Power Electronic Systems Laboratory

ETH zürich

Paradigm Shift in Power Electronics Towards Circular Economy Compatibility

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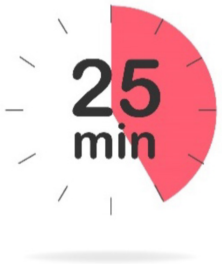
VDE ETG Event | CIPS

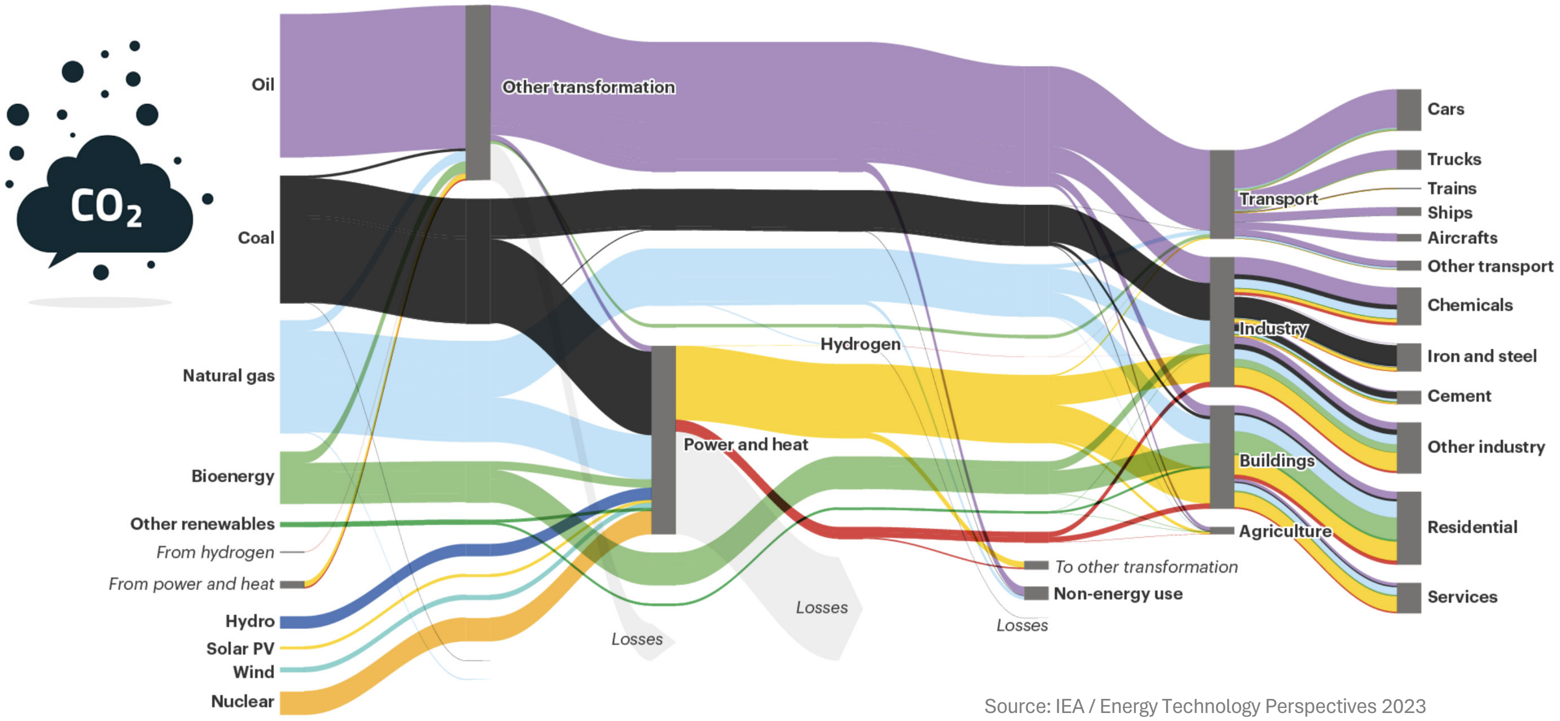


Outline

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

The Challenge

- Global energy flows — 2021

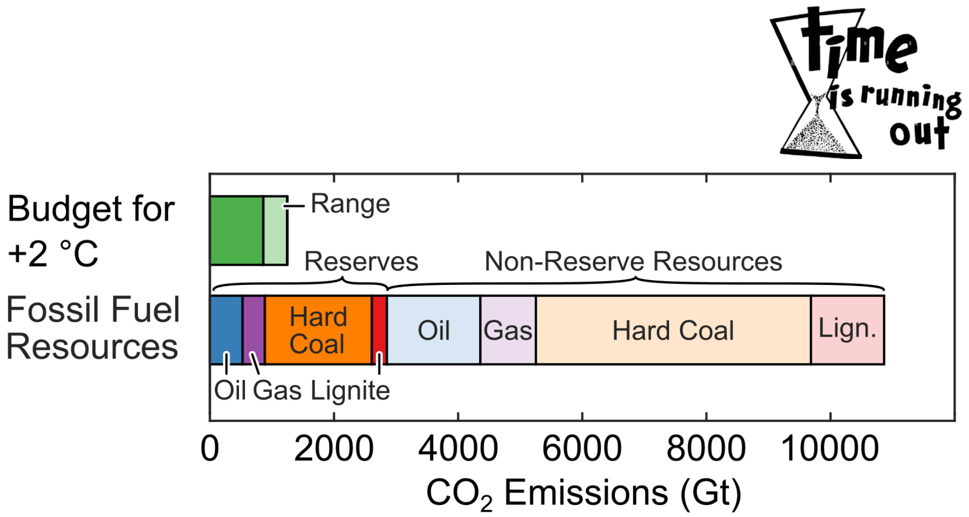


