques," *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4344–4358, Jun. 2017.

Design Space Diversity

- Very **different design space coordinates** map to very **similar performance space coordinates**



- Example: Google Littlebox design optimization w. PWM operation / Mutual comp. of HF and LF loss contrib.

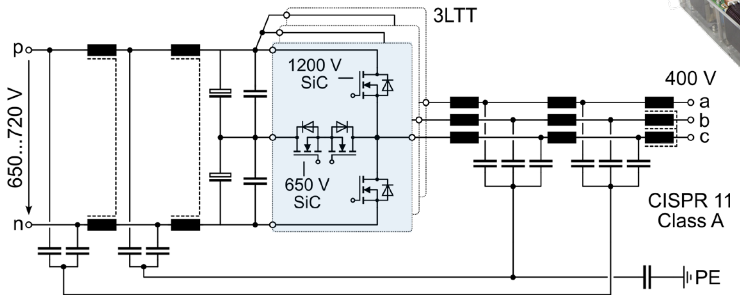
Source: J. W. Kolar, D. Neumayr, D. Bortis, M. Guacci, and J. Azurza Anderson, "Google Little-Box Reloaded," *Keynote at the 10th Int. Conf. Integr. Power Electron. (CIPS)*, Stuttgart, Germany, Mar. 2018.

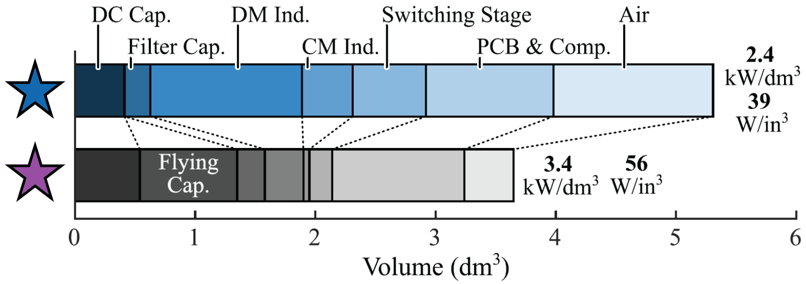
Design Space Diversity: 3L & 7L PV Inverters

- **Two concepts / similar specs — 12.5 kW, 650…720 V DC, CISPR 11 Class A — Similar perf. (η_{CEC} = 99.1%)**

3-Level All-SiC T-Type PV Inverter

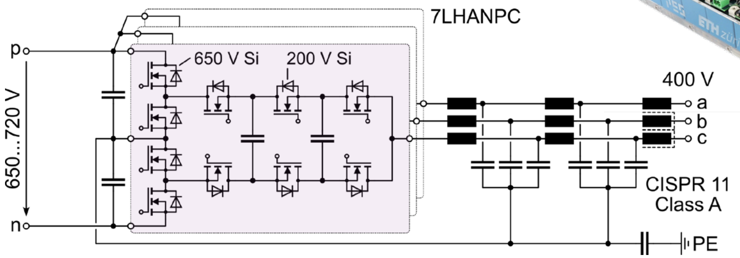
99.4%, 2.4 kW/dm^3

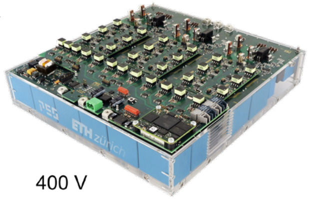


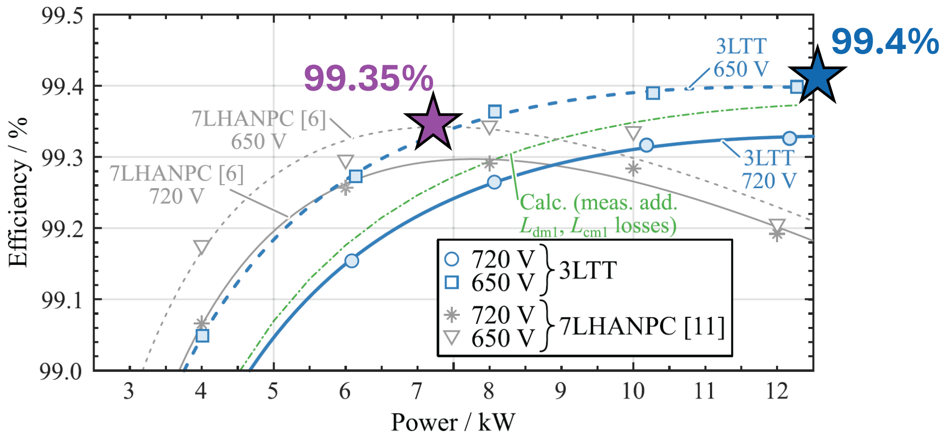


7-Level All-Si HANPC PV Inverter

99.35%, 3.4 kW/dm^3







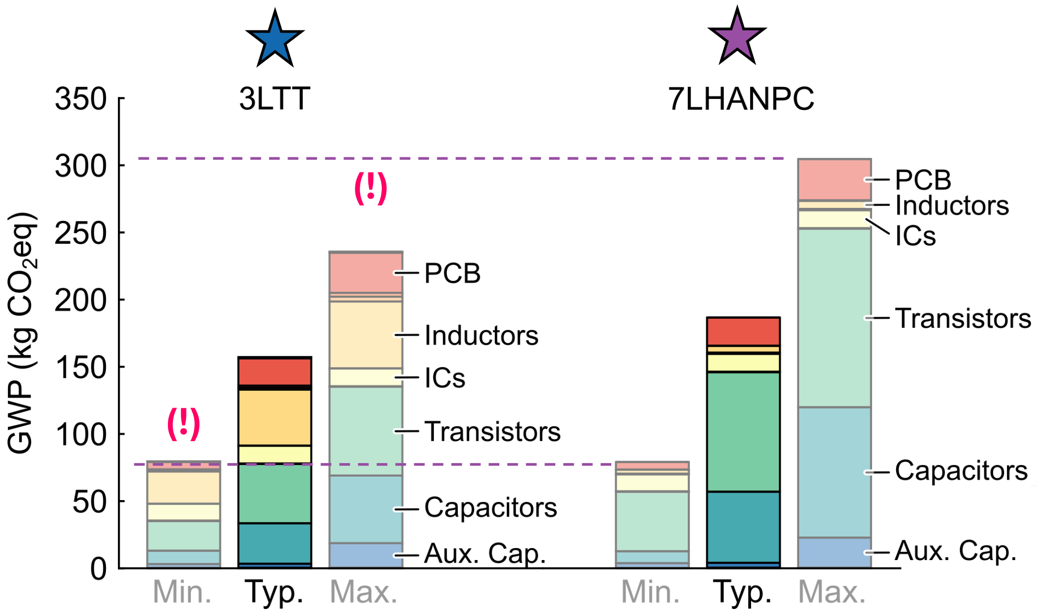
- **Differences in environmental impact?**

