Power Electronic Systems Laboratory

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

**Jonas Huber and Johann W. Kolar**

Power Electronic Systems Laboratory
ETH Zurich, Switzerland

June 27, 2024

pels IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

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**Jonas Huber, Johann W. Kolar, Luc Imperiali, and David Menzi**

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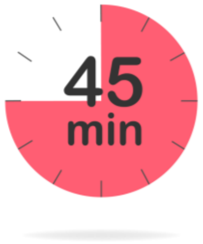
# Outline




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

Acknowledgment:
Franz Musil, Fronius International GmbH

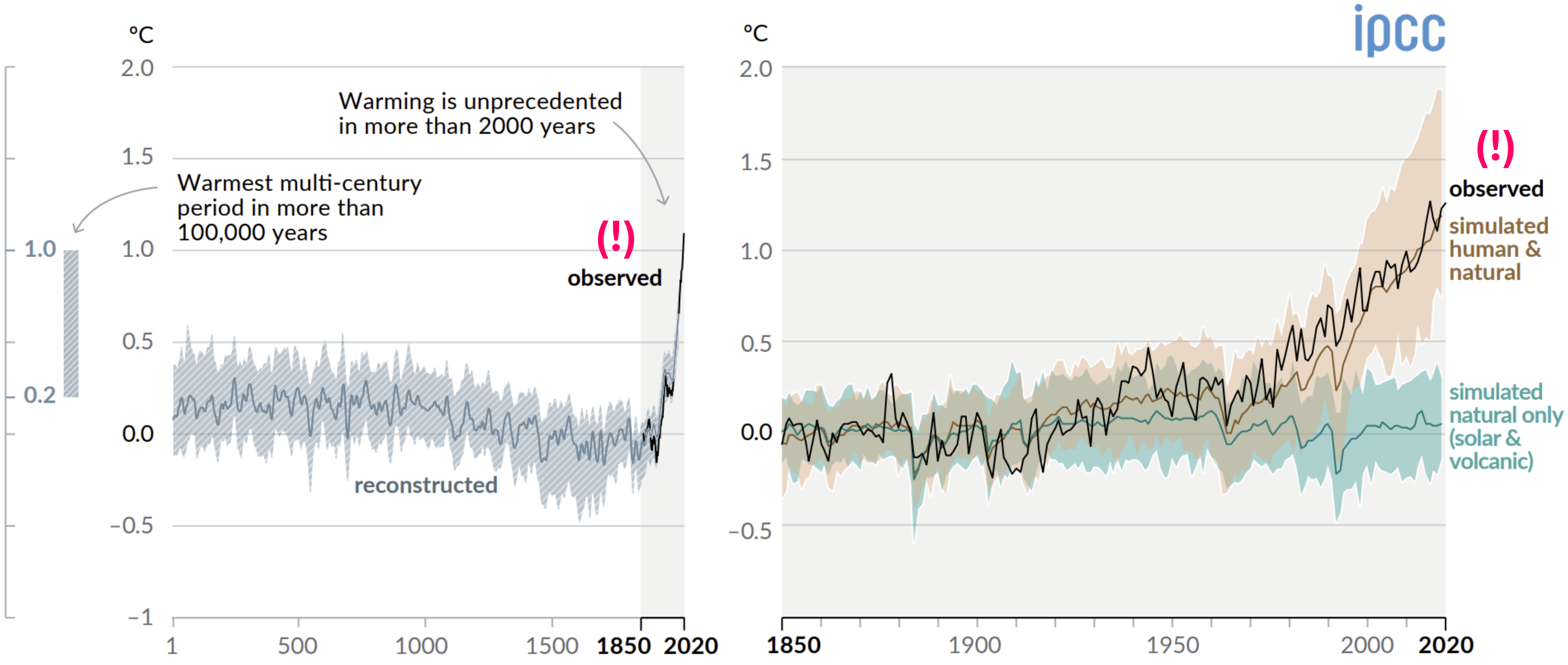
# The U.N. SUSTAINABLE DEVELOPMENT GOALS


Source: https://www.un.org/sustainabledevelopment

- #7 – "Affordable and clean energy" / #12 – "Responsible consumption and production" / ...

# The Challenge

- Fossil fuels facilitate rapid economic growth and development

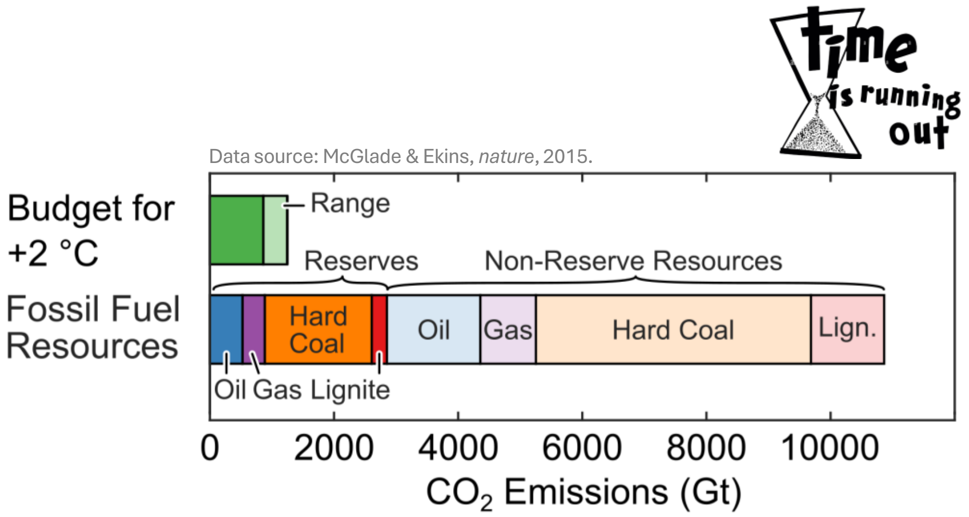


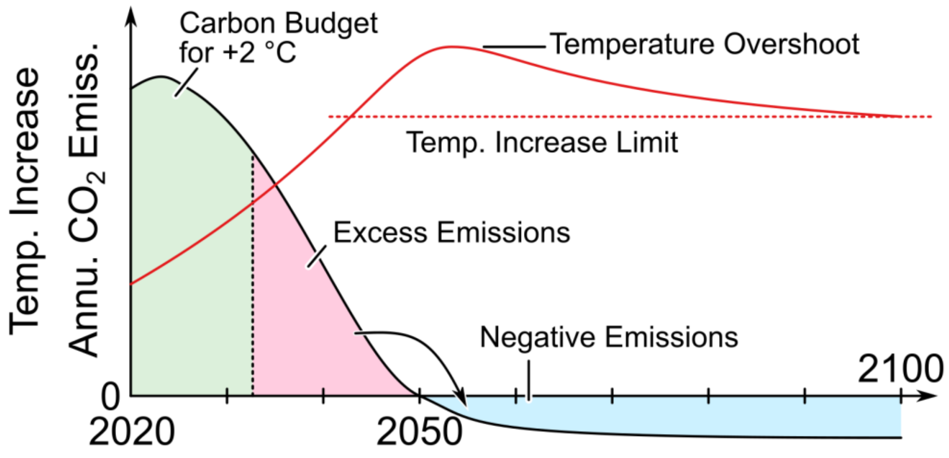

- Anthropogenic greenhouse gas emissions cause climate change / global warming

Source: IPCC, "Climate Change 2021: The Physical Science Basis," Summary for Policymakers, 2021.

# Decarbonization / Defossilization

- +2 °C target by 2100: Globally, 30% of oil, 50% of gas, and > 80% of coal reserves must remain unused (!)
- Ambitious pathway to "net-zero $CO_2$ emissions by 2050" → Temperature overshoot!



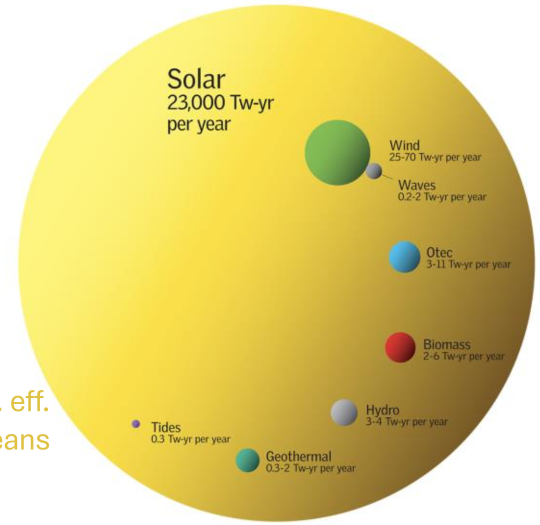




- Human history: Transition from lower to higher energy density fuel — Wood → Coal → Oil & Gas
- Challenge of stepping back from oil & gas quickly / Can't wait for disruptive technologies / panacea!

# The Opportunity

(2009) 16 TW-yr → 16 Tw-yr per year ← **27 TW-yr** (2050)

Renewable energy resources per year

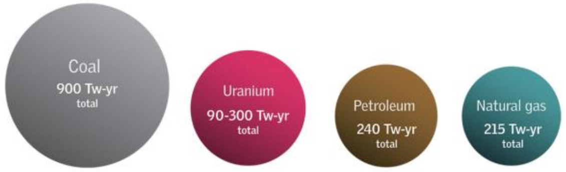



100% convers. eff.
Excl. oceans

**Note:** Graphical representation assumes spheres, not circles

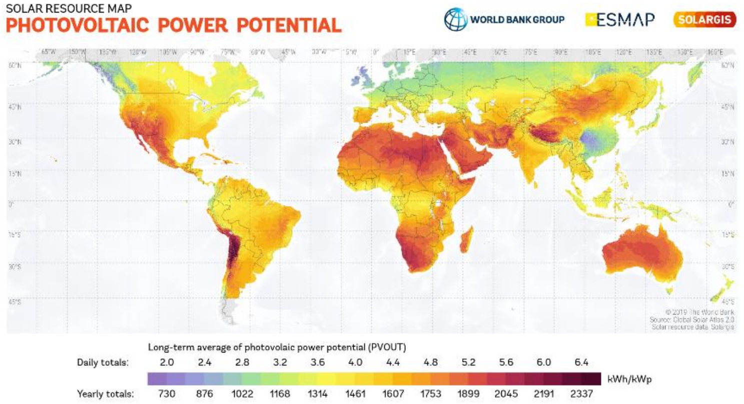
Primary consumption:
16 TWyr → 27 TWyr
Final consumption:
11 TWyr → 15 TWyr

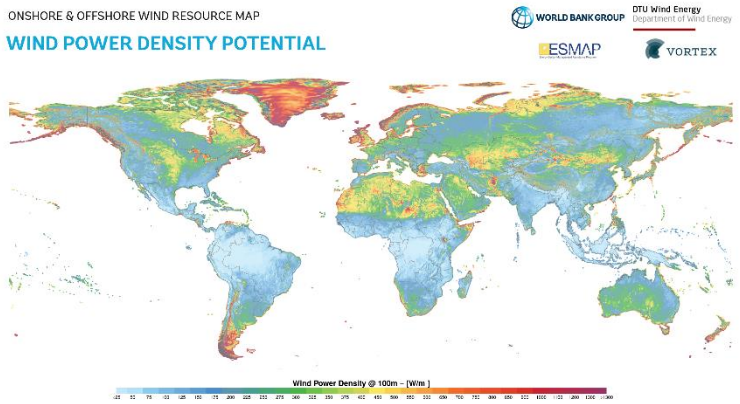
Fossil energy resources - total reserve left on earth




Source: R. Perez et al., IEA SHC Program Solar Update (2009)

■ **Global distribution of solar & wind resources**

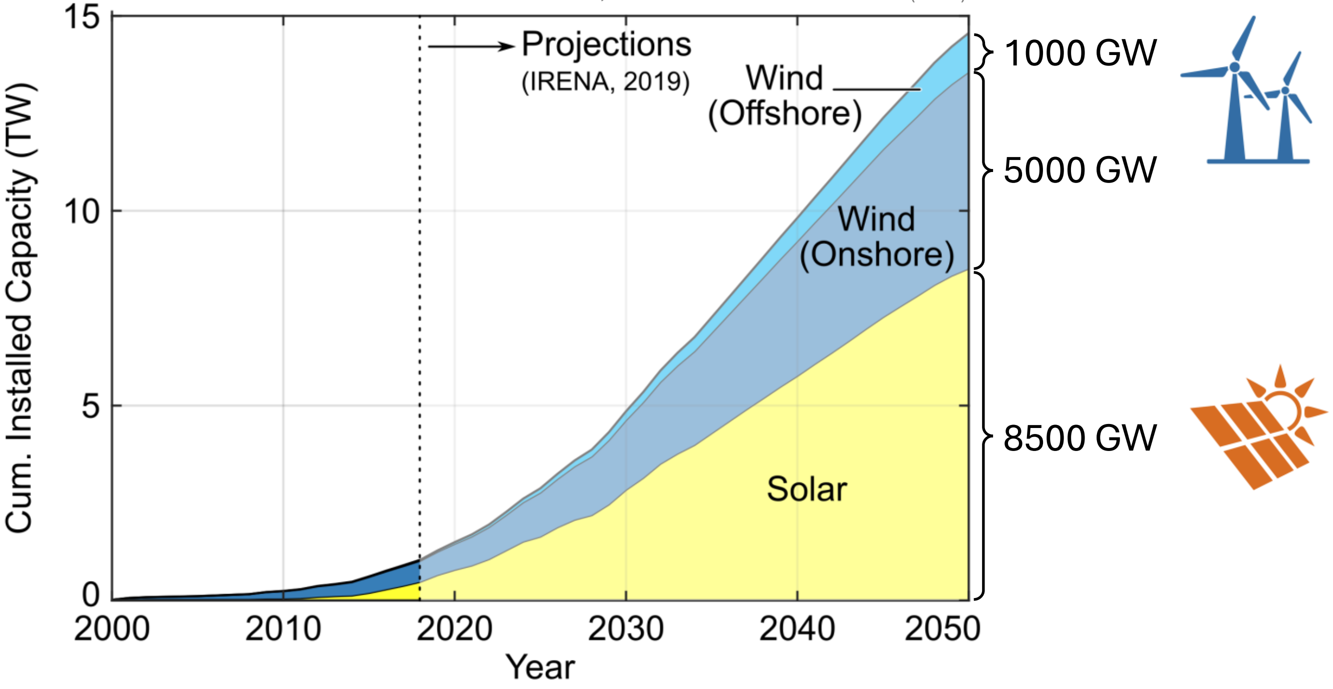


# The Approach

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

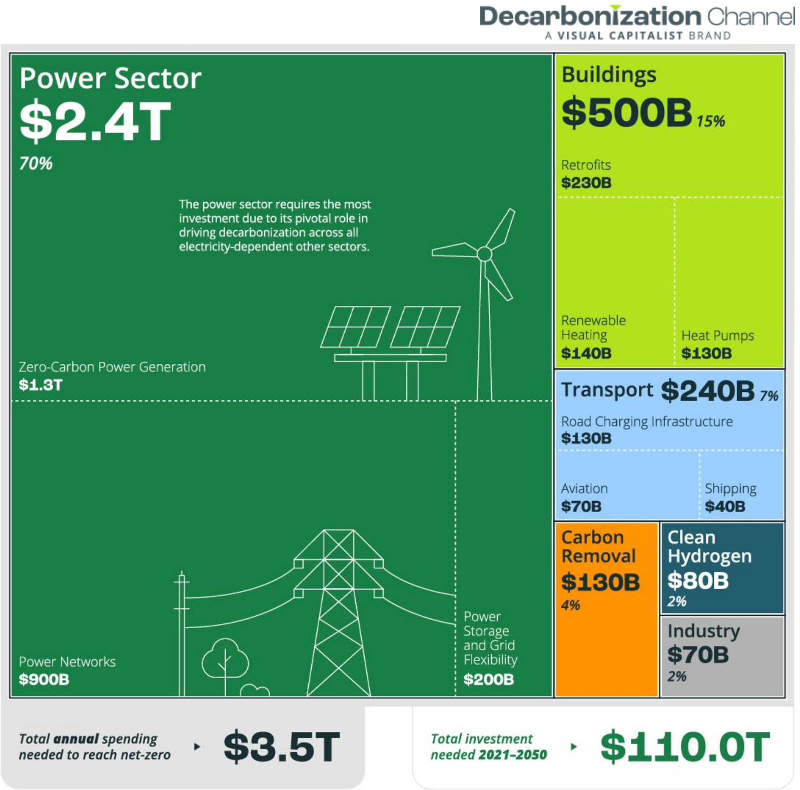
Source: IRENA, Future of Wind / Future of Solar PV (2019)




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

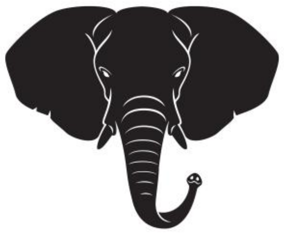
# Remark: Cost of the Clean Energy Transition

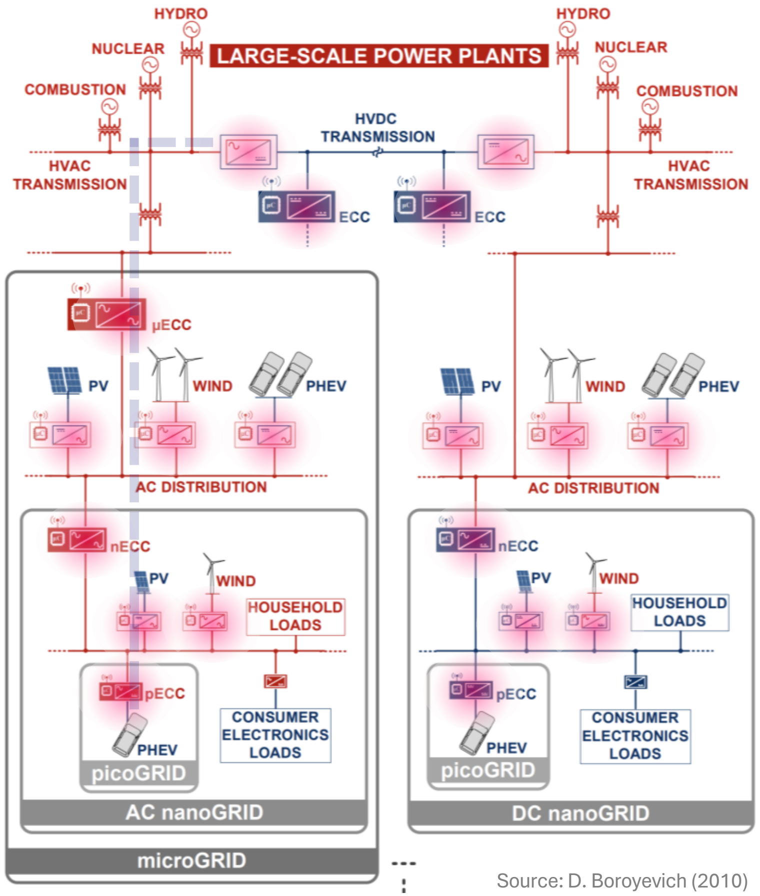
- Total annual spending for net-zero until 2050: 3.5 TUSD ($3.5 \cdot 10^{12}$ USD) / Total 110 TUSD until 2050




- 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.