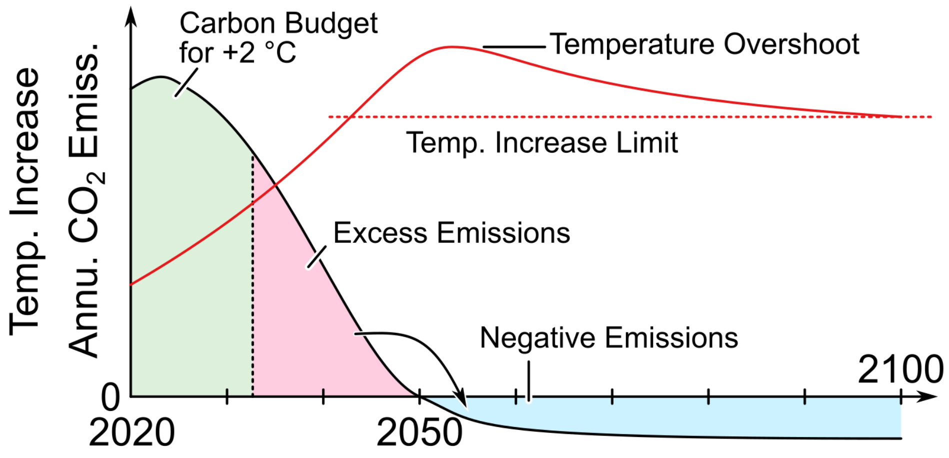
Source: IEA / Energy Technology Perspectives 2023

- Large share of fossil fuels (!)

Decarbonization / Defossilization

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



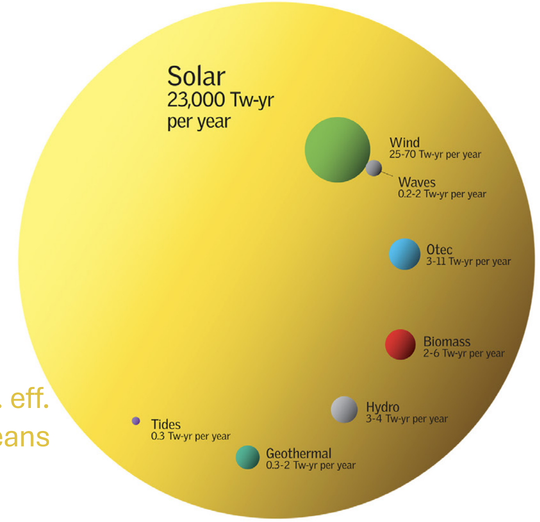


- Human history: Transition from lower to higher energy density fuel — Wood → Coal → Oil & Gas
- Challenge of stepping back from oil & gas quickly / Can't wait for disruptive technologies / panacea!