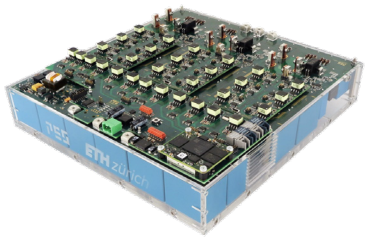
Source: J. A. Anderson, D. Marciano, J. Huber, G. Deboy, G. Busatto, and J. W. Kolar, "All-SiC 99.4%-efficient three-phase T-type inverter with DC-side common-mode filter," Electron. Lett., vol. 59, no. 12, p. e12821, 2023, doi: 10.1049/ell2.12821.

A Posteriori LCA of 3L & 7L PV Inverters (1)

- Two concepts / similar specs — 12.5 kW, 650...720 V DC, CISPR 11 Class A — Similar perf. (η_{CEC} = 99.1%)

2.4 kW/dm³, 11.8 kg





3.4 kW/dm³, 4.6 kg

GWP: Global Warming Potential

- Generic comp. models / ecoinvent database & lit. → Widely varying embodied carbon footprint (GWP) res. (!)
- Data availability / quality as key challenge!

Carbon Footprint is Not Enough!

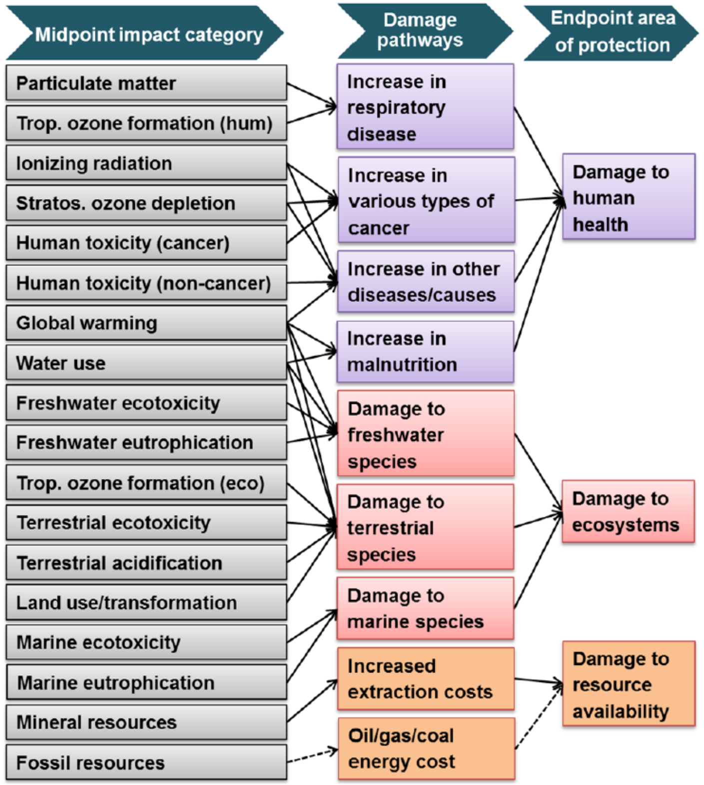
- Life cycle impact assessment (LCIA) phase of LCA — Environmental profile w. wide range of perf. indicators

- Example: ReCiPe 2016
  Three areas of protection / endpoint categories

- **Human Health**
  Damage to Human Health (DHH)
  in Disability-Adjusted Loss of Life Years (DALY)

- **Ecosystem Quality**
  Damage to ecosystem quality (DESQ)
  in Time-Integrated Species Loss (species · yr)

- **Resource Scarcity**
  Damage to resource availability (DRA)
  in surplus cost / dollars ($)