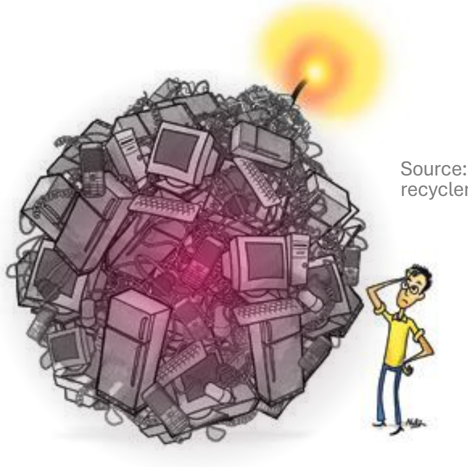
# The  in the Room




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

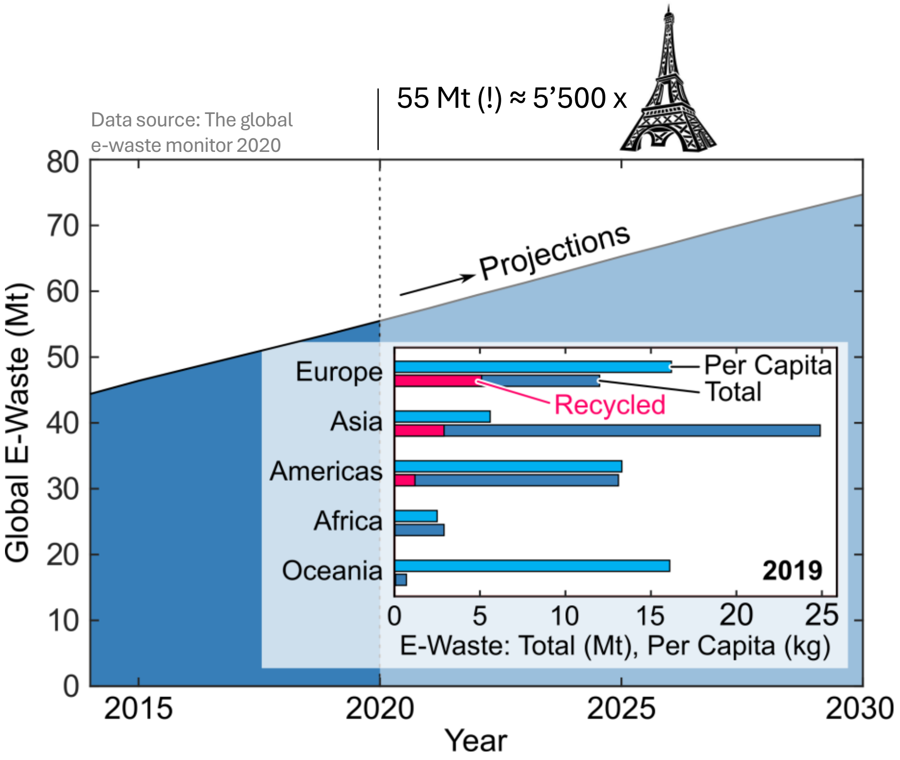


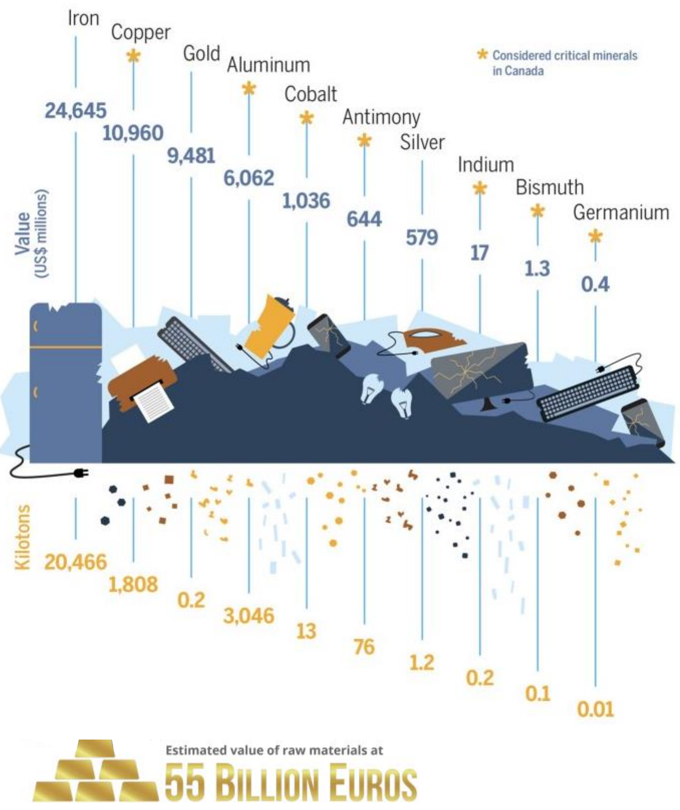
Source: www.e-waste-recyclers.co.in

- **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**



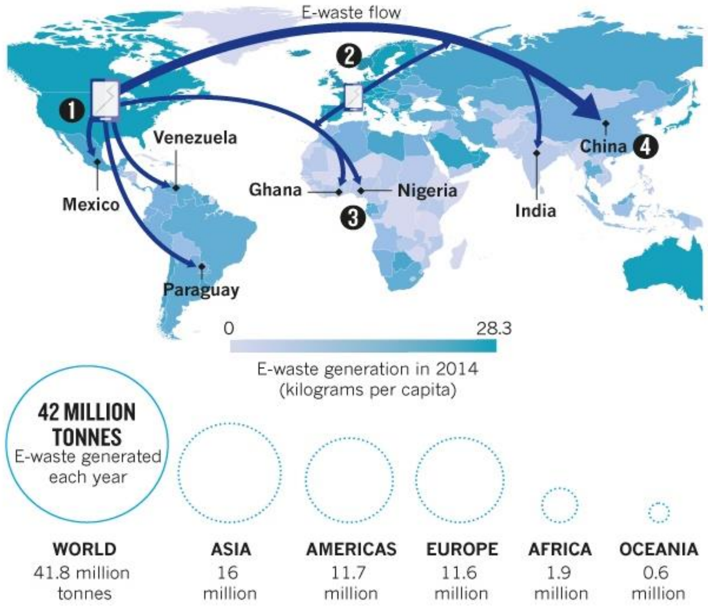

Global, 2019

Source: Library of Parliament, Canada, 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



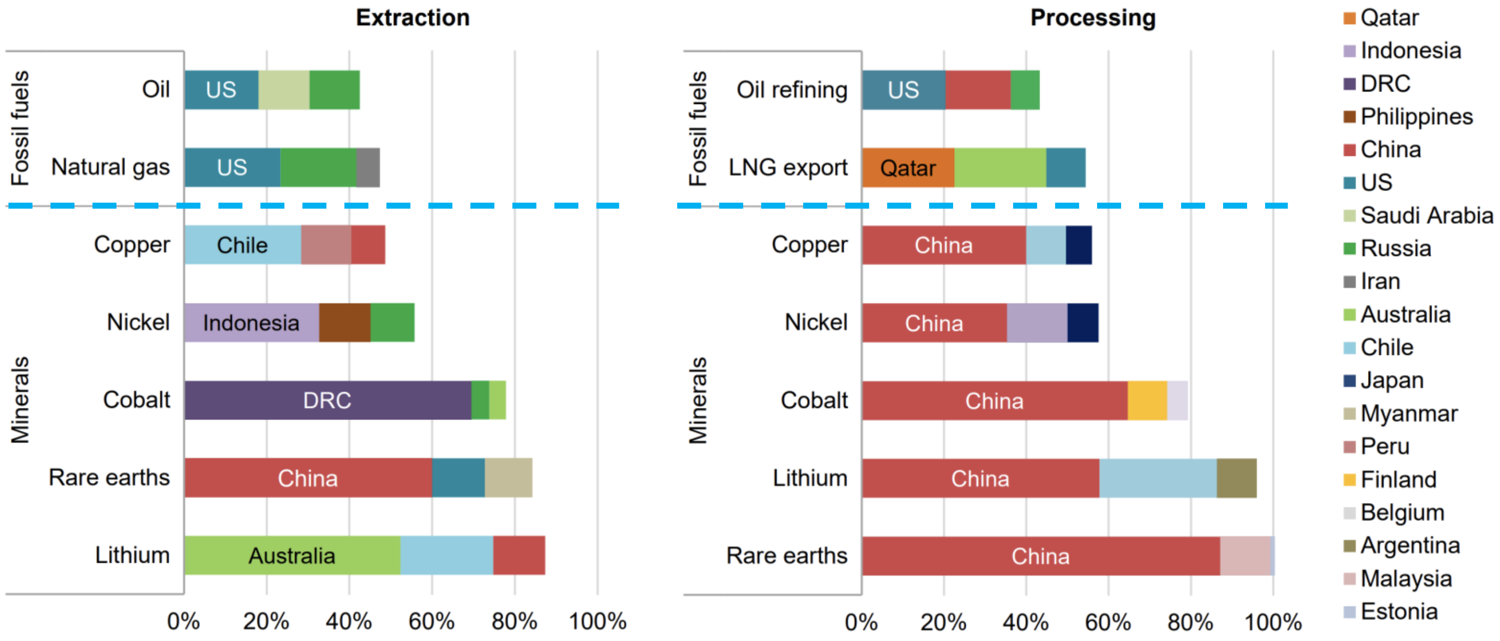

Source: nature

Source: Green IT Solution

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

# Remark: Critical Minerals

- Production of selected minerals critical for the clean energy transition



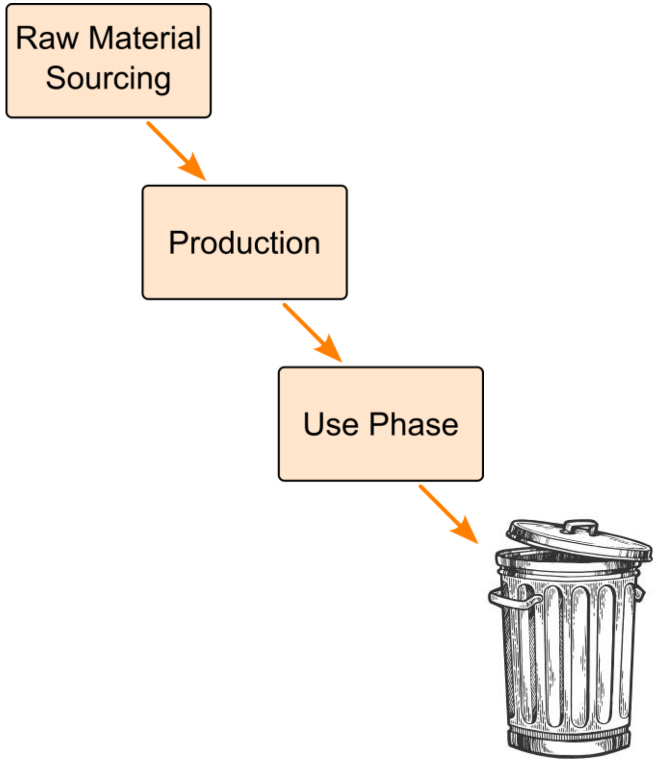

Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

- Extraction & processing more geographically concentrated than for oil & gas (!)

# The Paradigm Shift

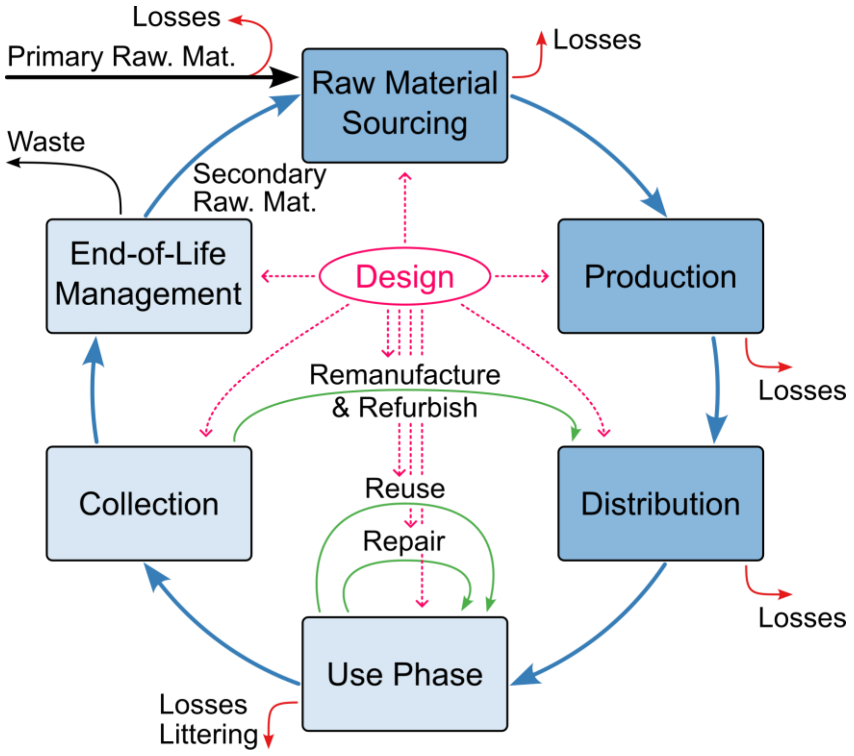
## ■ Linear Economy

- Take – make – dispose




## ■ Circular Economy

- Perpetual flow of resources




- Resources returned into the product cycle at end of life

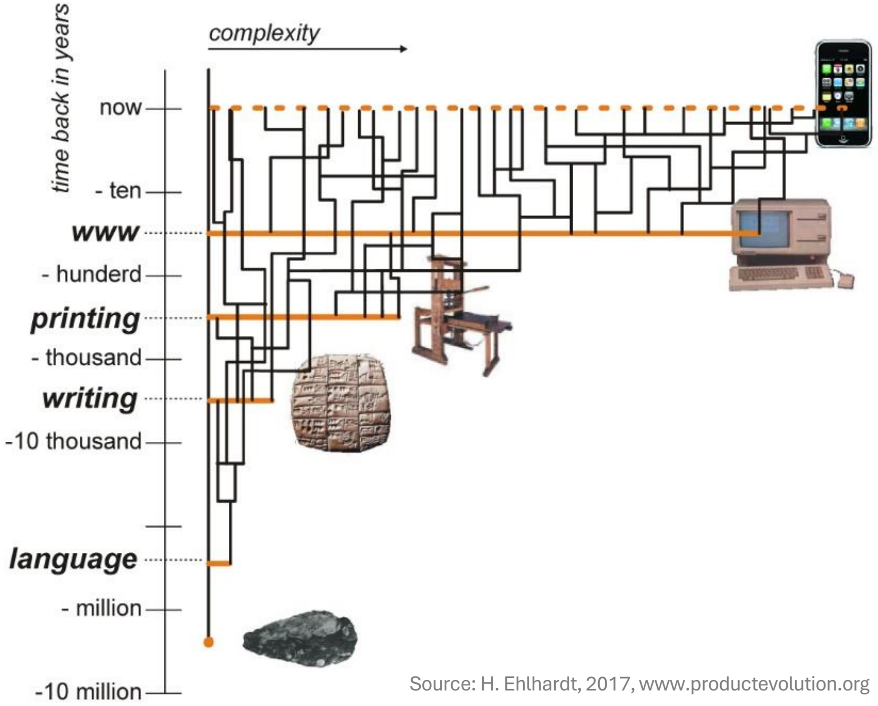
# Remark: Policymaking / Regulations / Standardization

- **European Green Deal**
  - Circular Economy Action Plan
  - Net-Zero Industry Act
  - Critical Raw Materials Act
  - Environmental Footprint Methods
  - Right to Repair
  - Ecodesign for Sustainable Products Regulation
  - ...

- **Standardization (Examples)**
  - ISO 14040/14044 Life-cycle assessment
  - ISO 14067 Carbon footprint of products
  - ISO 4555x Ecodesign and material efficiency
  - IEC 62430 Environmentally conscious design for el. & electron. products
  - IEC 61800-9-1/2 Ecodesign for drive systems
  - ...

# Complexity Challenge

- Technological innovation — Increasing level of complexity & diversity of modern products
- Exponentially accelerating technological advancement (R. Kurzweil)


Source: H. Ehlhardt, 2017, www.productevolution.org

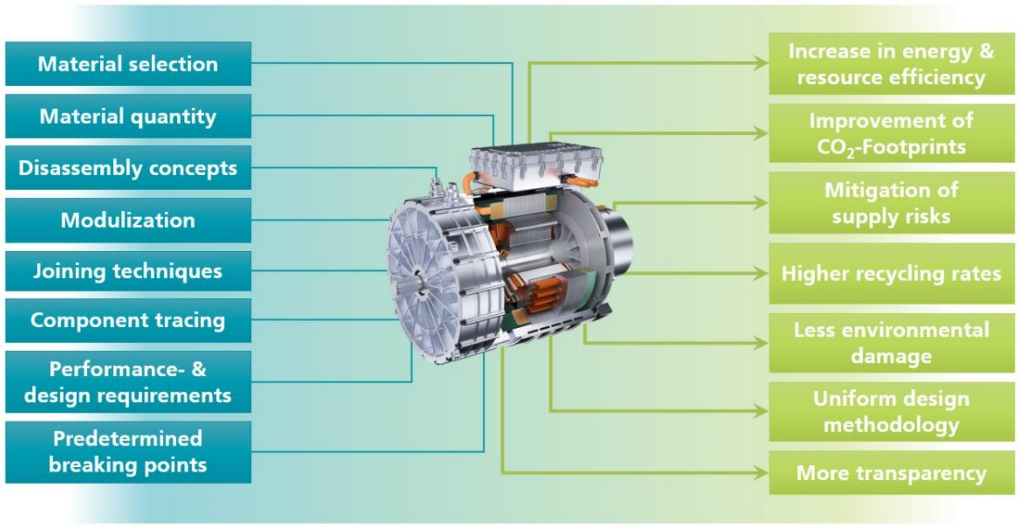
- Ultra-compact systems / functional integration — Major obstacle for material separation!?