The Opportunity

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

Renewable energy resources per year

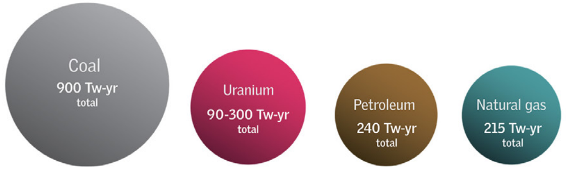


100% convers. eff.
Excl. oceans

Note: Graphical representation assumes spheres, not circles

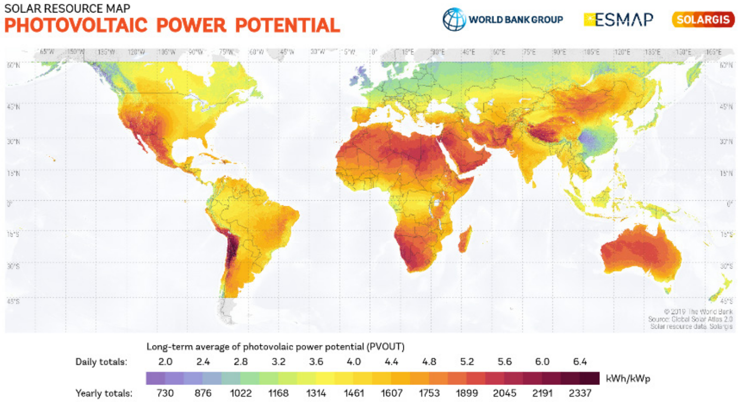
Primary consumption:
16 TWyr → 27 TWyr
Final consumption:
11 TWyr → 15 TWyr

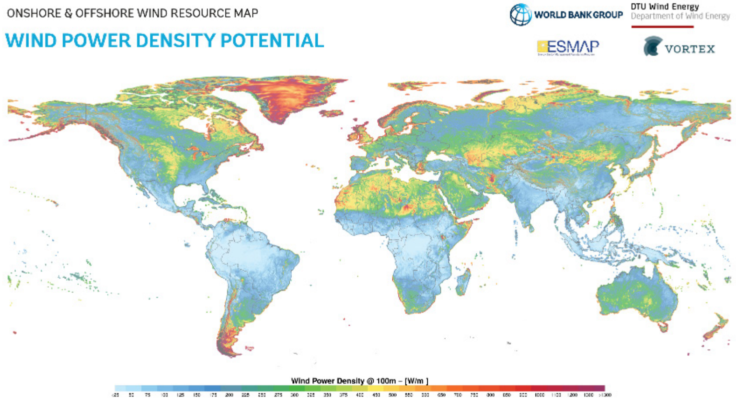
Fossil energy resources - total reserve left on earth