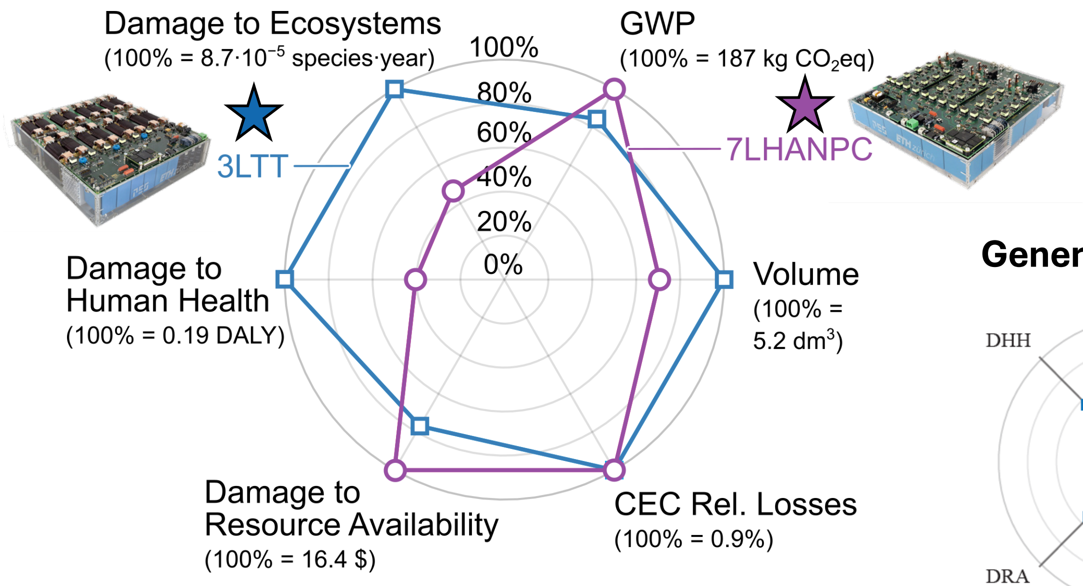


Source: Huijbregts et al., ReCiPe 2016 v1.1 Report

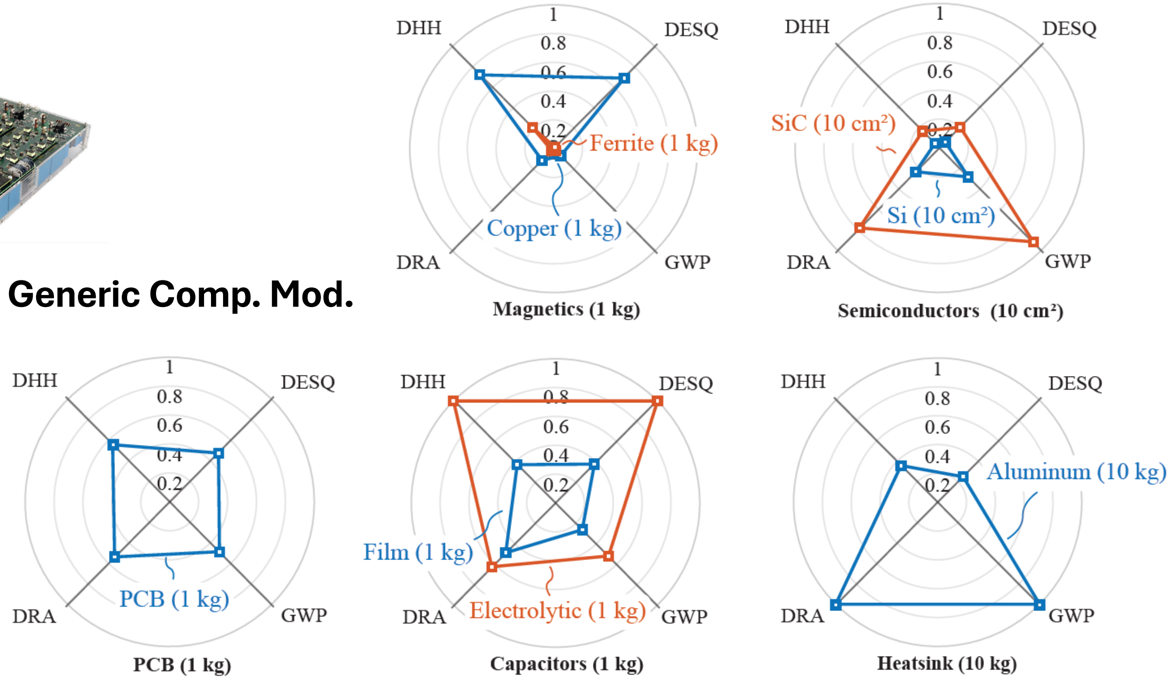
- Value choices (individualist / hierarchist / egalitarian) affect time horizon, included effects, etc.
- Alternative frameworks like EU Environmental Footprint (EF 3.1) exist

A Posteriori LCA of 3L & 7L PV Inverters (2)

- **Two concepts / similar specs — 12.5 kW, 650…720 V DC, CISPR 11 Class A — Similar perf. (η_{CEC} = 99.1%)**
- **Life Cycle Impact Assessment (LCIA) w. ReCiPe framework:**
  - Damage to ecosystems (DESQ) | Damage to human health (DHH) | Damage to resource availability (DRA)



Generic Comp. Mod.

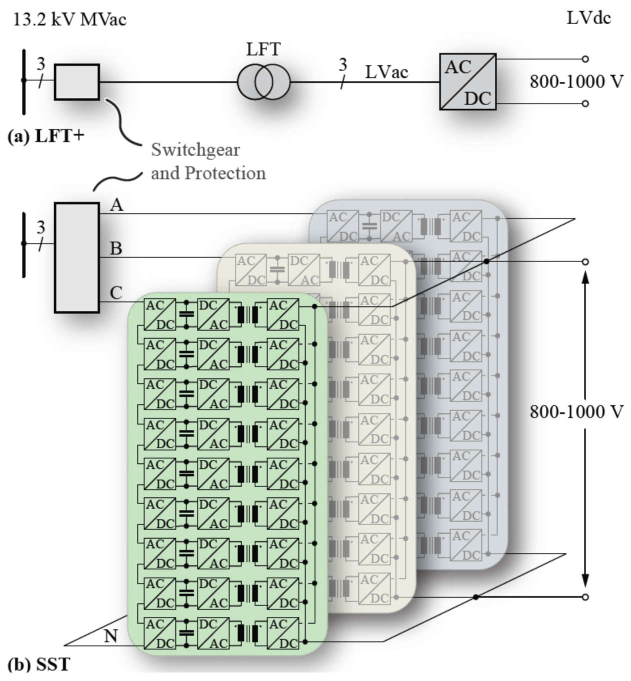


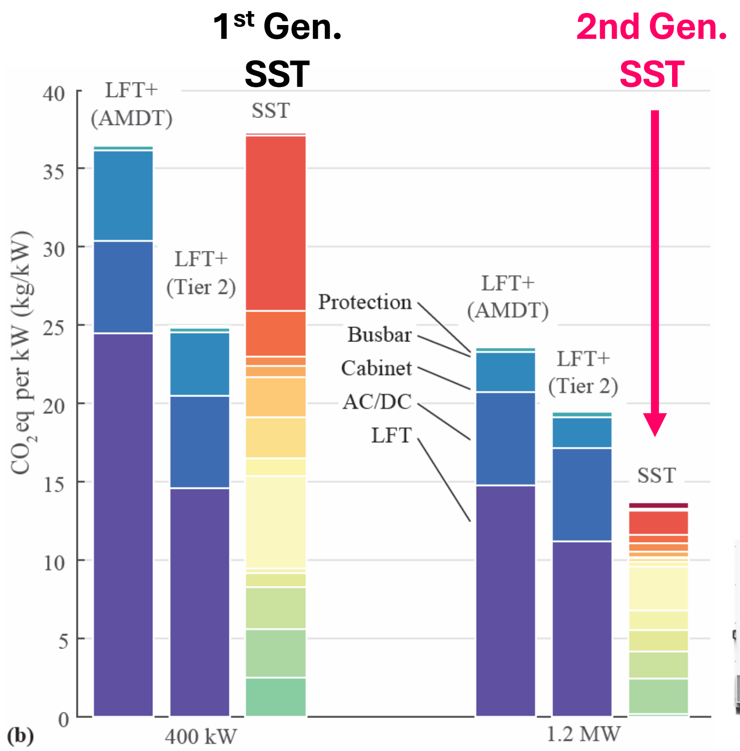
Normalized scales due to ecoinvent licensing restrictions.