# 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/

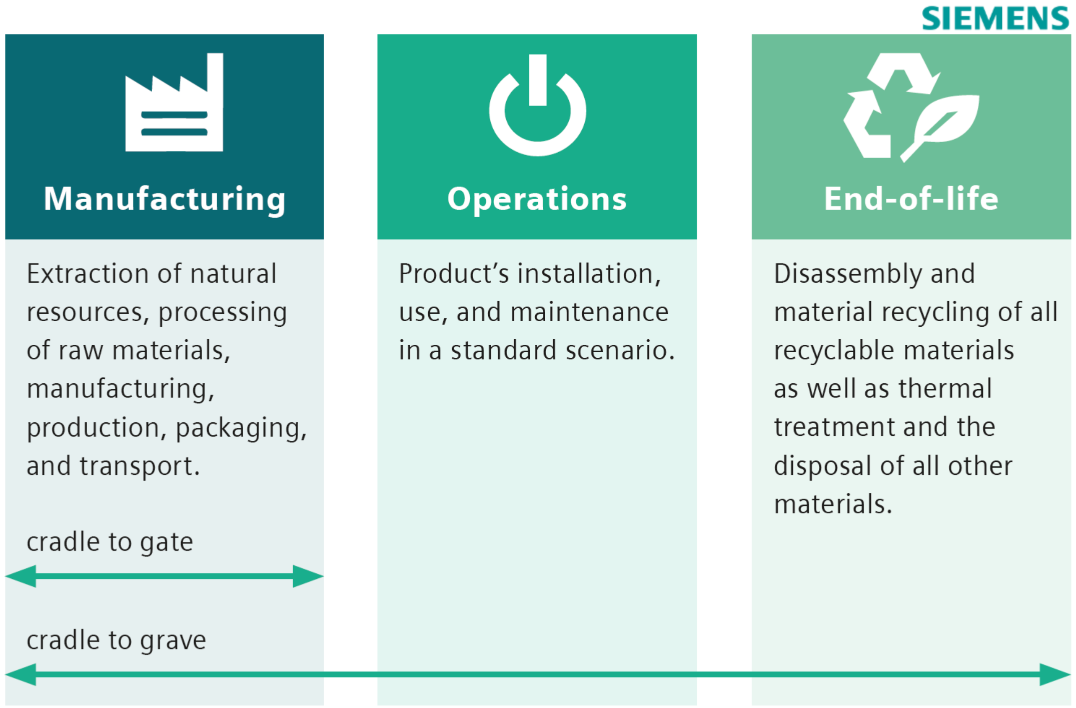
Source: DLR




- FAIRPHONE — Modular design / man. replaceable parts / 100% recycl. of sold products / fairtrade materials
- "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: Life Cycle Assessment (1)

- **Quantification / benchmarking of eco-design & circular economy approaches**

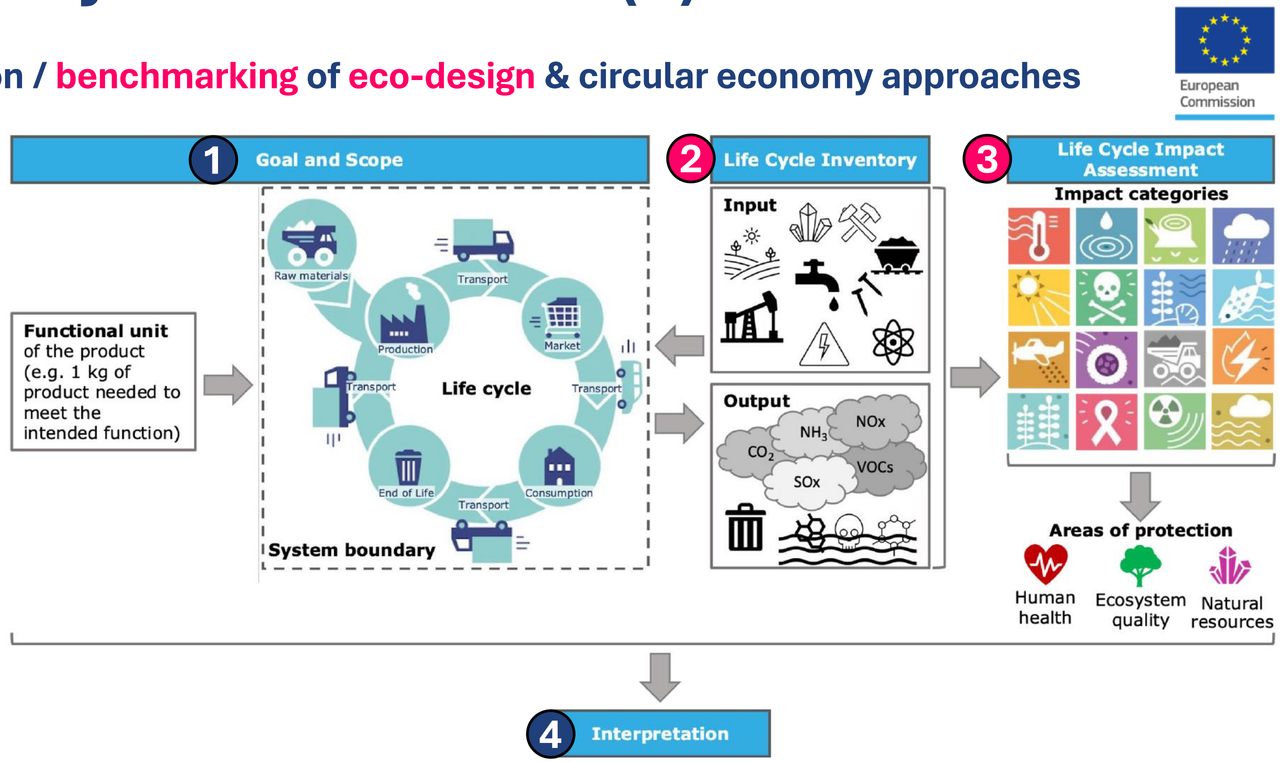



- **Scope of LCA can include**
  - **All** life-cycle phases (**cradle to grave**) or
  - **Individual** life-cycle phases (**cradle to gate** or gate to gate)

Image source: SIEMENS AG, "Ecodesign: Multiplying impact, shaping the world." 2023.
https://assets.new.siemens.com/siemens/assets/api/uuid:f7d929ad-971f-44df-ac51-7783cc28dac7/Ecodesign-WP.pdf

# LCA: Life Cycle Assessment (2)

- Quantification / benchmarking of eco-design & circular economy approaches




**2 LCI – Life Cycle Inventory**
Compilation & quantification of inputs and outputs for a product throughout its life cycle

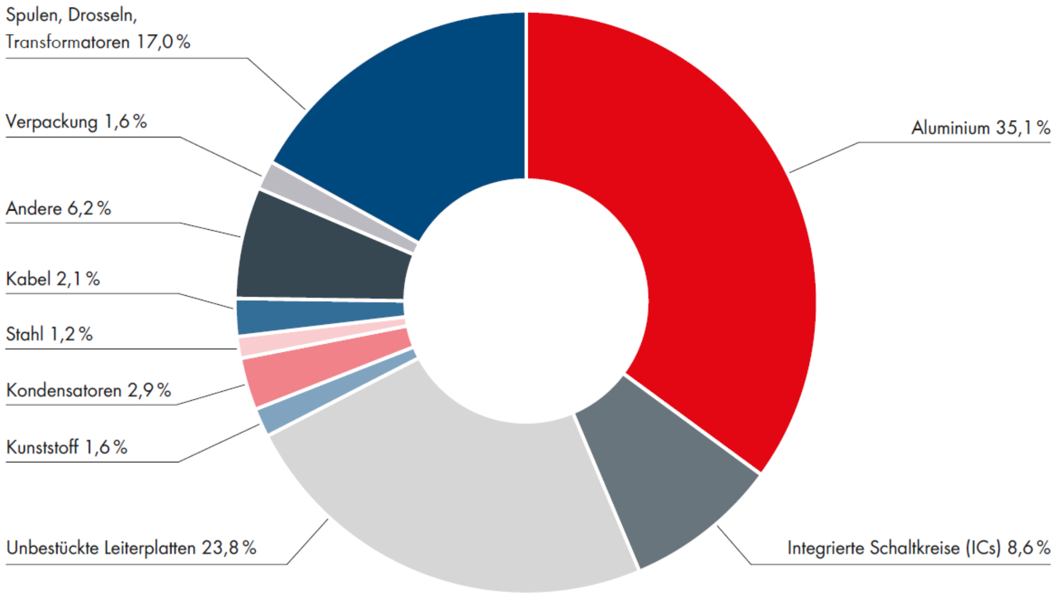
**3 LCIA – Life Cycle Impact Assessment**
Assignment of LCI results to (environmental) impact categories / Aggregation involves weighting factors & value choices

Source: M. Damiani, N. Ferrara, and F. Ardente, "Understanding product environmental footprint and organisation environmental footprint methods," Publications Office of the European Union, Luxemburg, JRC129907, 2022. https://data.europa.eu/doi/10.2760/11564

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

- Production phase / embodied carbon footprint of 903 kg $CO_2$eq (15…20% of life-cycle carbon footprint)
- Use phase contributes >80% to life-cycle carbon footprint (conversion losses & standby/night consumption)


**_Embodied Carbon Footprint_**

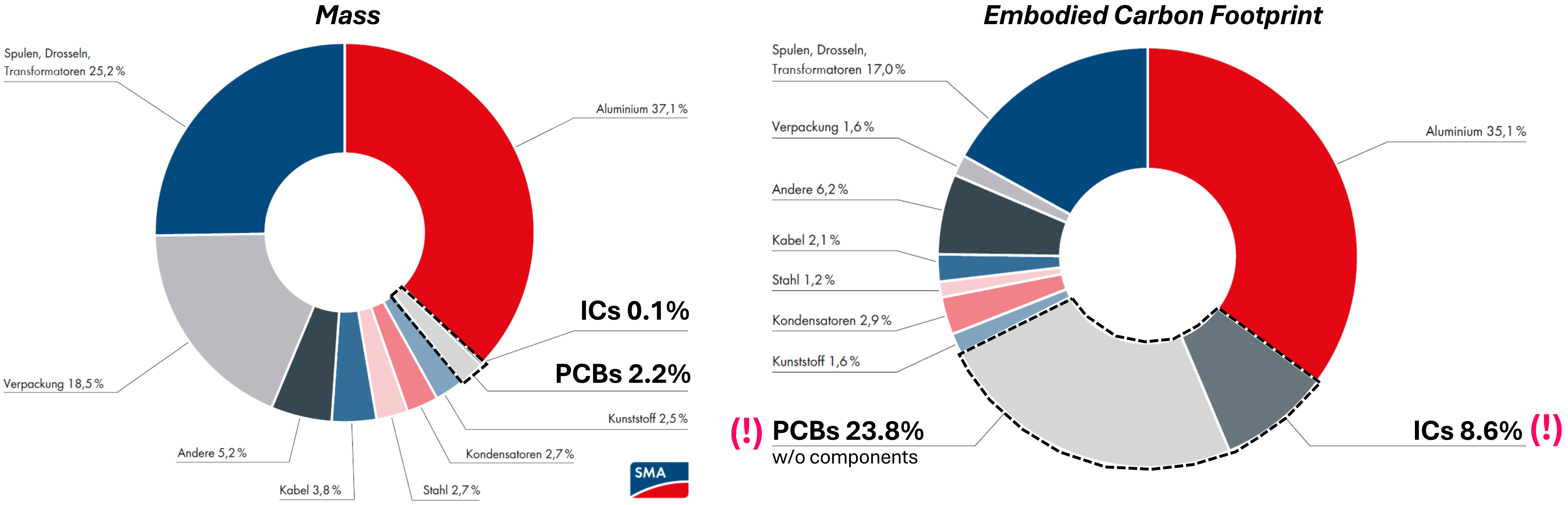



- 150 kW rated power for typ. 225 $kW_p$ PV system

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

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

- Production phase / embodied carbon footprint of 903 kg $CO_2$eq (15…20% of life-cycle carbon footprint)
- Use phase contributes >80% to life-cycle carbon footprint (conversion losses & standby/night consumption)




- Small / lightweight components with large contributions to carbon footprint (!)

# Carbon Footprint is Not Enough!

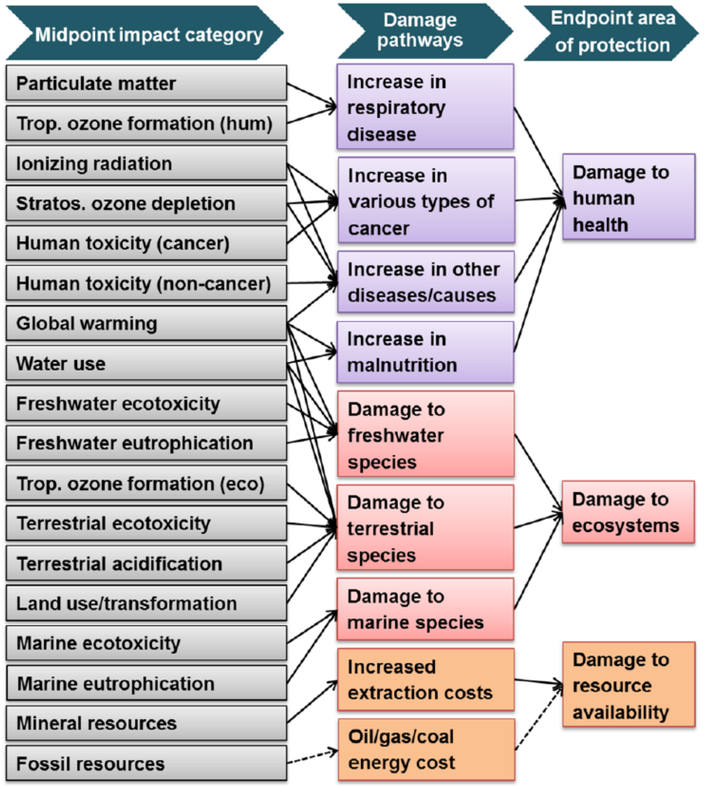
- Life cycle impact assessment (LCIA) phase of LCA — Environmental profile w. wide range of perf. indicators

- 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 ($)

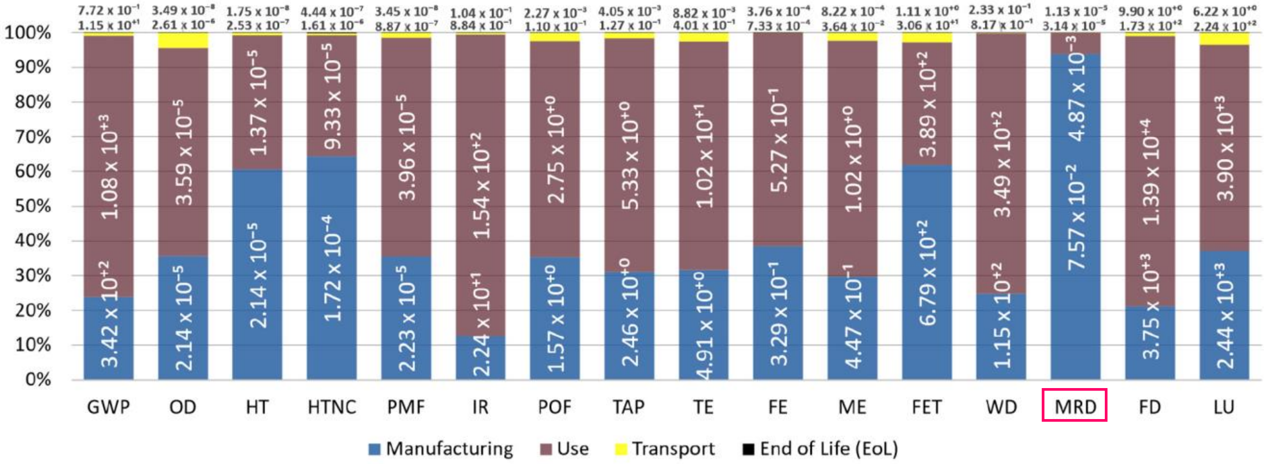


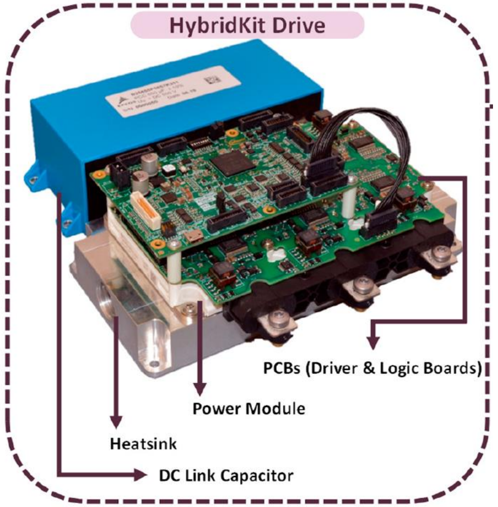
Source: Huijbregts et al., ReCiPe 2016 v1.1 Report