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

■ Global distribution of solar & wind resources



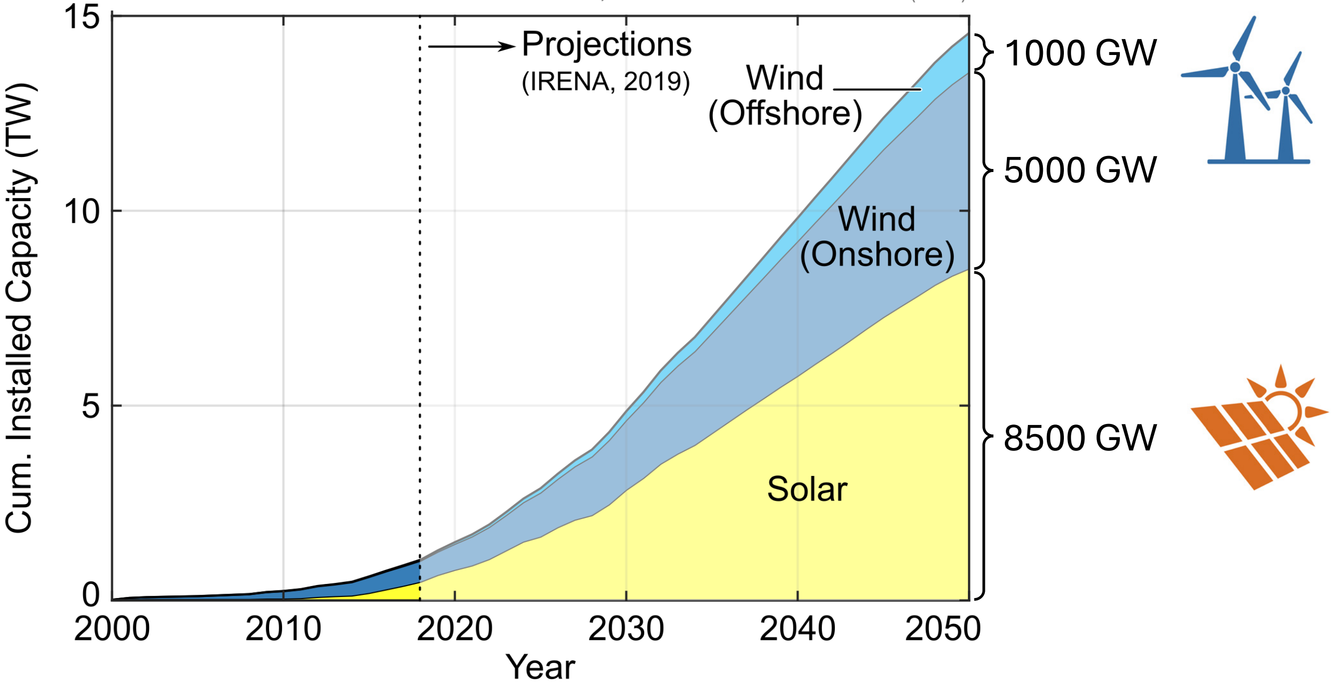


The Approach

■ **Outlook of global cumulative installations until 2050**

● In 2050 deployment of 370 GW/yr (PV) and 200 GW/yr (onshore wind) incl. replacements

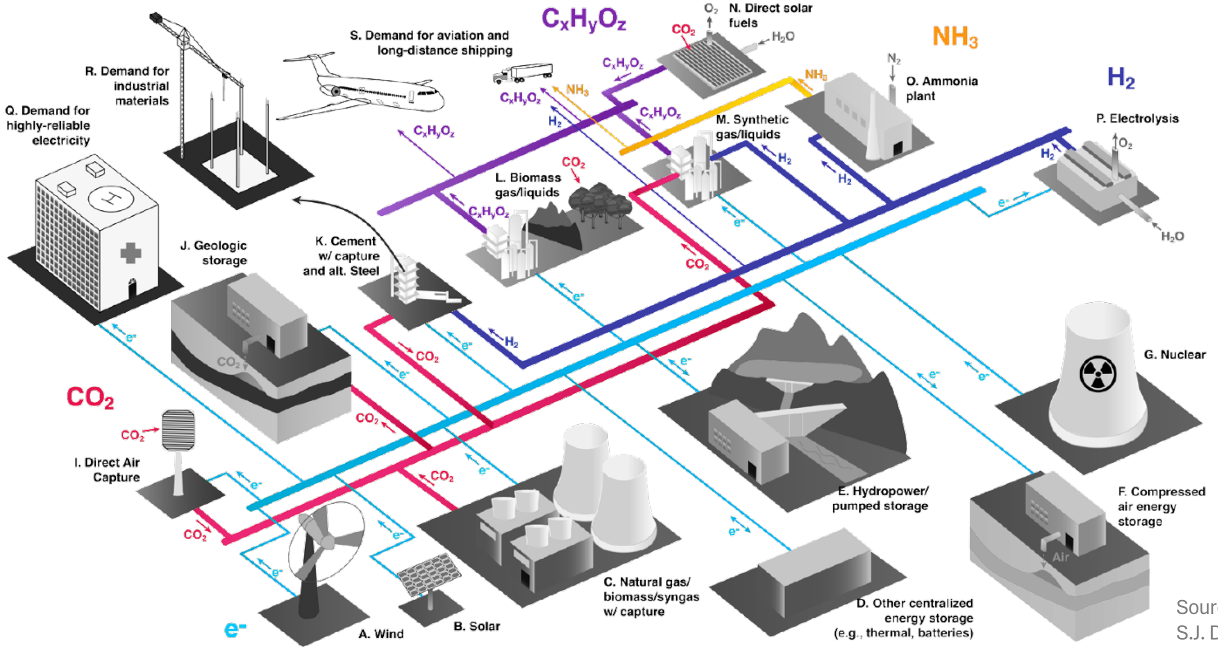
Source: IRENA, Future of Wind / Future of Solar PV (2019)