- **Environmental footprint of converter as aggregate of components' environmental footprints**

Design Space Diversity: MVac-LVdc with LFT or SST

- Identical specifications — 13.8 kV MVac to 800 V LVdc / 400 kW or 1200 kW
- Similar efficiencies and use-phase emissions



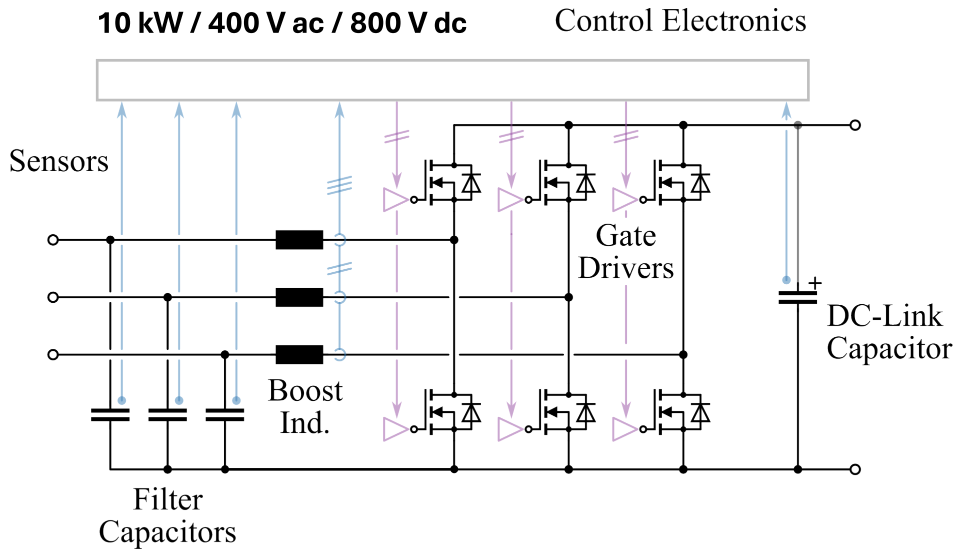


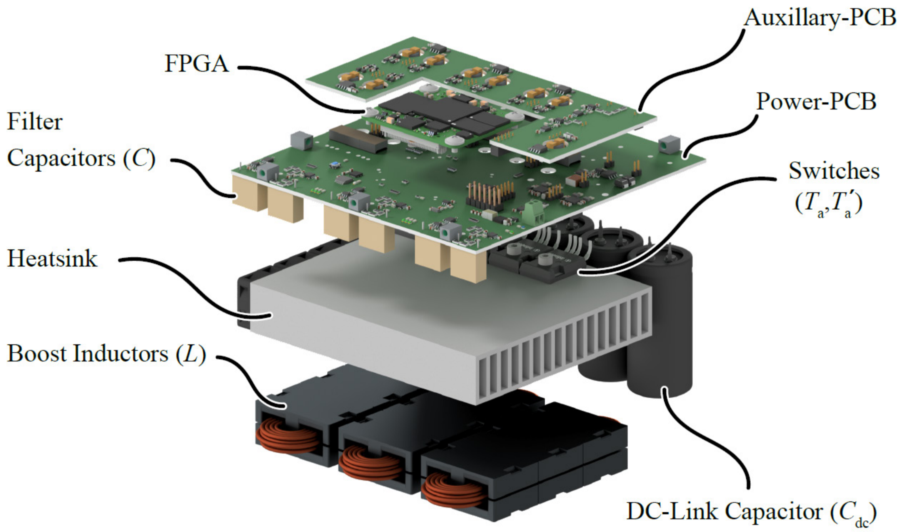
- Embodied carbon footprint aggregate of components' carbon footprints
- Significant improvement from Gen. 1 → Gen. 2 SST: Optimization is key for leveraging PE potential!

A Priori Consideration of Environmental Impacts in the Design Process?