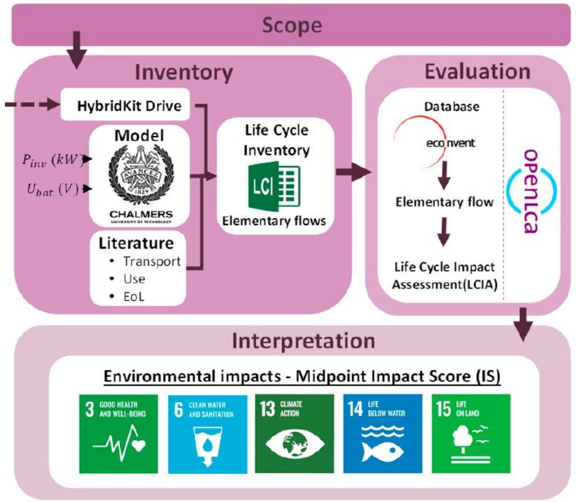
- Value choices (individualist / hierarchist / egalitarian) affect time horizon, included effects, etc.
- Alternative frameworks like EU Environmental Footprint (EF 3.1) exist

# LCA Example: 150-kW EV Drive Inverter (1)

- 150-kW inverter, 450 V DC bus 15 years / 10’000 operating hours w. avg. 97% efficiency (WLTP driving cycle)
- 16 Impact categories: EU Product Environmental Footprint (PEF)
  - **GWP:** Climate change (carbon footprint)
  - **MRD:** Resource use, minerals and metals,
  - …



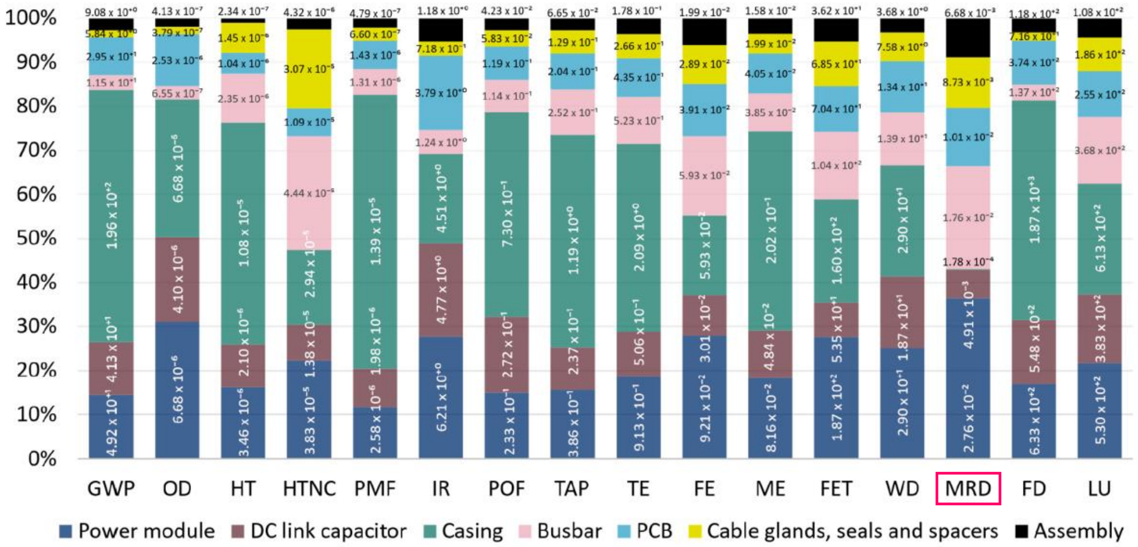



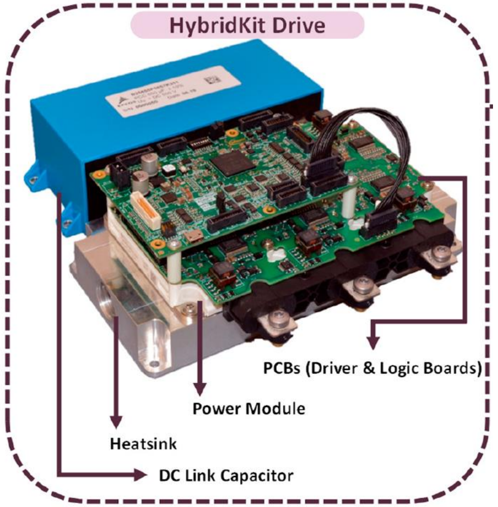

- Production and use phase dominate all indicators

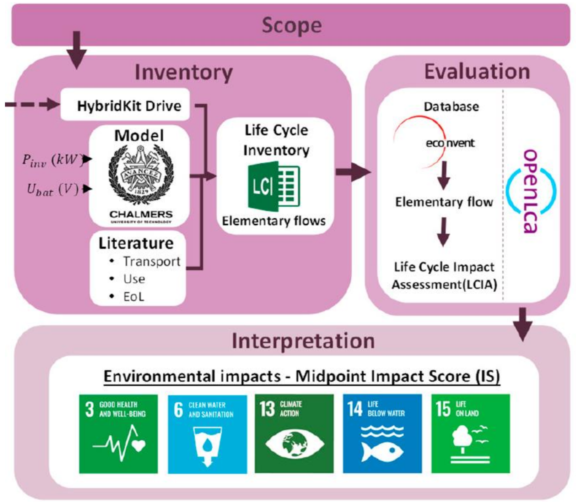
Source: B. Baudais, H. Ben Ahmed, G. Jodin, N. Degrenne, and S. Lefebvre, “Life cycle assessment of a 150 kW electronic power inverter,” *Energies,* vol. 16, no. 5, Art. no. 5, Jan. 2023, doi: 10.3390/en16052192.

# LCA Example: 150-kW EV Drive Inverter (2)

- **150-kW inverter, 450 V DC bus 15 years / 10’000 operating hours w. avg. 97% efficiency (WLTP driving cycle)**
- **16 Impact categories: EU Product Environmental Footprint (PEF)**
  - **GWP:** Climate change (carbon footprint)
  - **MRD:** Resource use, minerals and metals
  - …




- **Detailed breakdown of component contributions to prod. phase**

Source: B. Baudais, H. Ben Ahmed, G. Jodin, N. Degrenne, and S. Lefebvre, “Life cycle assessment of a 150 kW electronic power inverter,” *Energies,* vol. 16, no. 5, Art. no. 5, Jan. 2023, doi: 10.3390/en16052192.

# New Holistic Design Procedure

Multi-Objective Optimization with Environmental Impacts as New Performance Indicators

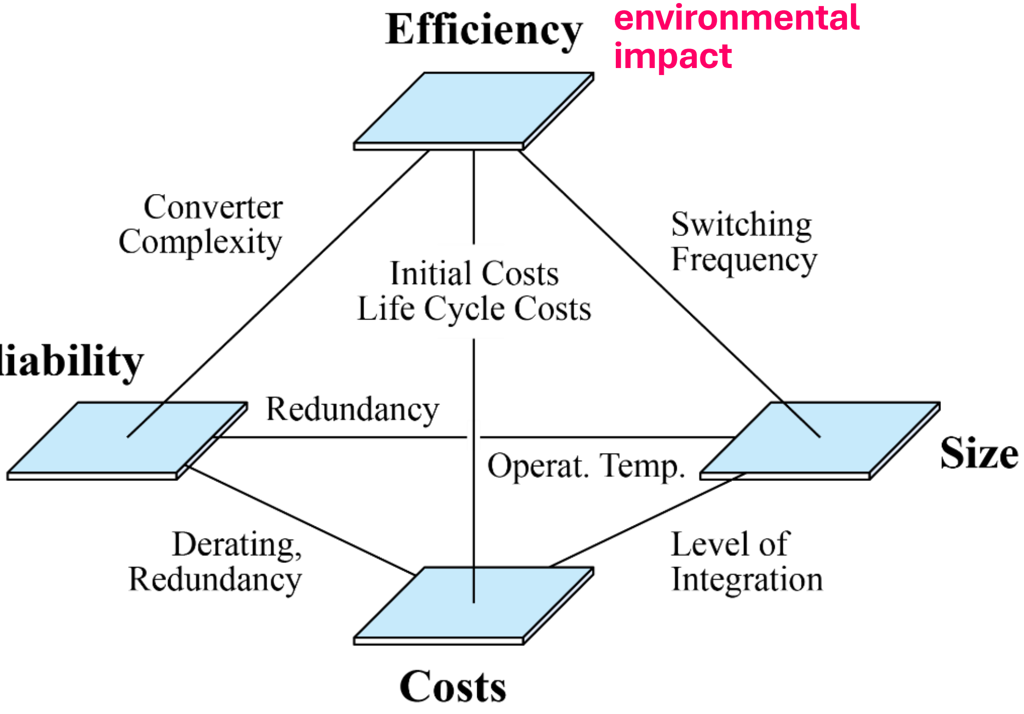
# System Design Challenge

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

Use-phase environmental impact

Lifetime / Replacements

Embodied environmental impact



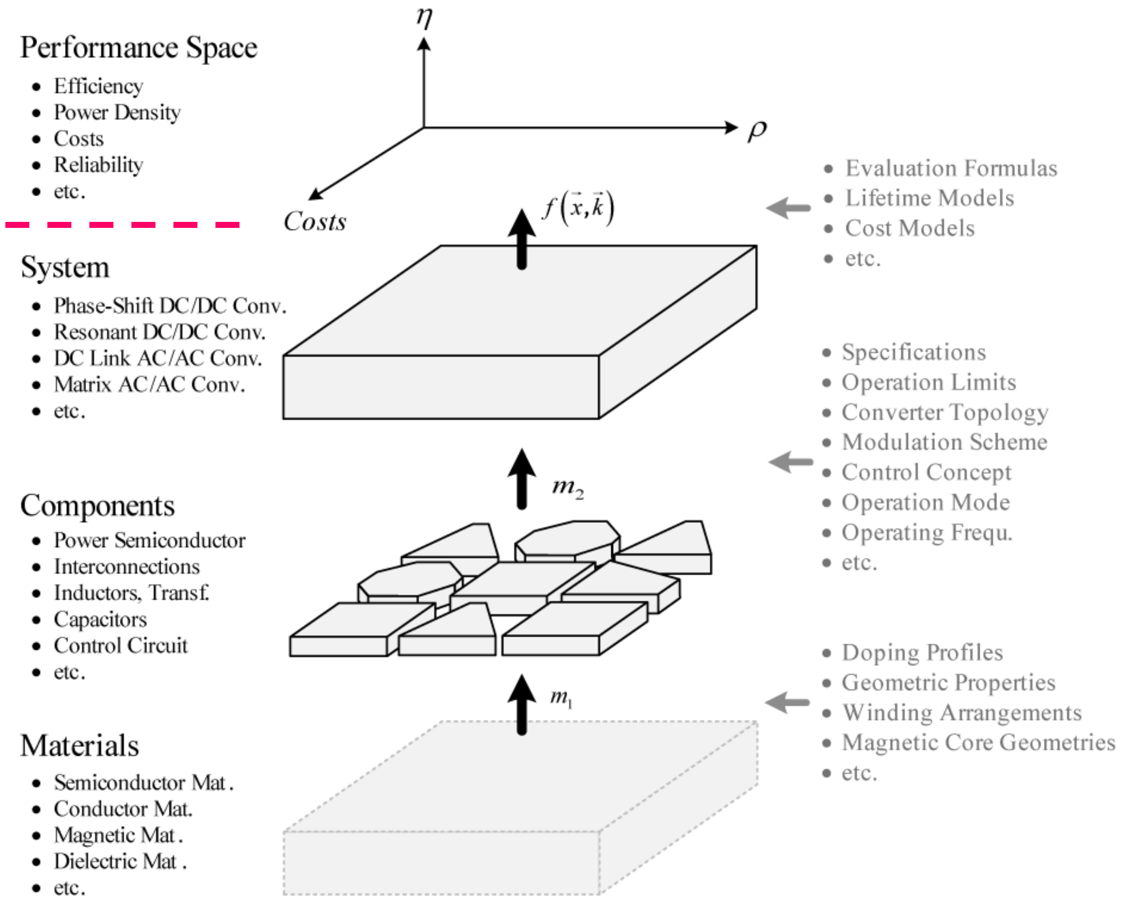

- **For optimized systems, it is not possible to improve several perf. indicators *simultaneously***

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

Performance space

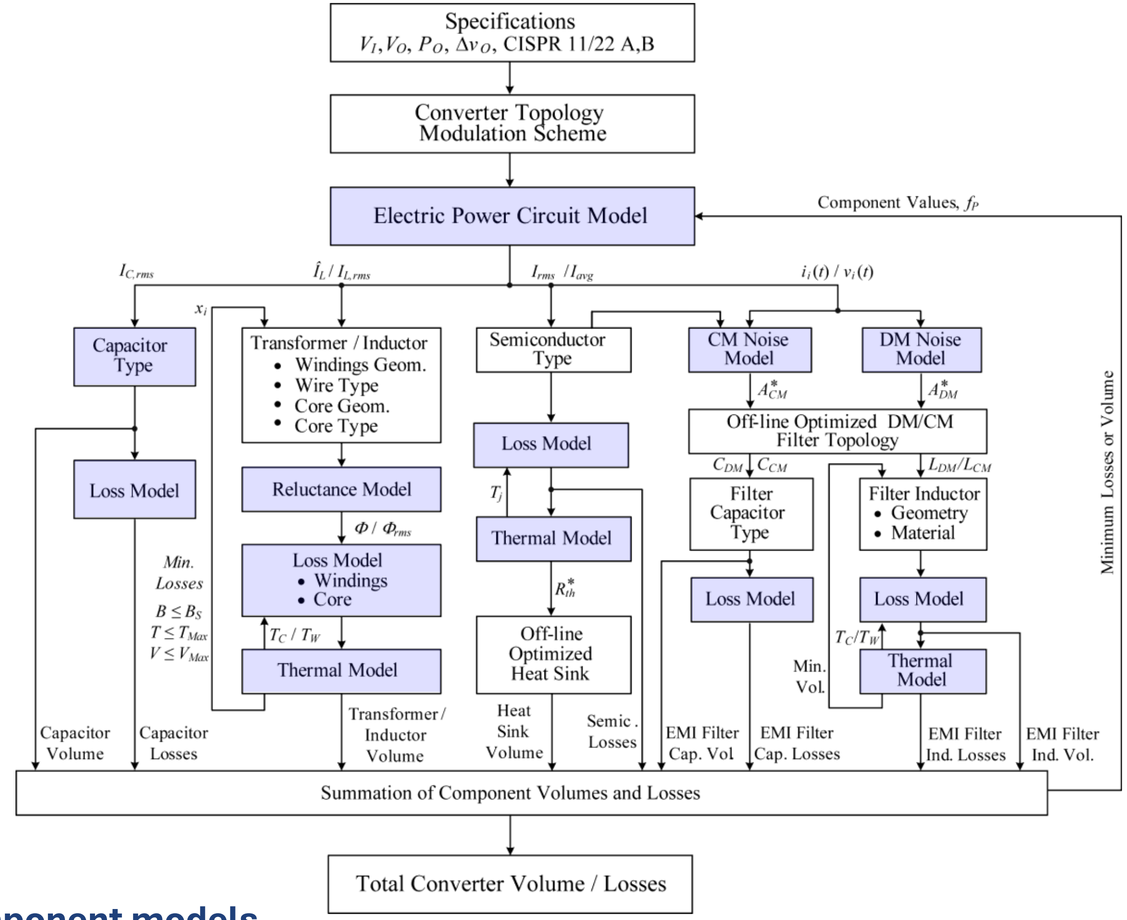
Design space




- 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.

# Modeling of Converter Designs

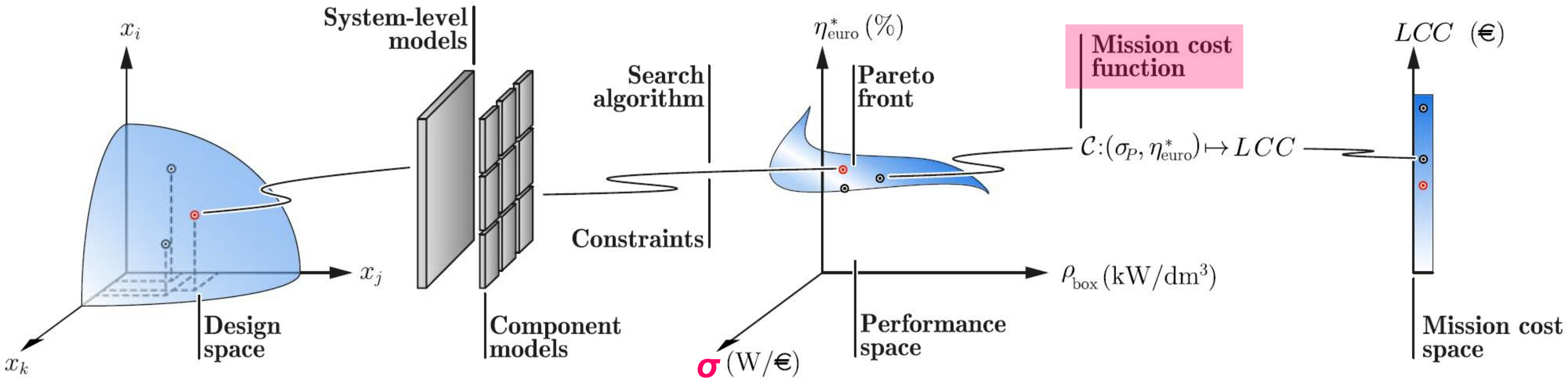



- System/circuit & component models
- Iteration over all combinations of design degrees of freedom