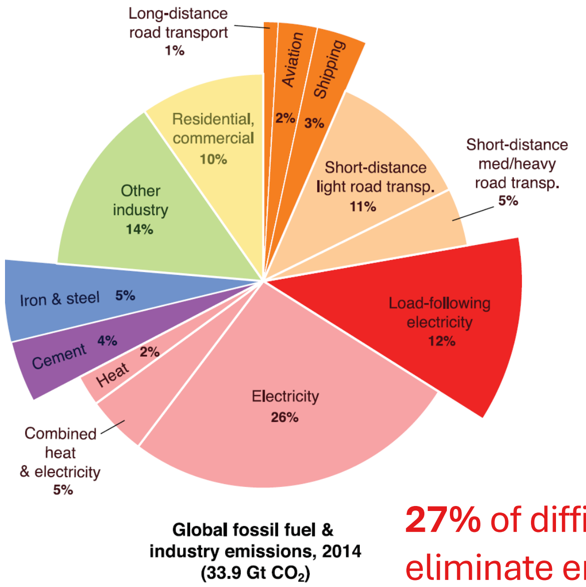
■ **Dominant share of electric energy — Power electronics as key enabling technology (!)**

Net-Zero Multi-Carrier Energy Systems (1)

- CO_2-free electricity / electrification — Viable pathway for reducing emissions & costs (long term)
- E-fuels & power-to-X for long-haul transport, aviation, etc. & short-term seasonal storage



Source:
S.J. Davis et al., *Science* (2018)