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

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

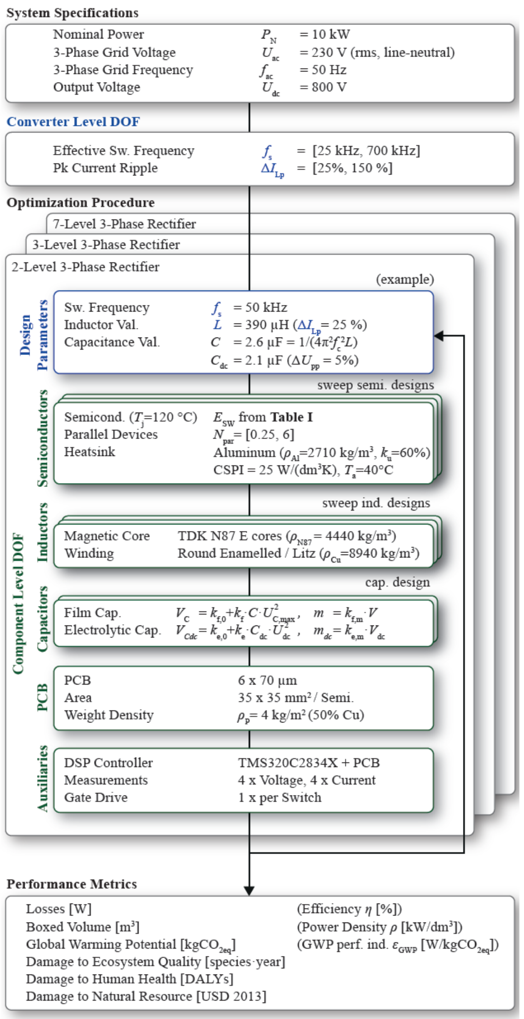


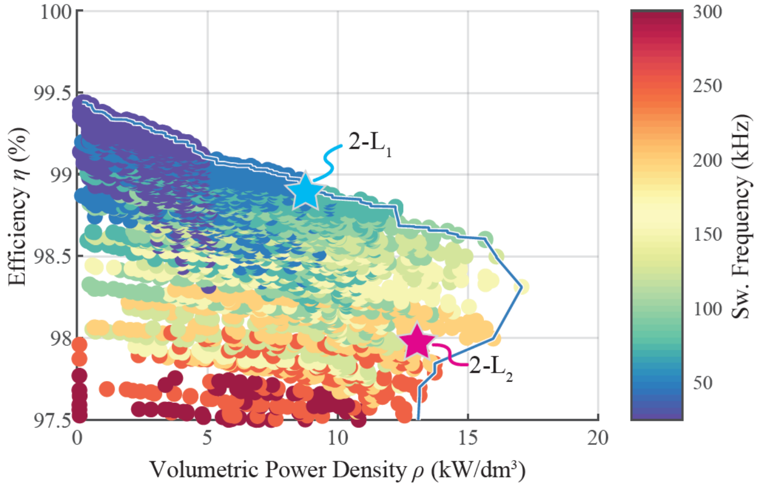


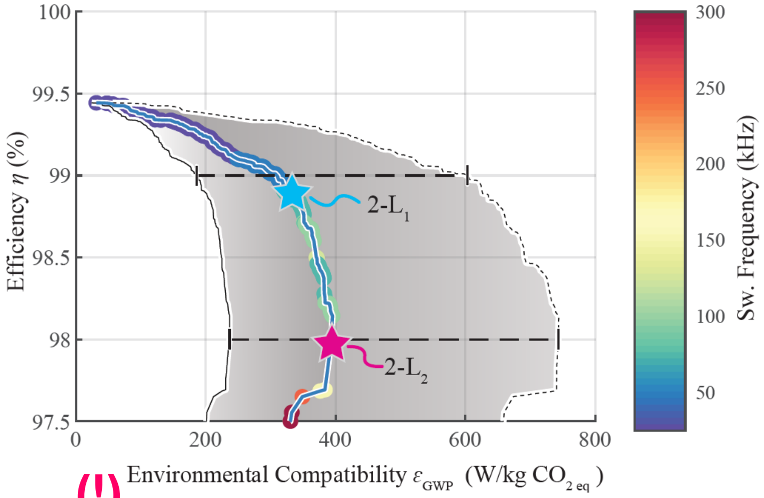
- **Degrees of freedom:**
  - Switching freq. [25…700 kHz]
  - Rel. Ind. Peak cur. ripple [0.25…1.5]
  - Var. transistor chip area
  - Variable ind. size (N87; solid/litz)

- **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 (1)







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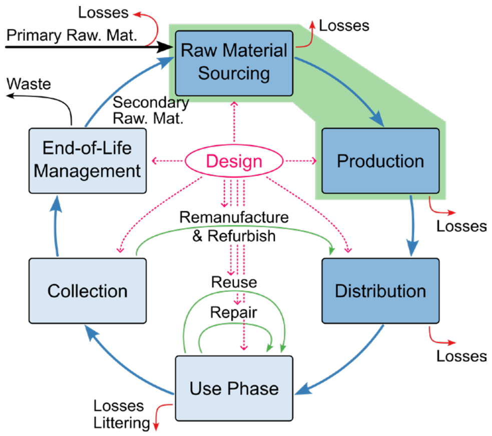
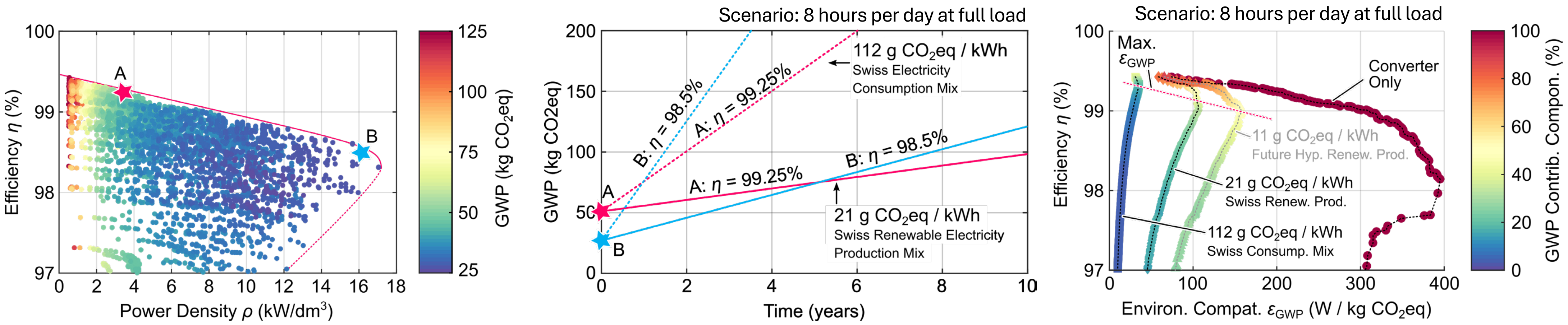
- **Trade-Offs**
  - Efficiency vs. power density
  - Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)
- **Env. Impacts with high uncertainties due to data availability/quality**



Multi-Objective Optimization Including the Use Phase

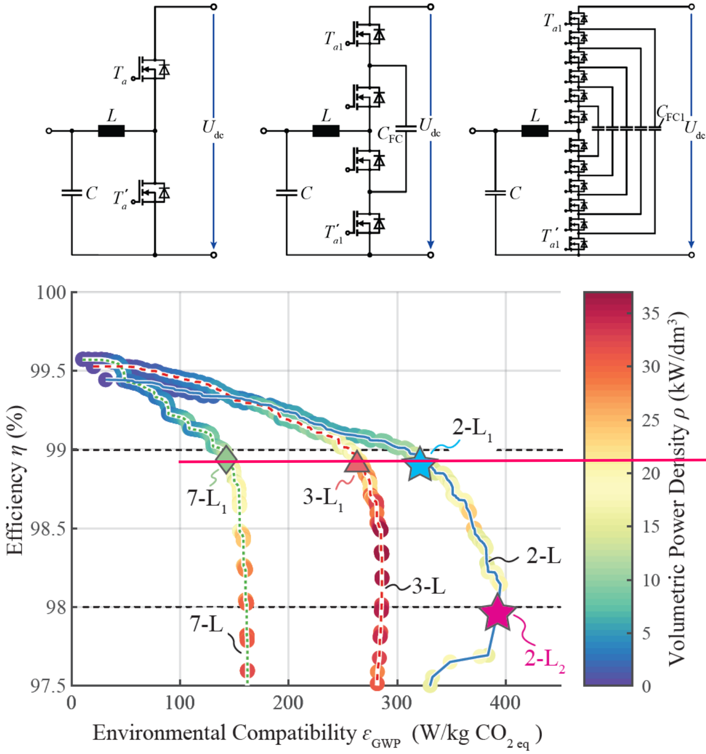
- **Life-cycle carbon footprint strongly depends on electricity mix and mission profile / usage intensity**