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* (!)**

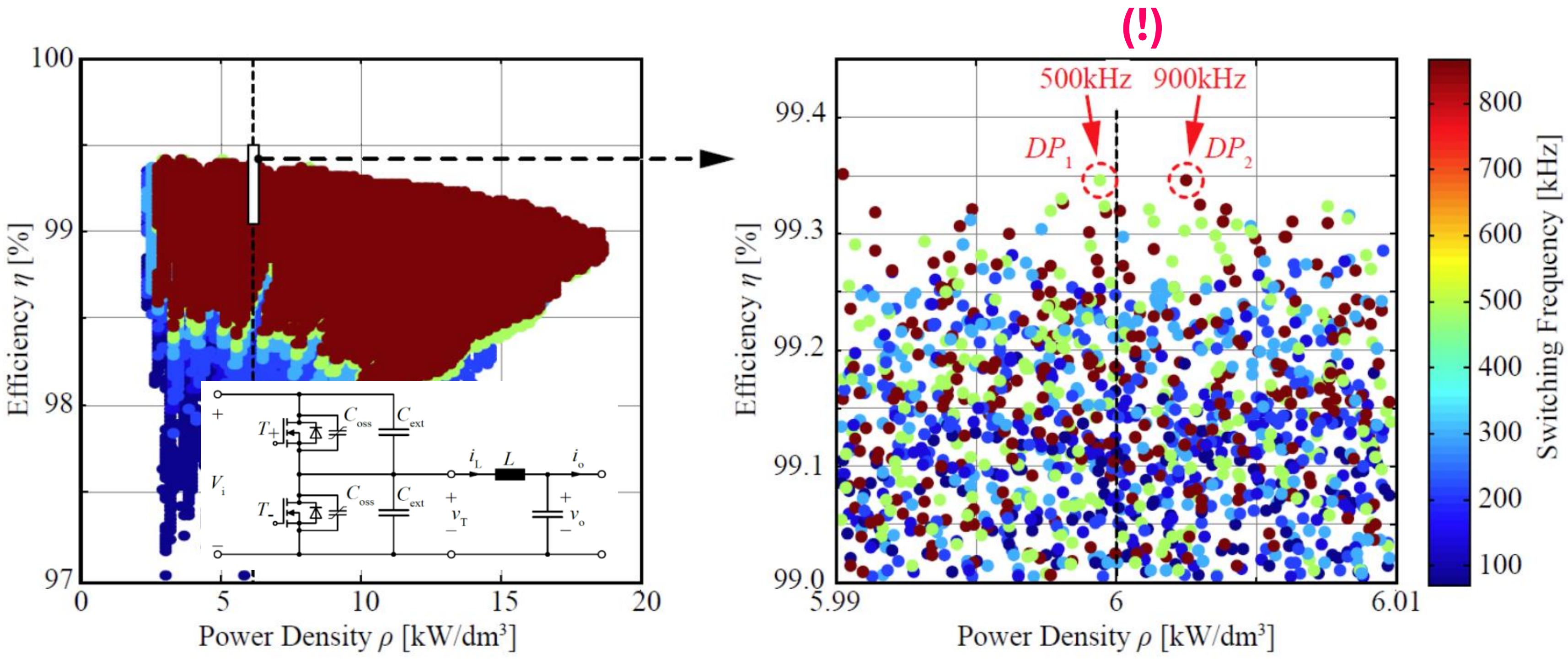



- **Typically considered performance indices:**
  - **η** Efficiency in %
  - **ρ** Volumetric power density in kW/dm$^3$
  - **γ** Gravimetric power density in kW/kg
  - **σ** **Cost density in W/€**

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**



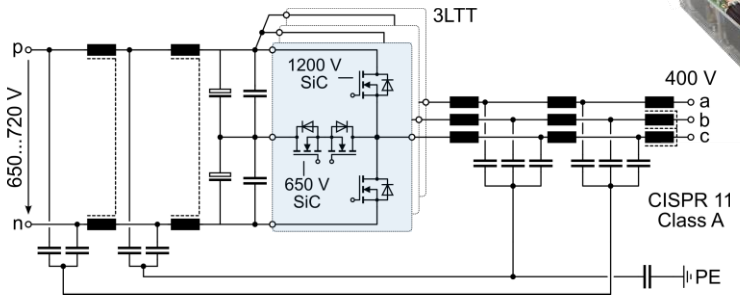

- Example: Google Littlebox design optimization w. PWM operation / Mutual comp. of HF and LF loss contrib.

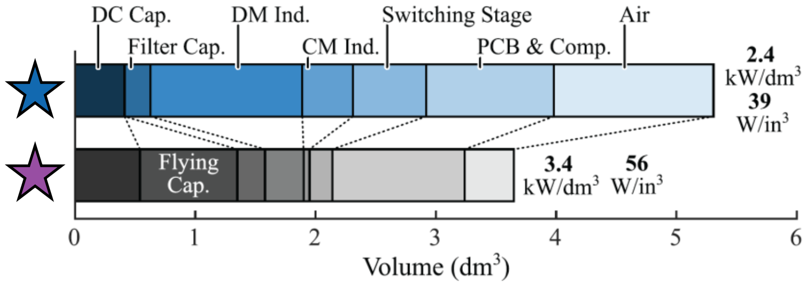
Source: J. W. Kolar, D. Neumayr, D. Bortis, M. Guacci, and J. Azurza Anderson, "Google Little-Box Reloaded," *Keynote at the 10th Int. Conf. Integr. Power Electron. (CIPS)*, Stuttgart, Germany, Mar. 2018.

# Design Space Diversity: 3L & 7L PV Inverters

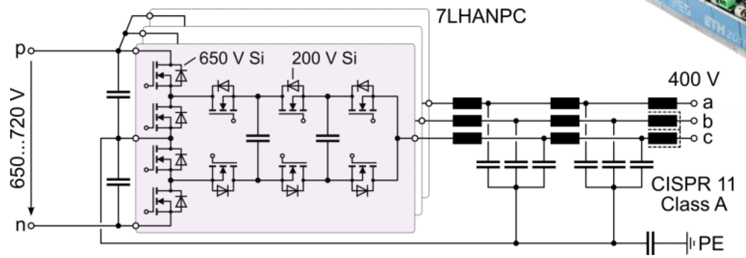
- **Two concepts / similar specs — 12.5 kW, 650...720 V DC, CISPR 11 Class A — Similar perf. ($\eta_{CEC}$ = 99.1%)**

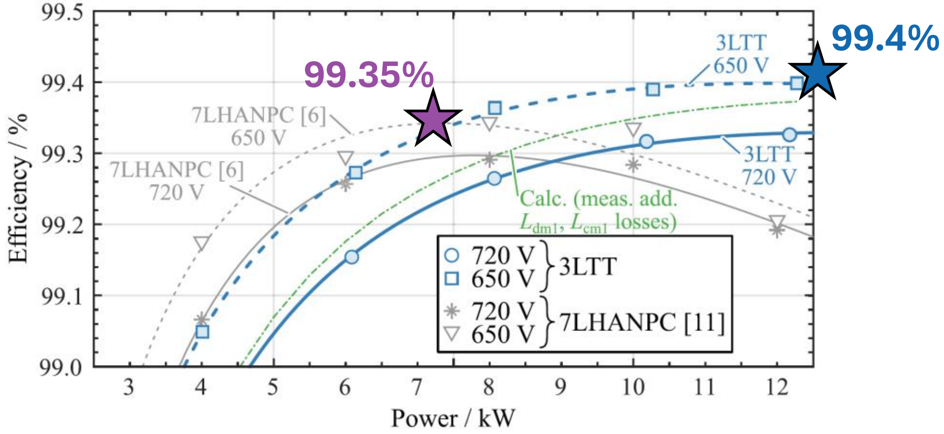
***3-Level All-SiC T-Type PV Inverter***
99.4%, 2.4 kW/dm$^3$




***7-Level All-Si HANPC PV Inverter***
99.35%, 3.4 kW/dm$^3$



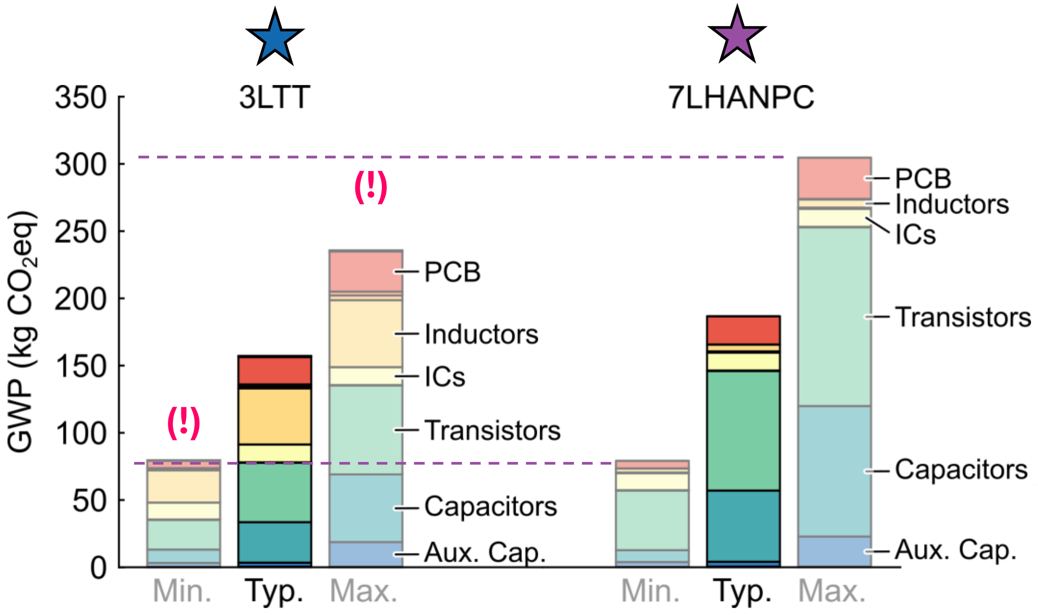

- **Differences in environmental impact?**

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. ($\eta_{CEC}$ = 99.1%)

2.4 kW/dm$^3$, 11.8 kg



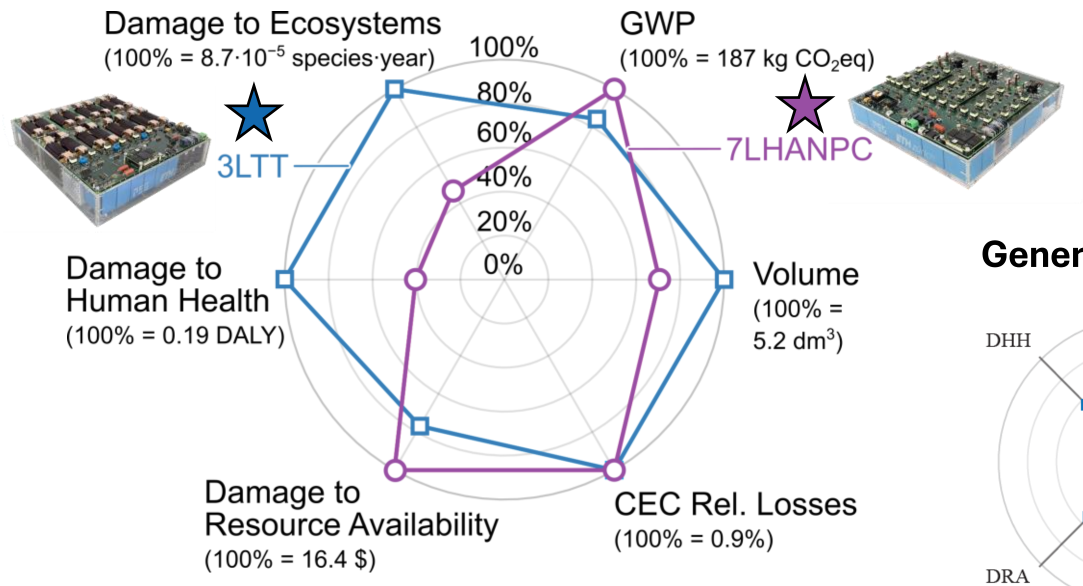

**GWP:** Global Warming Potential

3.4 kW/dm$^3$, 4.6 kg

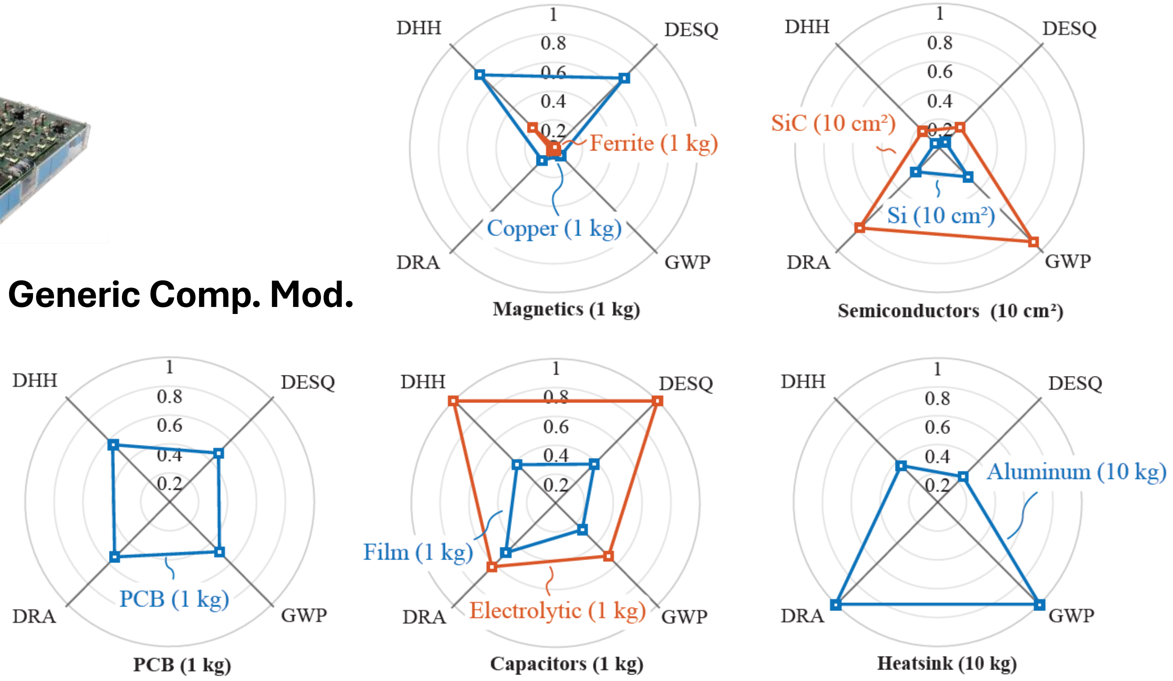
- Generic comp. models / ecoinvent database & lit. → Widely varying embodied carbon footprint (GWP) res. (!)
- Data availability / quality as key challenge!

# *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. ($\eta_{CEC}$ = 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.**



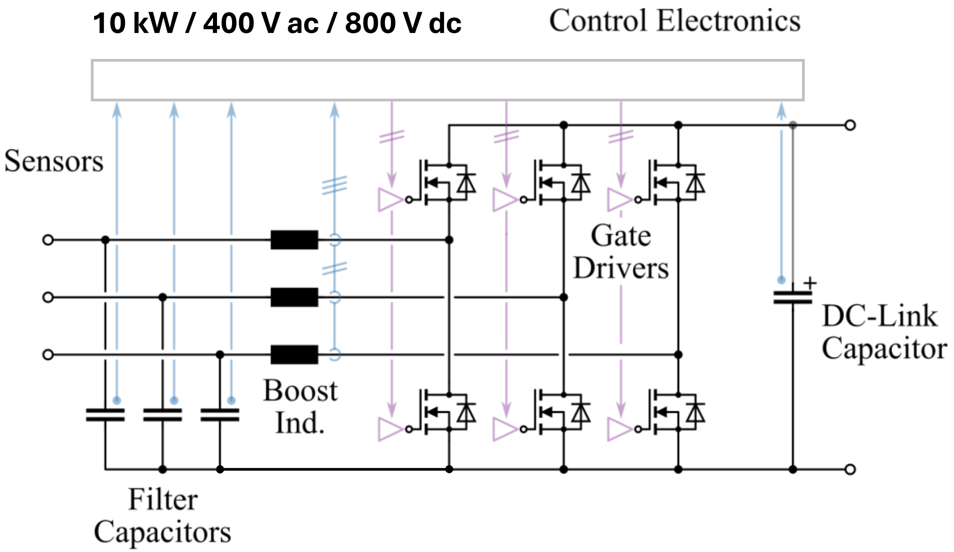

Normalized scales due to ecoinvent licensing restrictions.

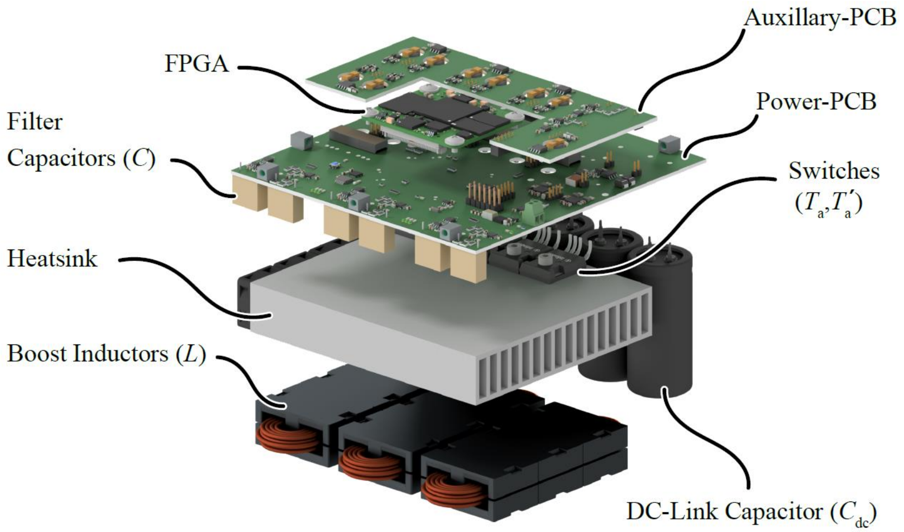
- **Environmental footprint of converter as aggregate of components' environmental footprints**

## A Priori Consideration of Environmental Impacts in the Design Process?

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

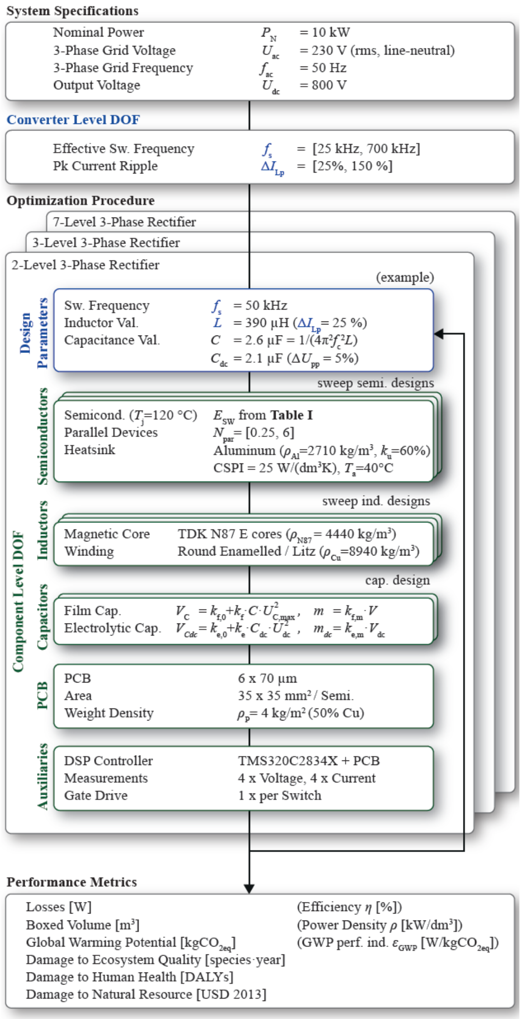
- Key power electronic building block (PEBB) for three-phase PFC rectifiers & inverters