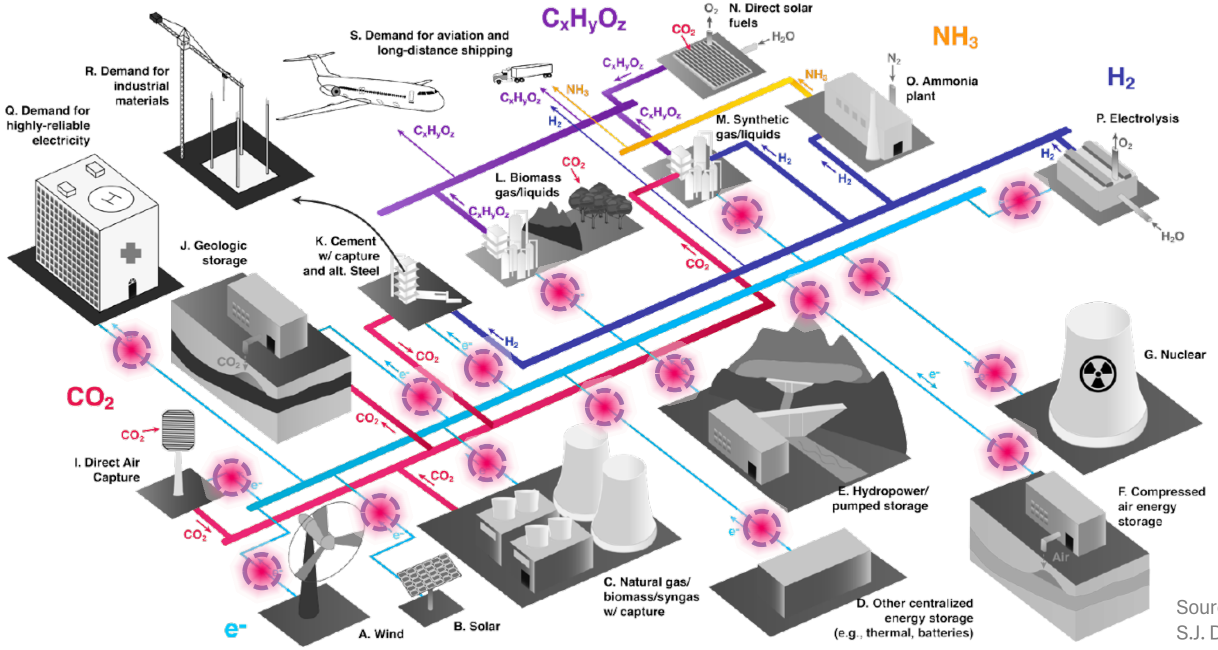


27% of difficult-to-eliminate emissions!

- Integrated net-zero multi-carrier energy system — Electric energy | heat & cold | … | storage | CO_2 capture & stor.
- Missing multi-disciplinary research on cross-sector converters / technologies / geo. diversity / economics / …

Net-Zero Multi-Carrier Energy Systems (2)

- **Power electronics — A key enabling technology!**



Source:
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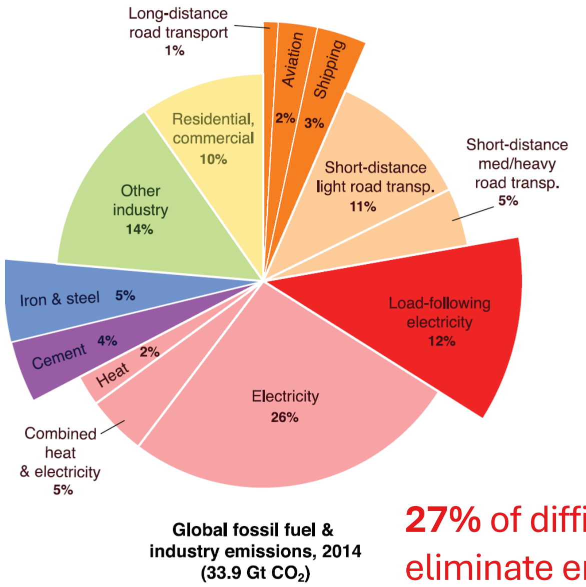
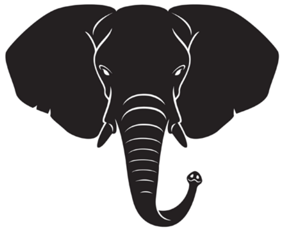
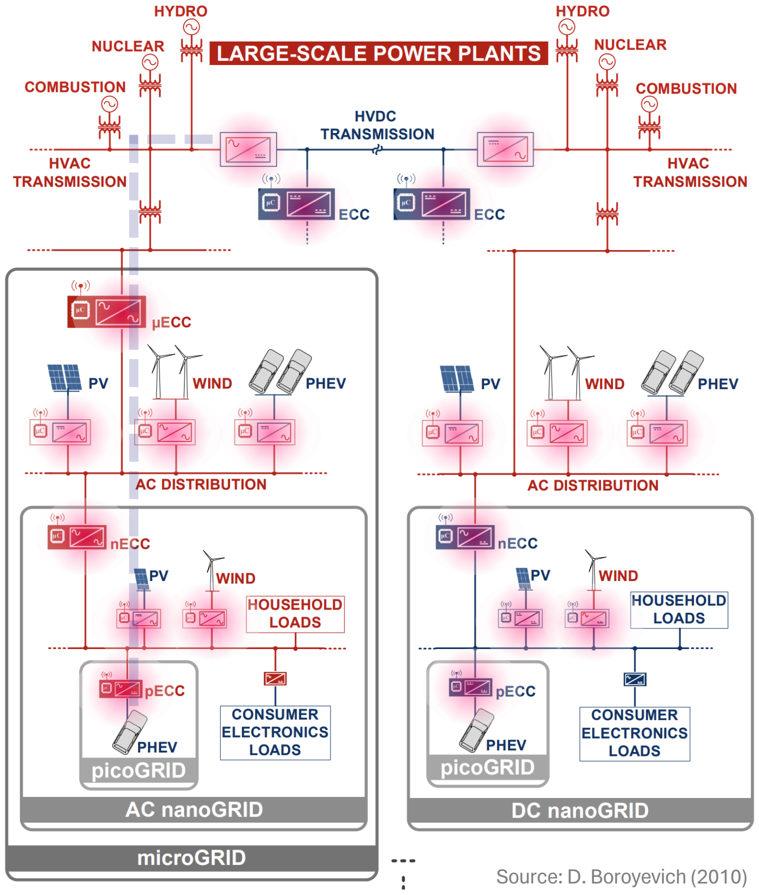