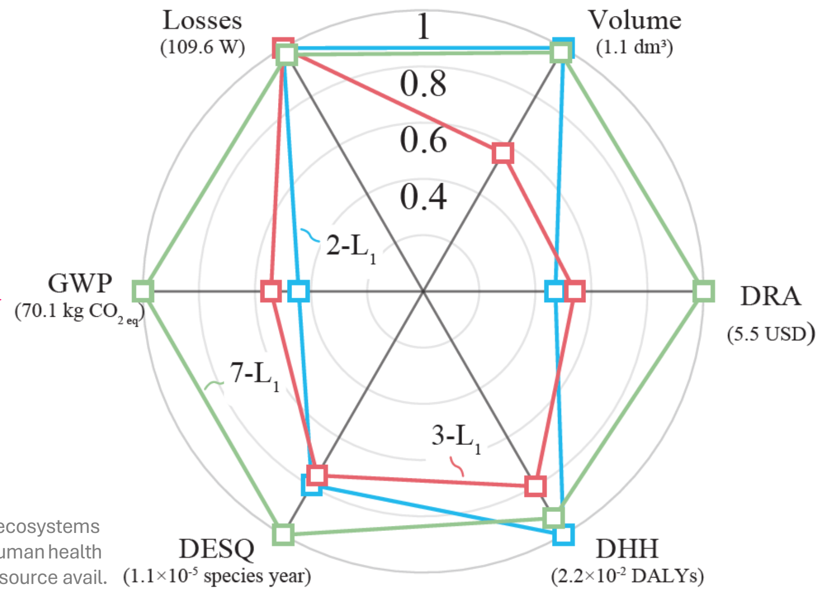
- **Design should consider use phase for best life-cycle performance**
- **Analogy to total cost of ownership (TCO) perspective**

Comprehensive Environmental Impact Profiles

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



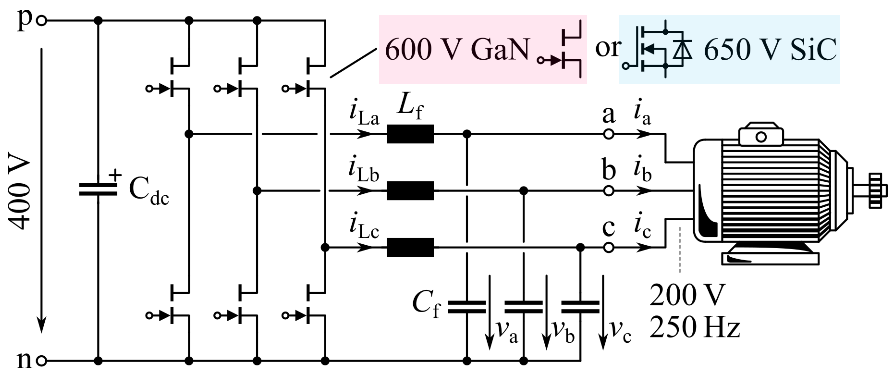
ReCiPe 2016:
DESQ—Damage to ecosystems
DHH—Damage to human health
DRA—Damage to resource avail.

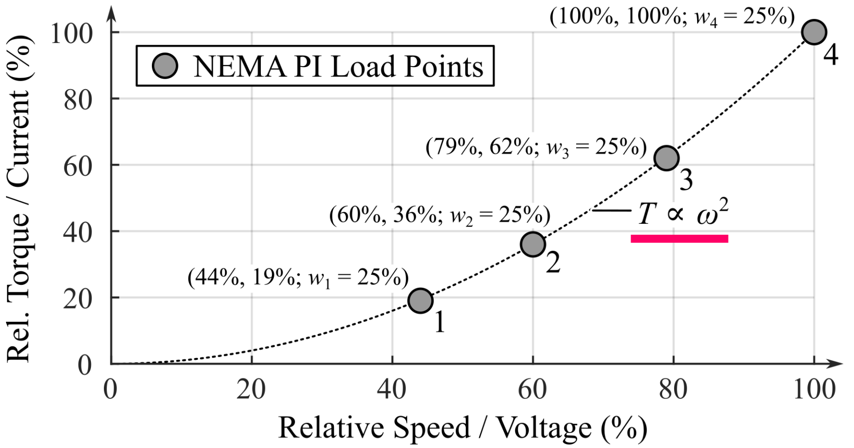


- Embod. env. footprint of 2L/3L/7L-designs with $\eta \approx 99\%$ and max. env. compat. ε_{GWP} in W / kg CO_2eq
- Same efficiency via different usage of act./pass. components — Different environmental impact profile!

A Priori LCA Example: 600-V/650-V GaN/SiC LV Motor Drives

- **45% of all electric energy used in motor-driven applications** Source: IEA, 2011
- **Significant share of variable-load centrifugal systems (pumps, fans, compressor) | < 50% with VSD** Source: Malinowski et al., *IAS Mag.*, Nov. 2023
- **NEMA Power Index (PI)** quant. energy savings w.r.t. fixed-frequency motor | Std. mission profile & default motor