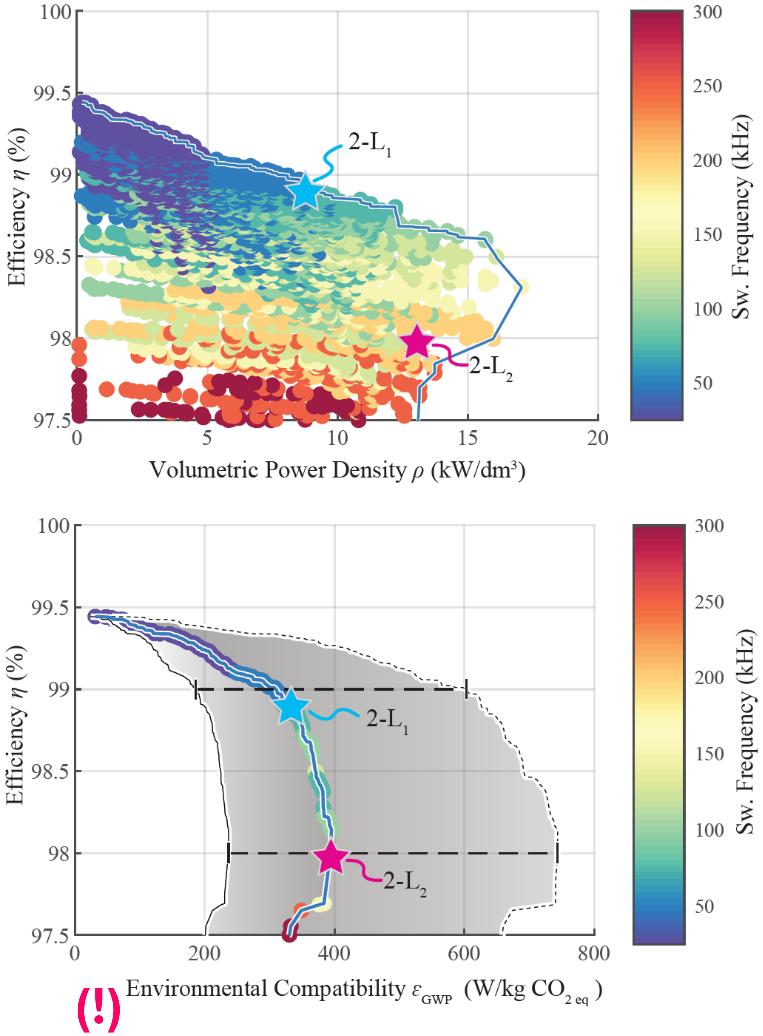



- **Degrees of freedom:**
  - Switching freq. [25...700 kHz]
  - Rel. Ind. Peak cur. ripple [0.25...1.5]
  - Var. transistor chip area
  - Variable ind. size (N87; solid/litz)
- **Assumptions:**
  - Junction temp. @ 120 °C
  - Ambient temp. 40 °C
  - Necessary heat sink vol. via CSPI = 25 W/(K dm$^3$)

# Multi-Objective Optimization Including Env. Impacts (1)

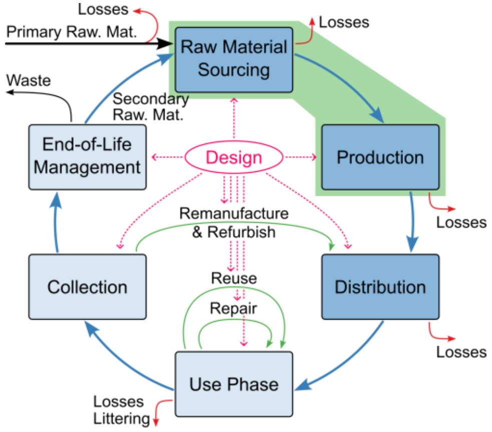


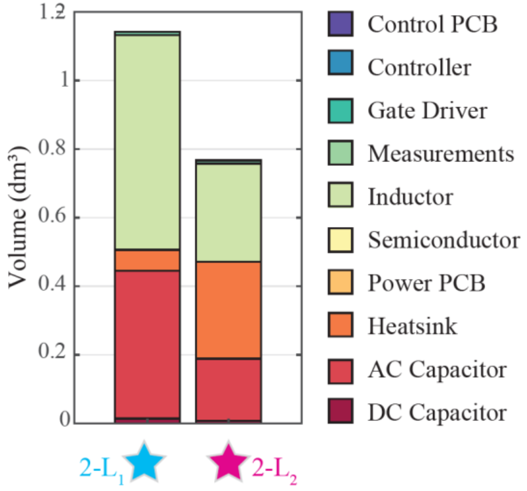

## Trade-Offs

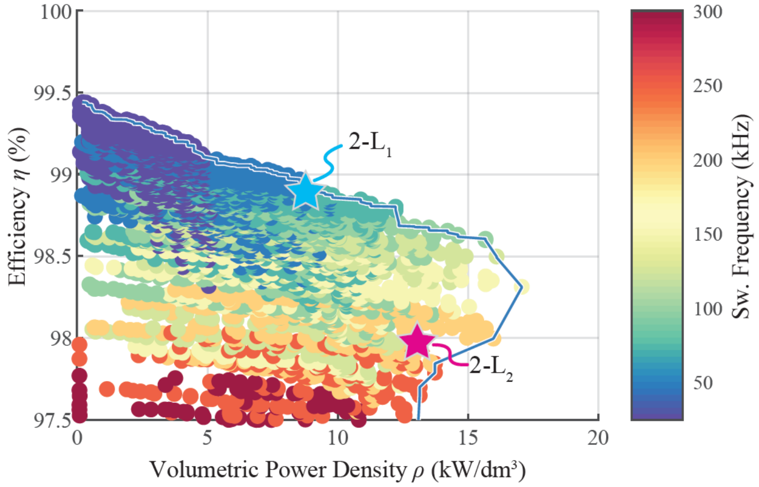
- Efficiency vs. power density
- Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)

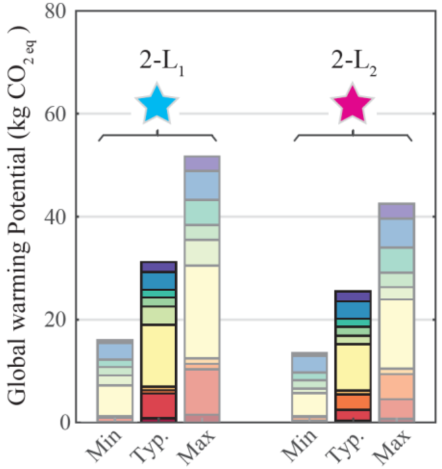
## Env. Impacts with high uncertainties due to data availability/quality

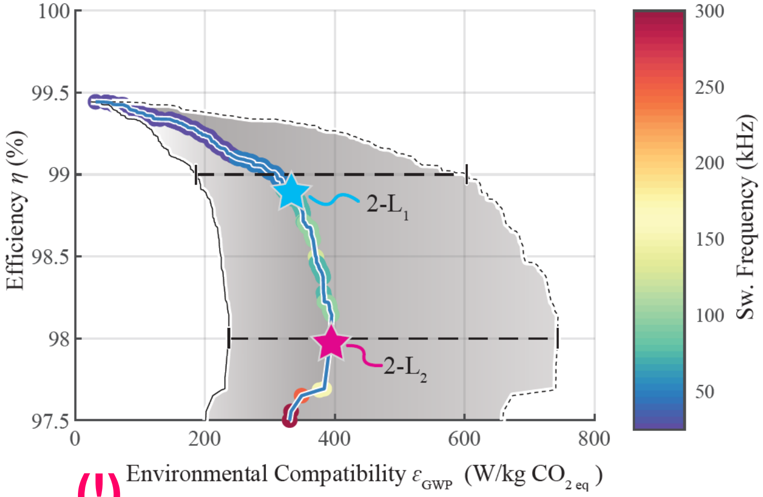


# Multi-Objective Optimization Including Env. Impacts (2)



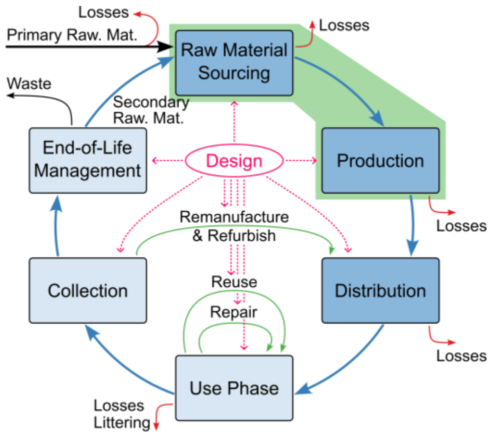



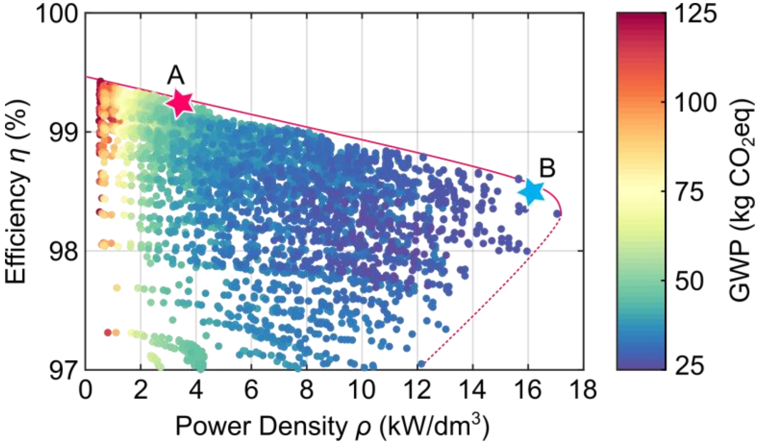

(!)

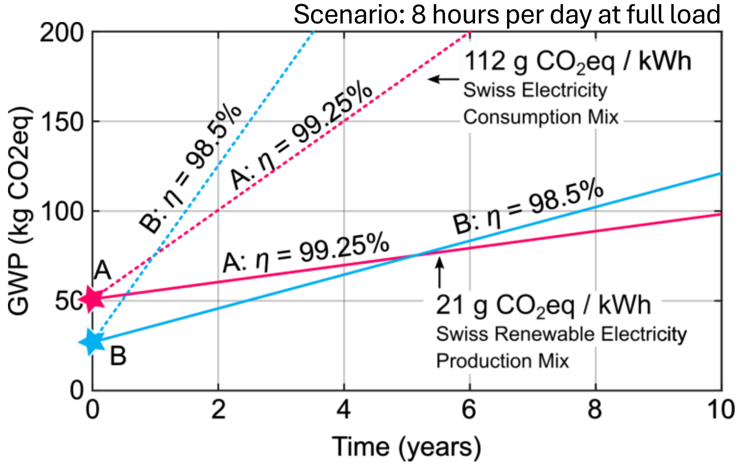
- **Trade-Offs**
  - Efficiency vs. power density
  - Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)
- **Env. Impacts with high uncertainties due to data availability/quality**



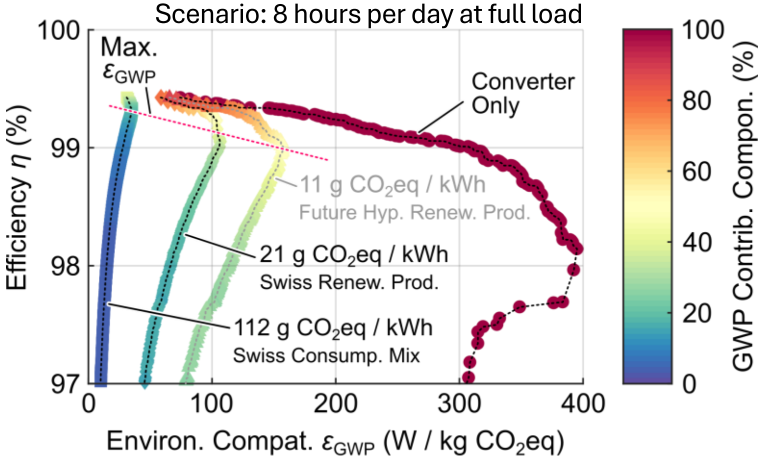
# Multi-Objective Optimization Including the Use Phase

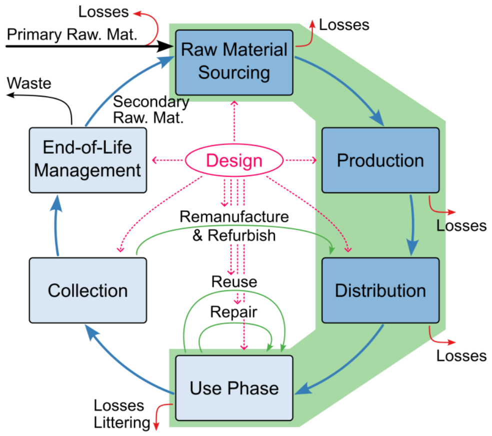
- **Life-cycle carbon footprint strongly depends on electricity mix and mission profile / usage intensity**




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



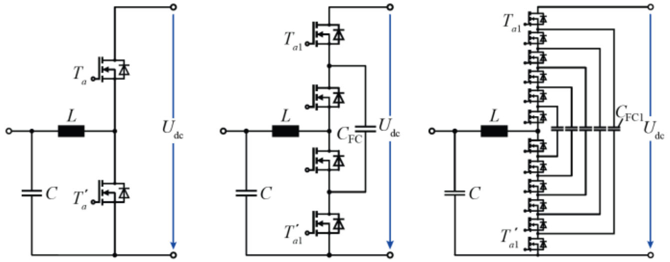



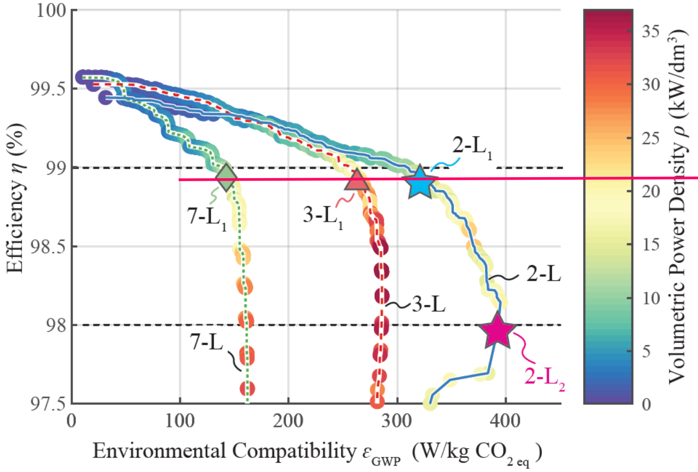
Power Electronic Systems Laboratory

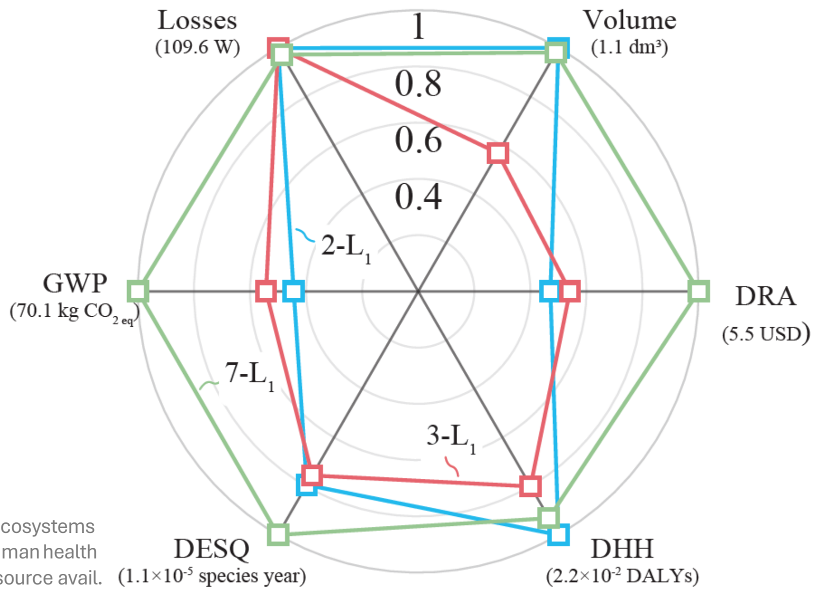
ETH zürich

# Comprehensive Environmental Impact Profiles

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



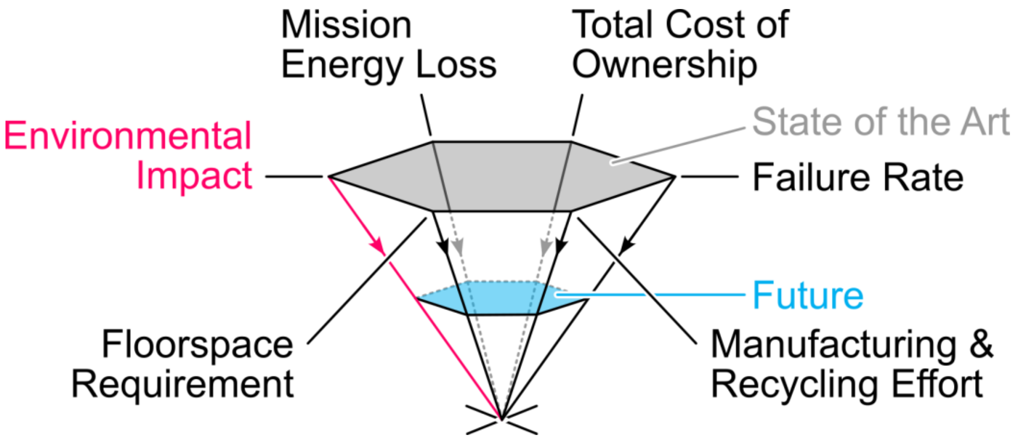

ReCiPe 2016:
DESQ—Damage to ecosystems
DHH—Damage to human health
DRA—Damage to resource avail.

- Embod. env. footprint of 2L/3L/7L-designs with $\eta \approx 99\%$ and max. env. compat. $\varepsilon_{GWP}$ in W / kg $CO_2$eq
- Same efficiency via different usage of act./pass. components — Different environmental impact profile!

# 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**

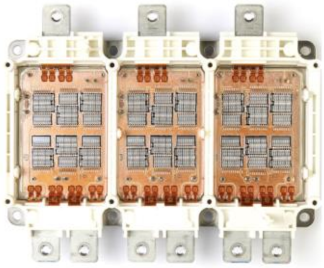
- **Complete set of new performance indicators**
  - Environmental impact [kg $CO_2$eq / kW, ...]
  - Resource efficiency [$kg_{xx}$ / kW]
  - Embodied energy [kWh / kW]
  - TCO [$ / kW]
  - Power density [$kW/dm^3$, $kW/dm^2$]
  - Mission efficiency [%]
  - Failure rate [$h^{-1}$]

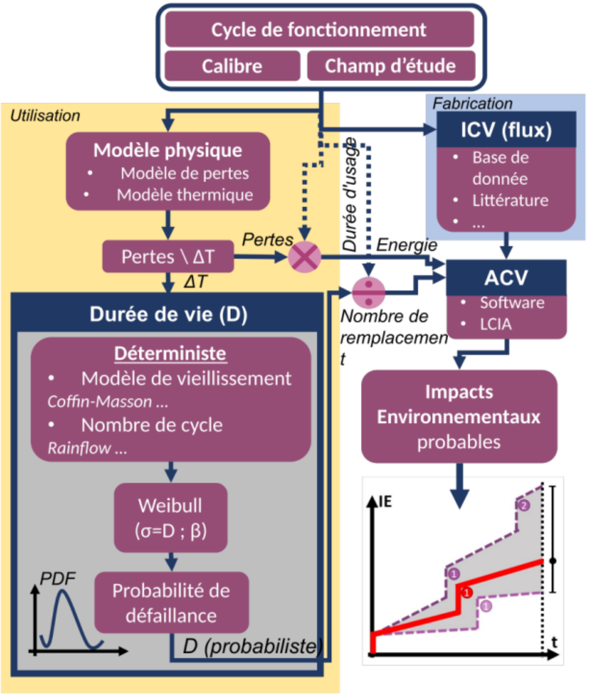


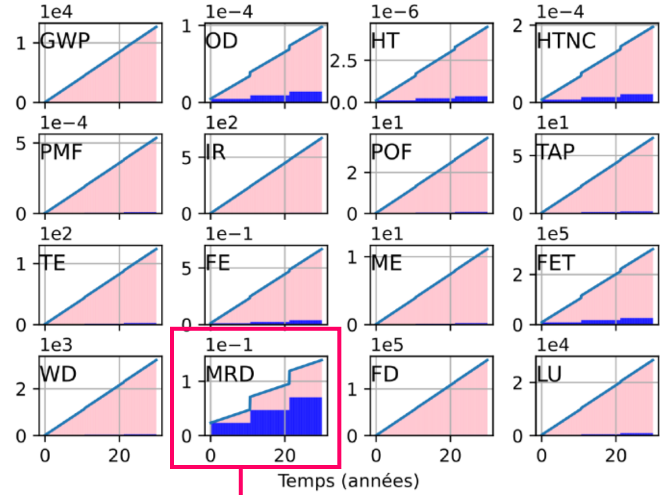

- **Mission/location-specific trade-off embod. vs. life-cycle environ. impact — Losses / Reliability / Lifetime**
- **Compatibility with a circular economy (!) — Repairability / Reusability / Recyclability**

# Remark: Ageing Modeling and Environmental Impacts (1)

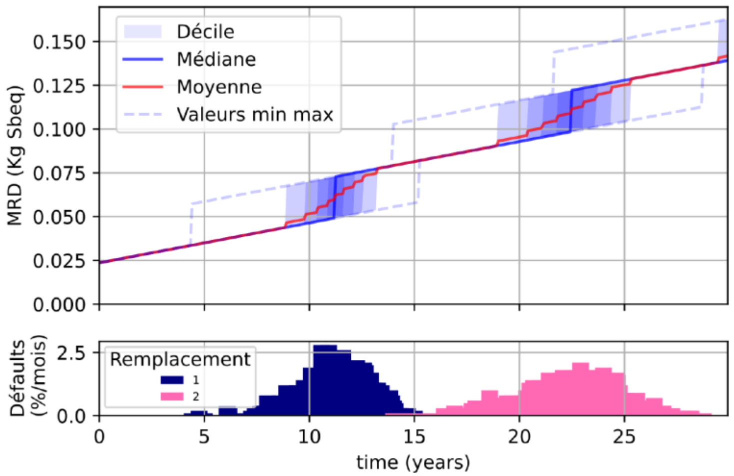
- IGBT module / 30 yr / 20’000 op. hours WLTP cycle
- Life-cycle environmental impacts with **(probabilistic) ageing models** (Coffin-Manson) & replacement
- Focus on **MRD — Resource use, minerals and metals**






**Deterministic Ageing Mod.**

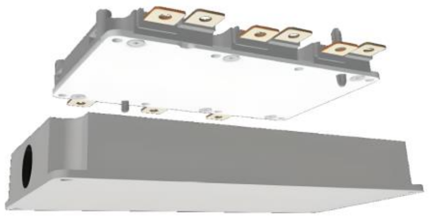


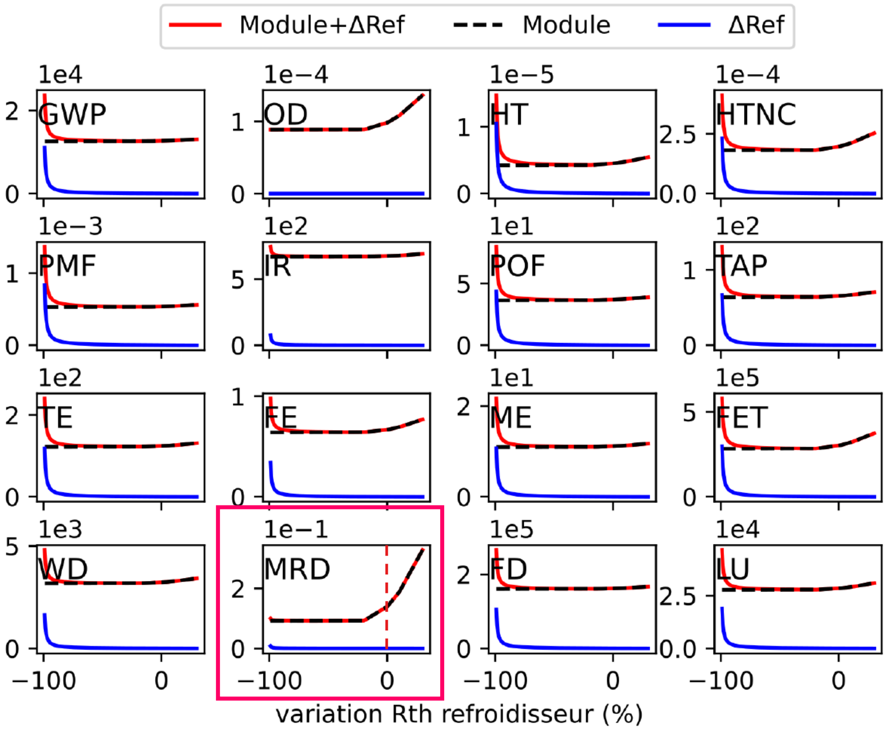

**Probabilistic Ageing Mod. (Weibull)**

Source: B. Baudais, H. Ben Ahmed, G. Jodin, N. Degrenne, and S. Lefebvre, “Influence des modèles de vieillissement sur les impacts environnementaux pour les composants d’électronique de puissance,” in Symposium de Génie Electrique (SGE2023), Lille, France, Jul. 2023. https://hal.science/hal-04189193

# Remark: Ageing Modeling and Environmental Impacts (2)

- Larger heat sink: Higher realization effort ↔ Lower temperatures and slower ageing
- IGBT module / 30 yr / 20’000 op. hours WLTP cycle



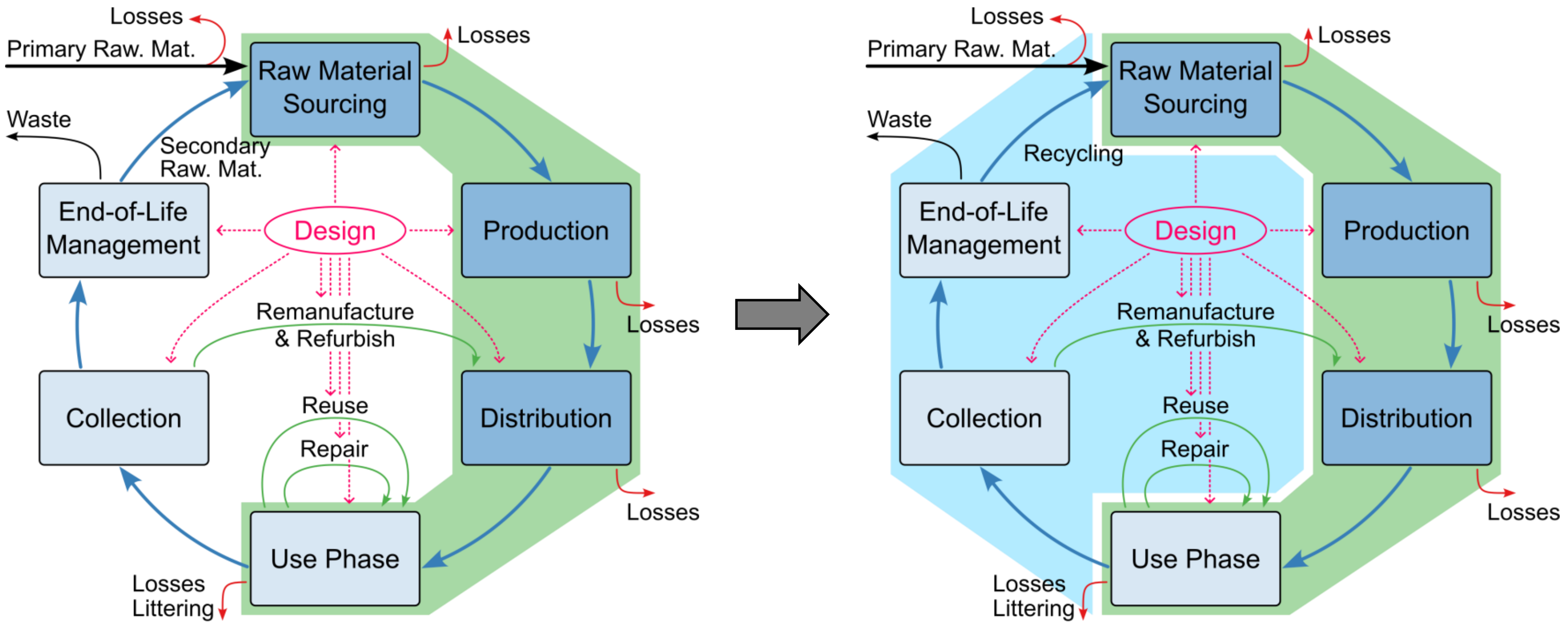



- Optimum thermal resistance $R_{th}$ (heat sink size) exists!

Source: B. Baudais, H. Ben Ahmed, G. Jodin, N. Degrenne, and S. Lefebvre, “Influence des modèles de vieillissement sur les impacts environnementaux pour les composants d’électronique de puissance,” in Symposium de Génie Electrique (SGE2023), Lille, France, Jul. 2023. https://hal.science/hal-04189193

# “Closing the Loop”

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

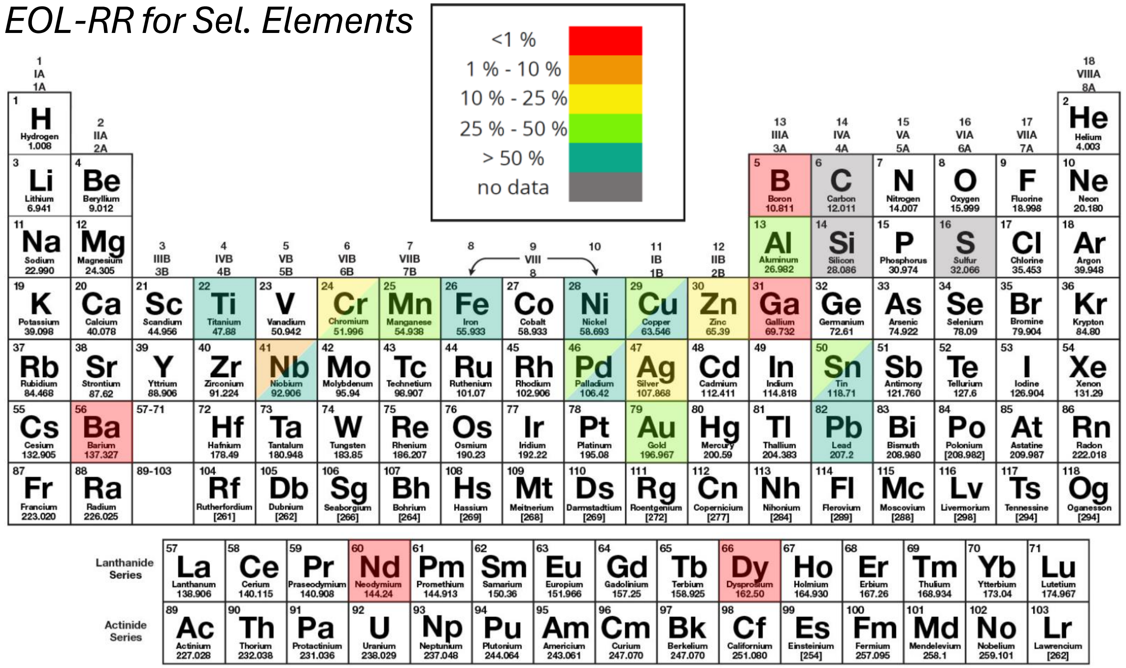


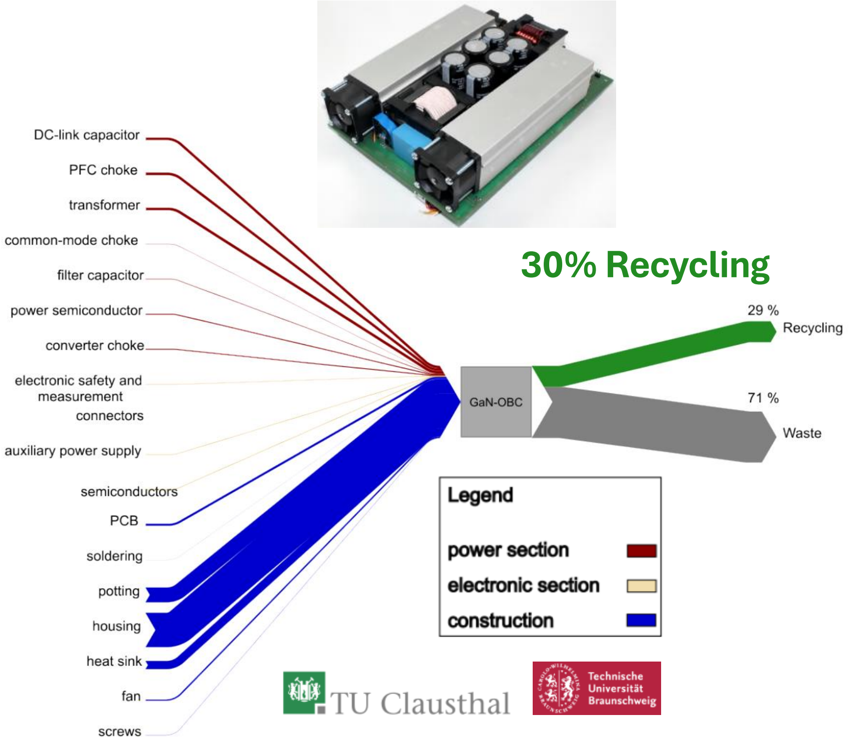

- How to quantify repairability / reusability / …?
- Value proposition through life-cycle cost perspective (suppliers *and* customers)?

# Recycling Potential of On-Board Chargers

- Theor. **best-case** mass-based **end-of-life recycling rates** (EOL-RR) for GaN-based 3.7-kW EV OBC

*EOL-RR for Sel. Elements*



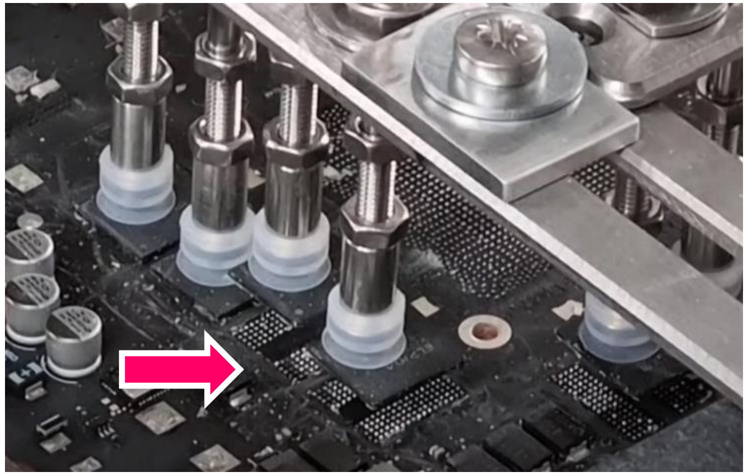

- Includes (currently) low typical collection rates
- EOL-RR data availability / quality: Only for metals, wide range of reported values

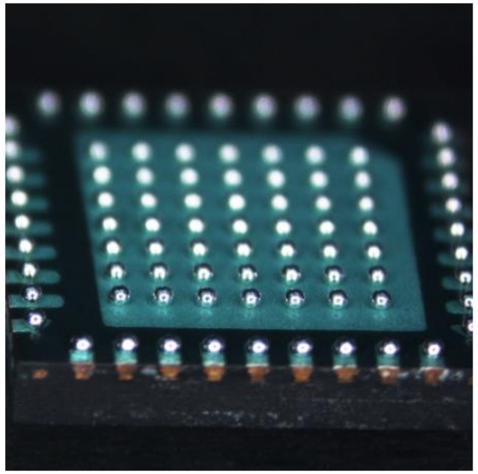
Source: C. Minke, R. Mallwitz, P. Burfeind, and D. Hu, "Recycling potential of power electronics solutions - an exemplary study about on-board chargers," in *Proc. 13th Int. Conf. Integrated Power Systems (CIPS)*, Düsseldorf, Germany, Mar. 2024.