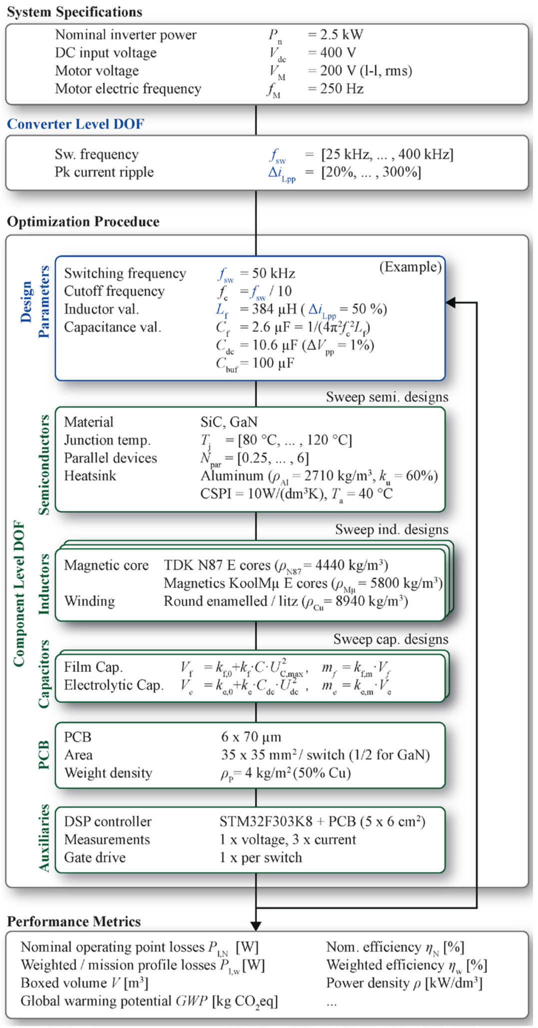




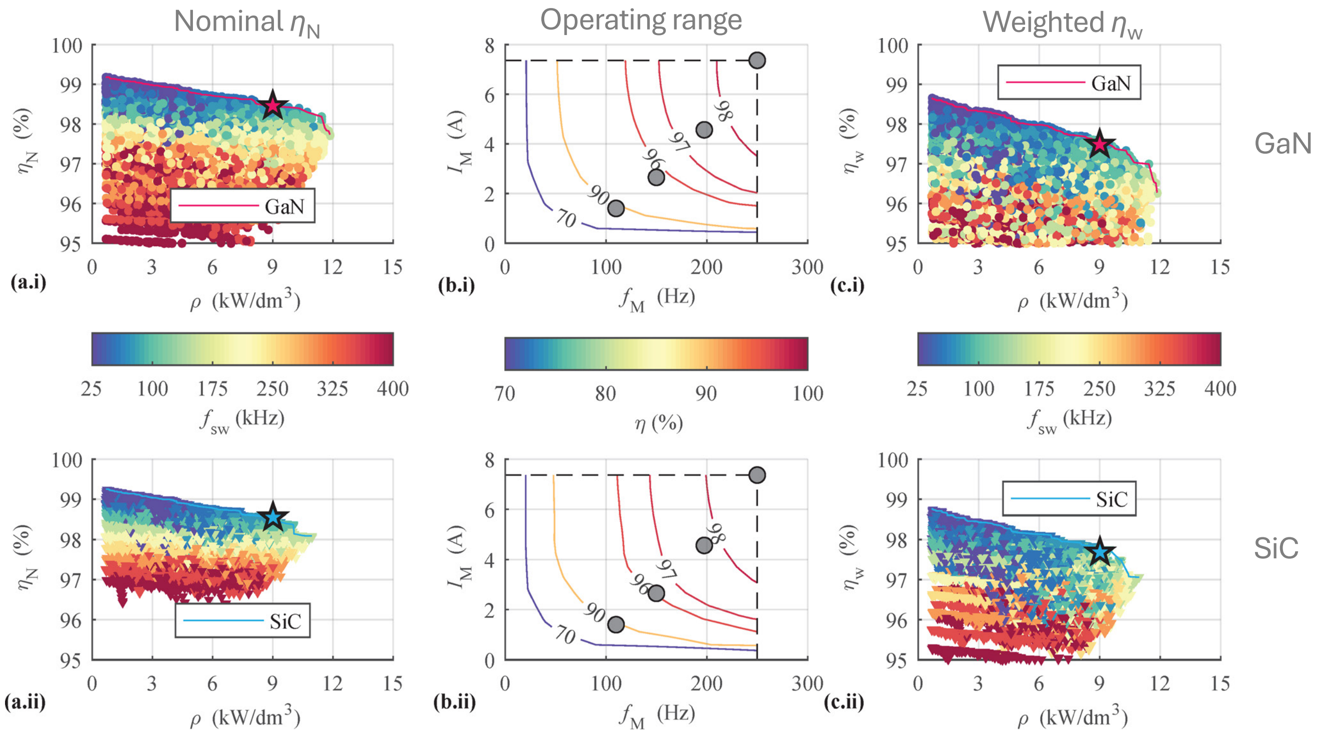
Specs: 2.5 kW inverter / 3-hp motor		
Input dc volt.	400	V
Motor volt.	0...200	V
Motor el. freq.	0...250	Hz

- **LV VSD inverter w. WBG and dc-bus-referenced LC output filter w. DM & CM attenuation (smooth mot. volt.)**
- **Mitigation of dv/dt issues (reflections, bearing currents, ...) | Standard motors | No harmonic motor losses**

Multi-Objective Optimization Procedure



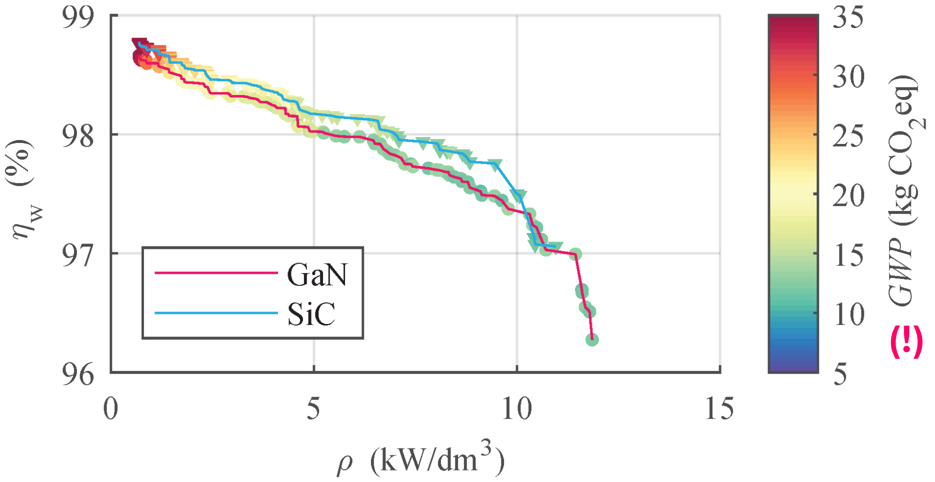
- **DoFs: Sw. freq. | Ind. cur. ripple | Var. chip area | Var. inductor designs**
- **Nominal eff. η_N & weighted eff. η_w (NEMA PI load profile)**

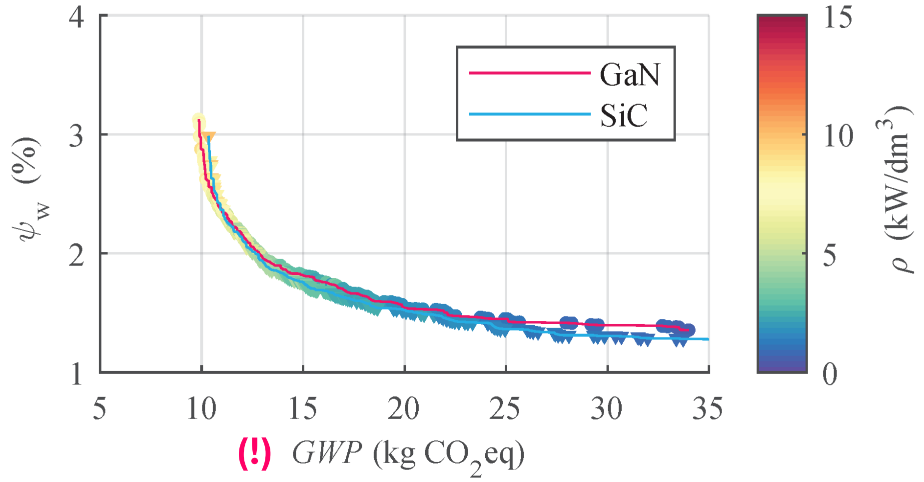


- GaN/SiC losses via scaling exemplary devices / Calorimetric meas. sw. loss.