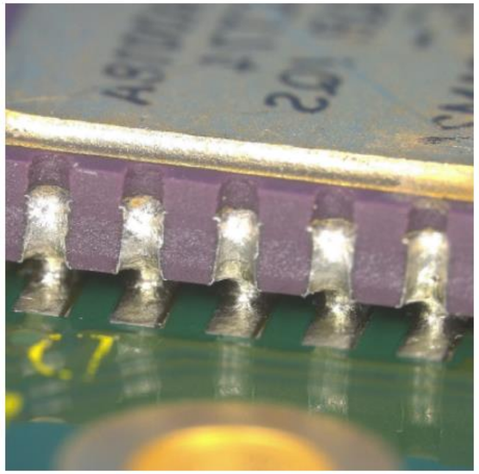
# Remark: Electronic Component Reclaim / Reuse

- Electronic waste recycling today: Shred / incinerate / extract most valuable resources — if at all!
- Alternative: Reclaim & refurbish / Desolder & re-ball

RETRONIX
A JABIL COMPANY





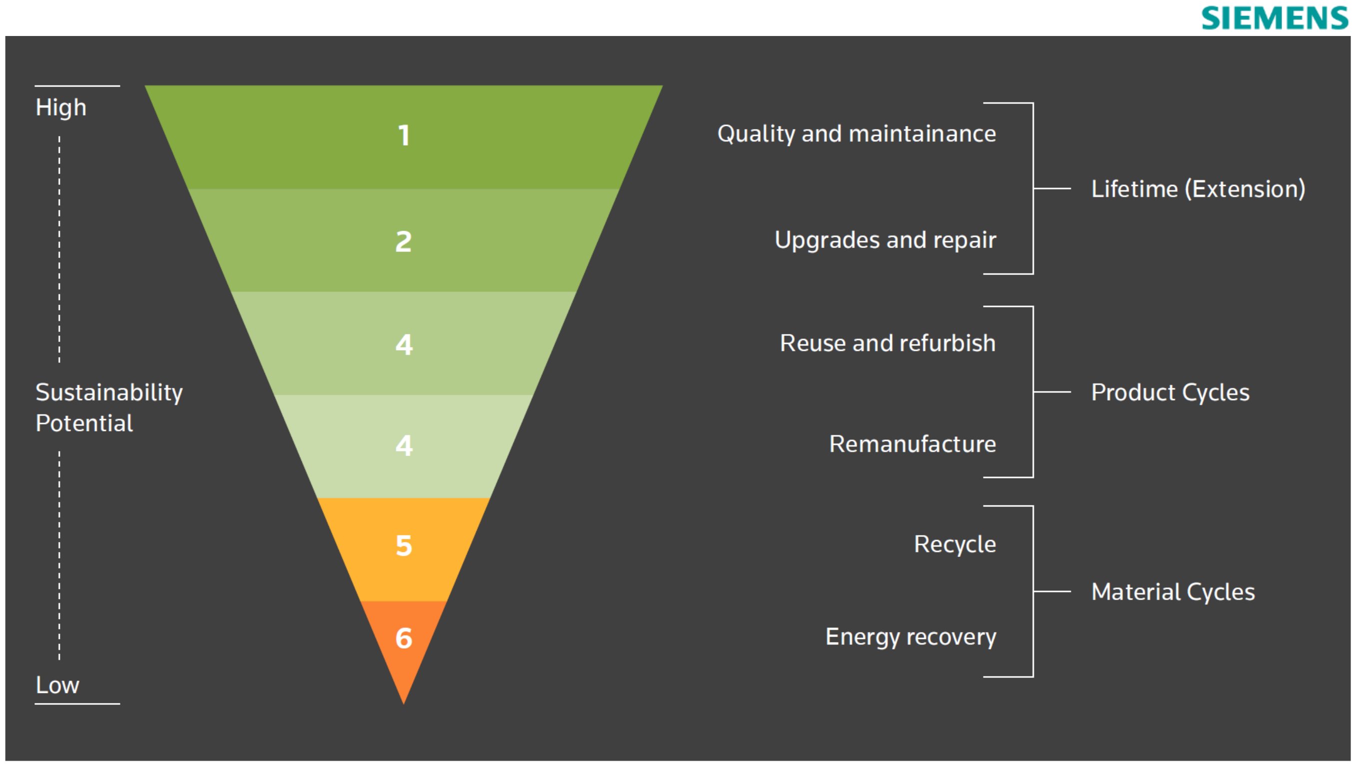


- Challenging logistics etc. for reclaiming PCBs from customers / Circular economy thinking needed
- Business case today especially for scarce / valuable components

Source: https://retronix.com/component-reclaim/

# Sustainability Potential

- 2nd ELLEN MACARTHUR FOUNDATION circular economy principle: Circulate products and materials at their highest values

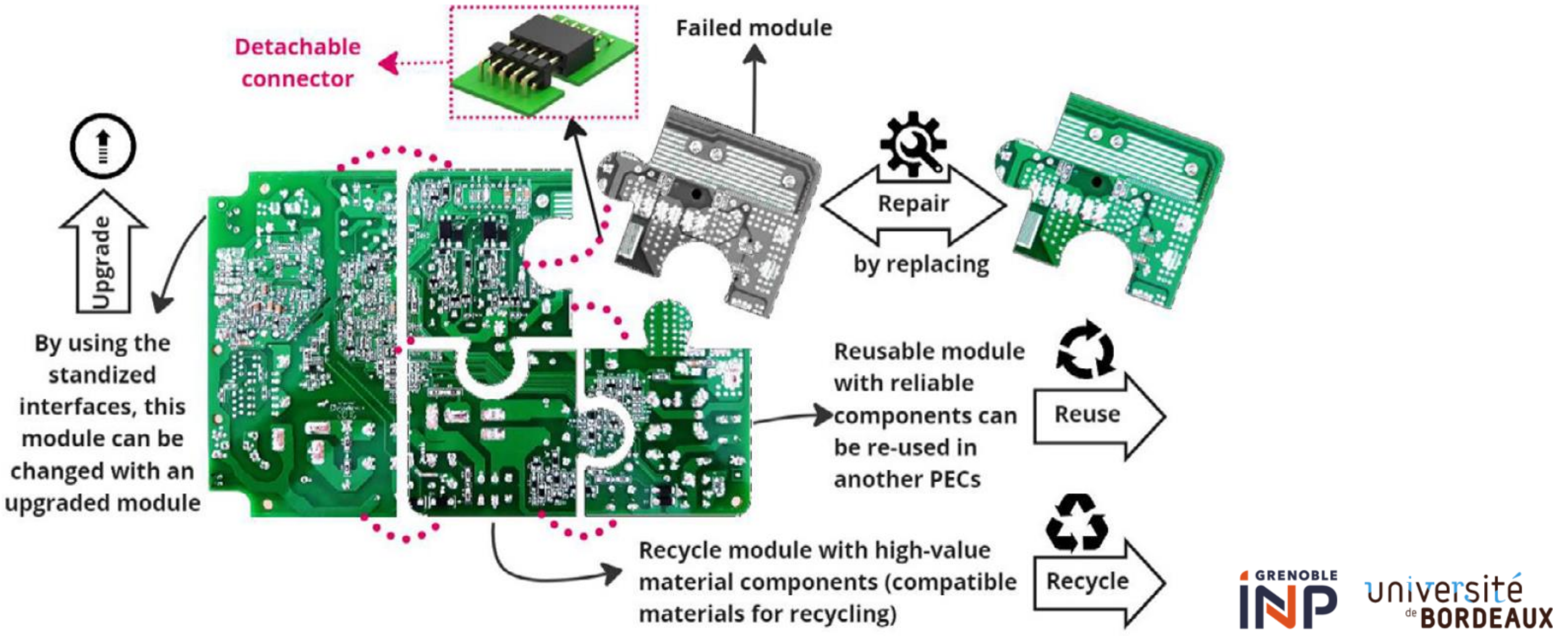



- High reliability / lifetime extension → Lifetime / aging modeling

Source: SIEMENS AG, "Towards a circular economy for industrial electronics." Reuters Events, Jun. 2023. https://www.siemens.com/global/en/company/about/businesses/smart-infrastructure/downloads-events/towards-a-circular-economy-for-industrial-electronics-white-paper.html

# Modularity: Upgrade, Reuse, Repair, ...

■ Module design for ease of disassembly: Maintainability, upgradability, repairability, reusability, recyclability




- Grouping of components according to reliability level and expected lifetime / level of reusability or recyclability / ...
- Standardized interfaces / Mechanically loose connections ↔ Electrical characteristics
- Potential for leveraging economies of scale to compensate interface costs

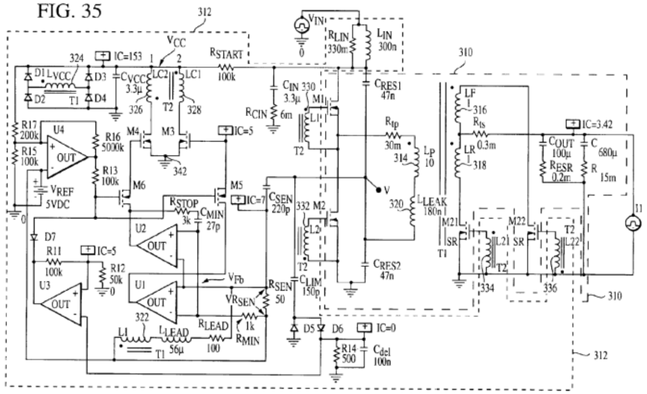
Source: T. T. Romano, T. Alix, Y. Lembeye, N. Perry, and J.-C. Crebier, "Towards circular power electronics in the Perspective of modularity," *Procedia CIRP,* vol. 116, pp. 588–593, Jan. 2023, doi: 10.1016/j.procir.2023.02.099.

# 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

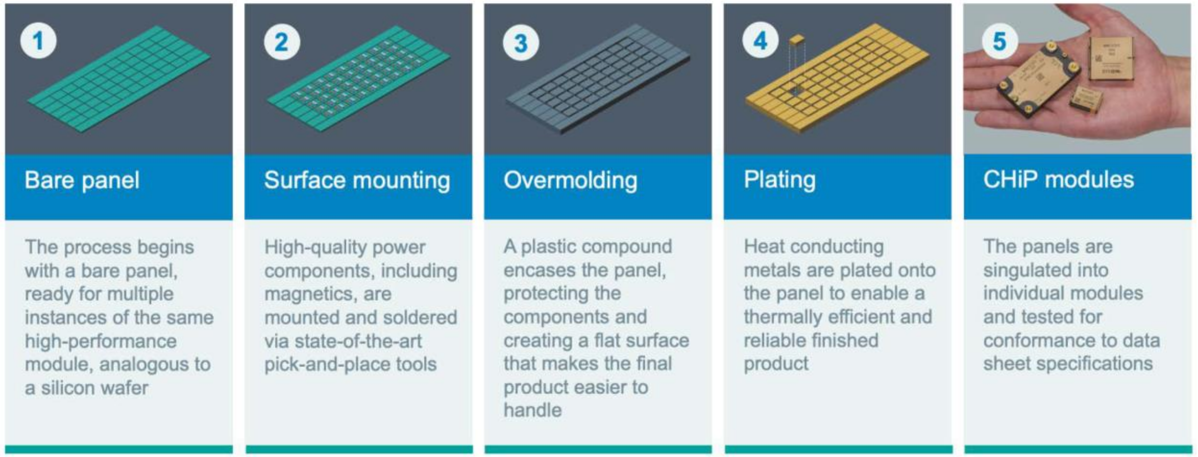

- **Low initial material usage ↔ Difficult material separation**
- **Importance of recyclability?**

FIG. 35



*Example: Isolated dc-dc*

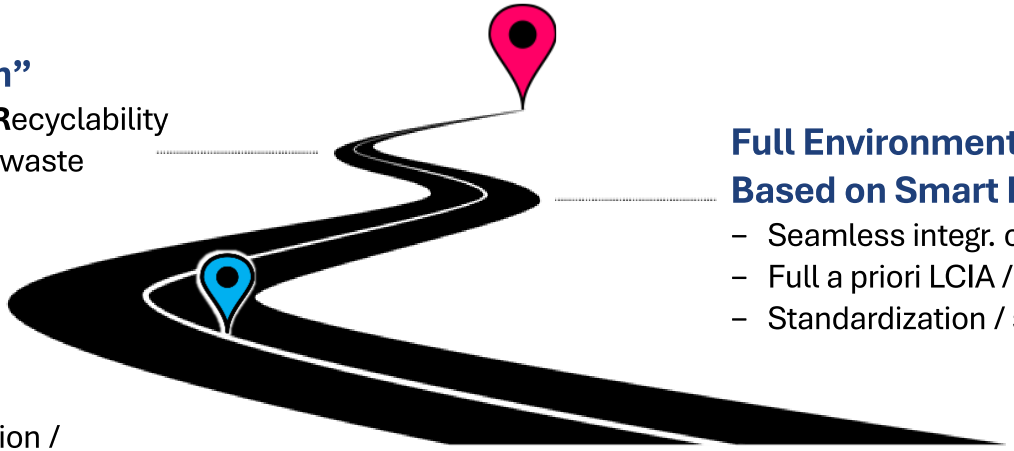
VICOR



# 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

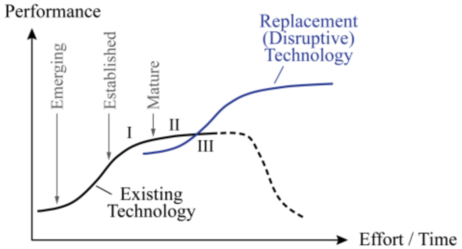
**Generic Life-Cycle Impact Analysis (LCIA)**
- New KPIs in multi-obj. opt.
- Data sources / quality / abstraction / generalization as key challenges

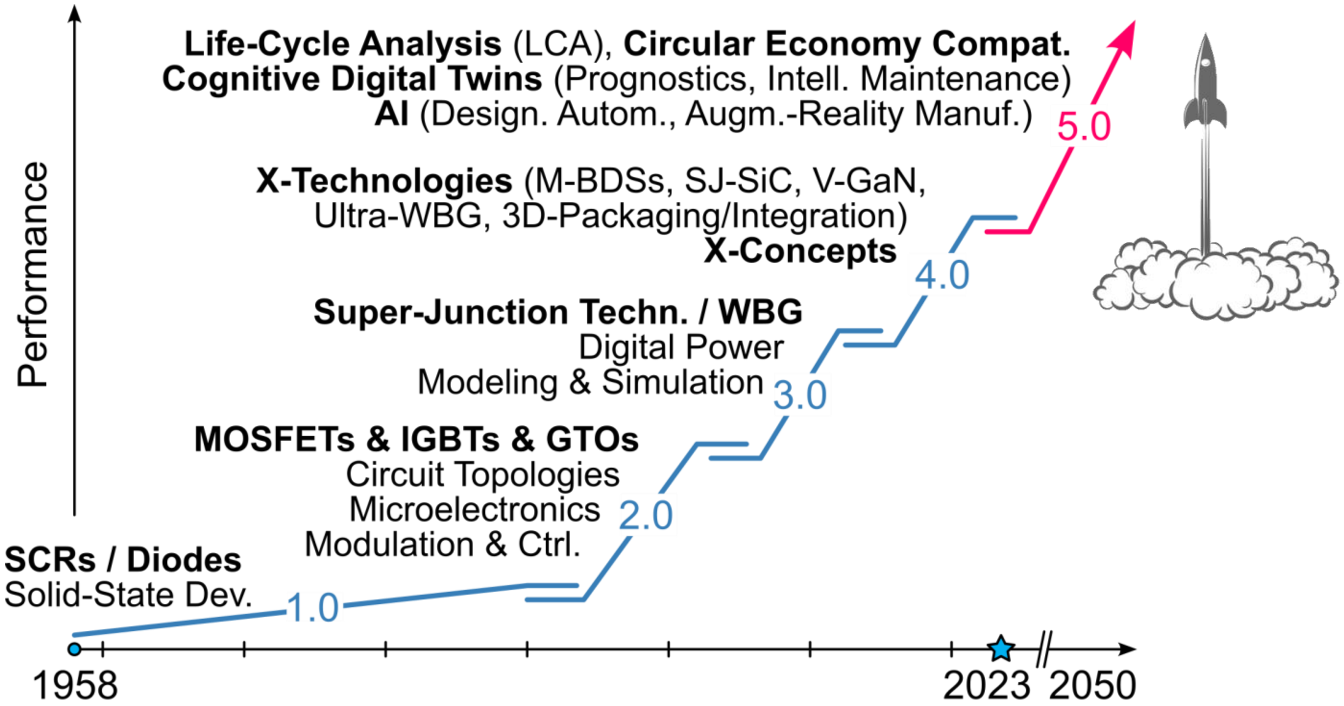
**Classical *ηρ*-Pareto Optimization / Design**
- Manual a posteriori LCA of complete converters

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

# Power Electronics 5.0

- Power Electronics 1.0 → Power Electronics 5.0
- X-Technologies & X-Concepts
- New main performance indicators (!)

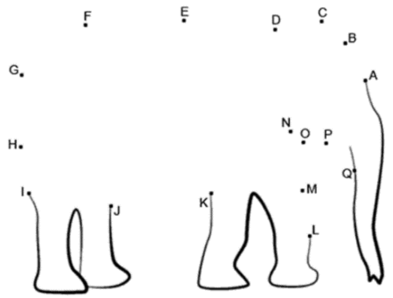



- Life-cycle analysis / circular economy compatibility are key for sustainable Power Electronics 5.0

Source: 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.

# 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.