Comparison of 600-V/650-V GaN/SiC LV Motor Drives

- Global warming potential (GWP) / carbon footprint in kg CO_2eq as new performance-space dimension
- Weight. eff. η_w and weight. rel. loss. ψ_w → Weight. avg. losses vs. weight. avg. output power (NEMA PI load profile)
- High volume designs (low power density ρ) tend to have high GWP



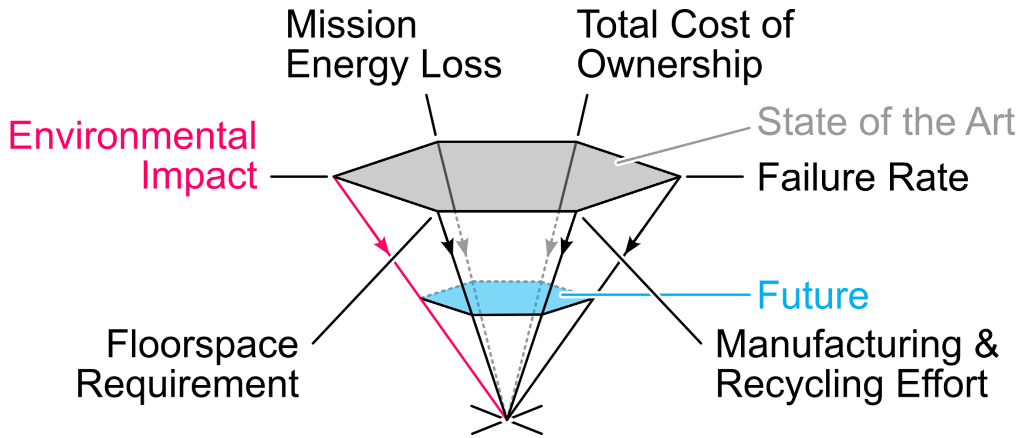


- Very similar performance of GaN-based & SiC-based designs | Limited accuracy of generalized comp. mod.
- "Snapshot in time" — Outcome dep. on available data & technological developments

Future Performance Indicators

- **Assuming 20+ years lifetime → Systems installed today reach end-of-life by 2050 (!)**
- **Life cycle assessment (LCA) mandatory for all future system designs**

- **Complete set of new performance indicators**
  - Environmental impact [kg CO_2eq / kW, ...]
  - Resource efficiency [kg_{xx} / kW]
  - Embodied energy [kWh / kW]
  - TCO [$ / kW]
  - Power density [kW/dm^3, kW/dm^2]
  - Mission efficiency [%]
  - Failure rate [h^{-1}]



- **Mission/location-specific trade-off embod. vs. life-cycle environ. impact — Losses / Reliability / Lifetime**
- **Compatibility with a circular economy (!) — Repairability / Reusability / Recyclability**

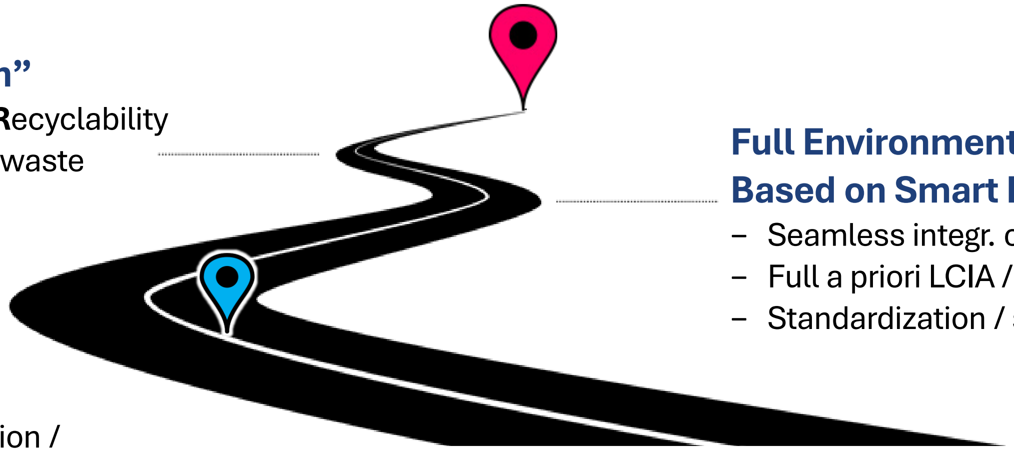
CEC Power Electronics Roadmap

■ **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

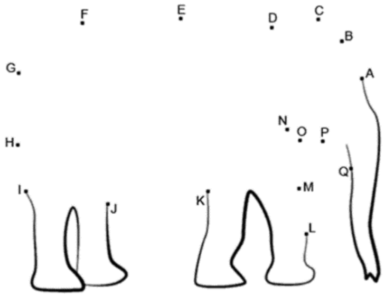


Generic Life-Cycle Impact Analysis (LCIA)
- New KPIs in multi-obj. opt.
- Data sources / quality / abstraction / generalization as key challenges

Classical $\eta\rho$-Pareto Optimization / Design
- Manual a posteriori LCA of complete converters

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

Thank You!



Further Reading

- J. Huber, L. Imperiali, D. Menzi, F. Musil, and J. W. Kolar, "Life-cycle carbon footprints of low-voltage motor drives with 600-V GaN or 650-V SiC power transistors," in *Proc. Int. Conf. Integr. Power Syst. (CIPS)*, Düsseldorf, Germany, Mar. 2024.

- J. Huber, L. Imperiali, D. Menzi, F. Musil, and J. W. Kolar, "Energy efficiency is not enough!," *IEEE Power Electron. Mag.*, vol. 11, no. 1, pp. 18–31, Mar. 2024.

- L. Imperiali, D. Menzi, J. W. Kolar, and J. Huber, "Multi-objective minimization of life-cycle environmental impacts of three-phase AC-DC converter building blocks," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Long Beach, CA, USA, Feb. 2024.

- J. W. Kolar, L. Imperiali, D. Menzi, J. Huber, and F. Musil, "Net zero CO_2 by 2050 is NOT Enough (!)," *Keynote at the 25th Europ. Conf. Power Electron. Appl. (EPE),* Aalborg, Denmark, Sep. 2023.