27% of difficult-to-eliminate emissions!

- Renew. gen. & cross-sector convers. — Heat pumps / electrolyzers / fuel cells / ... → All dep. on power plectron.

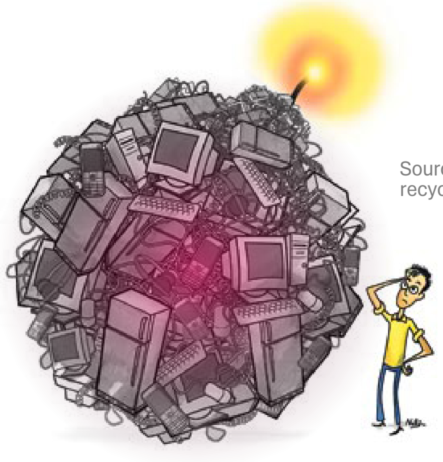
The  in the Room



Source: D. Boroyevich (2010)

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

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

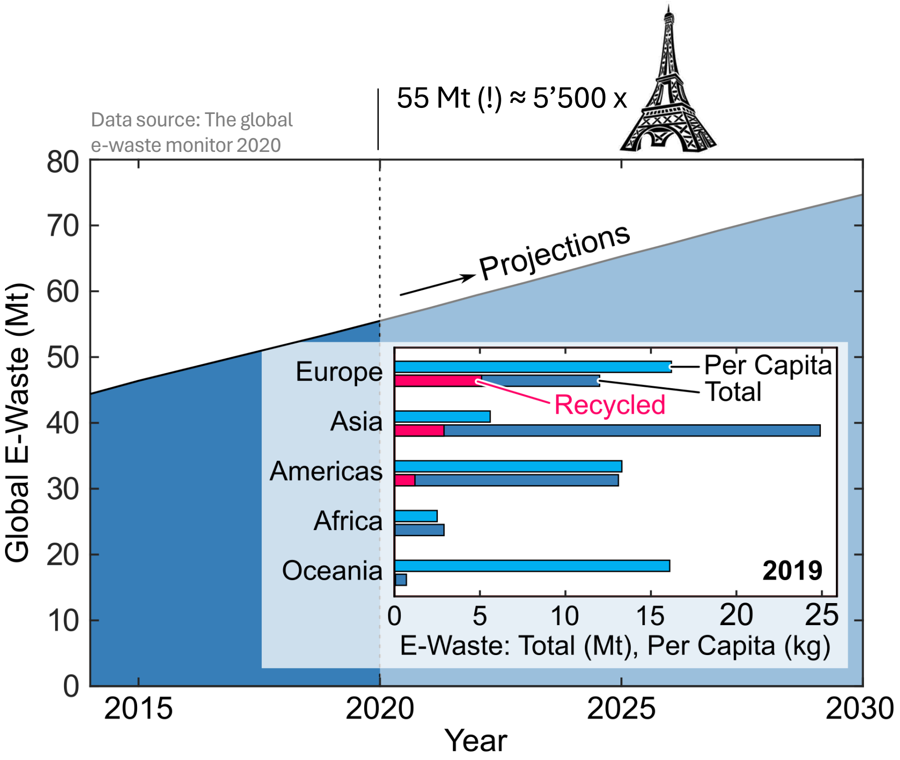


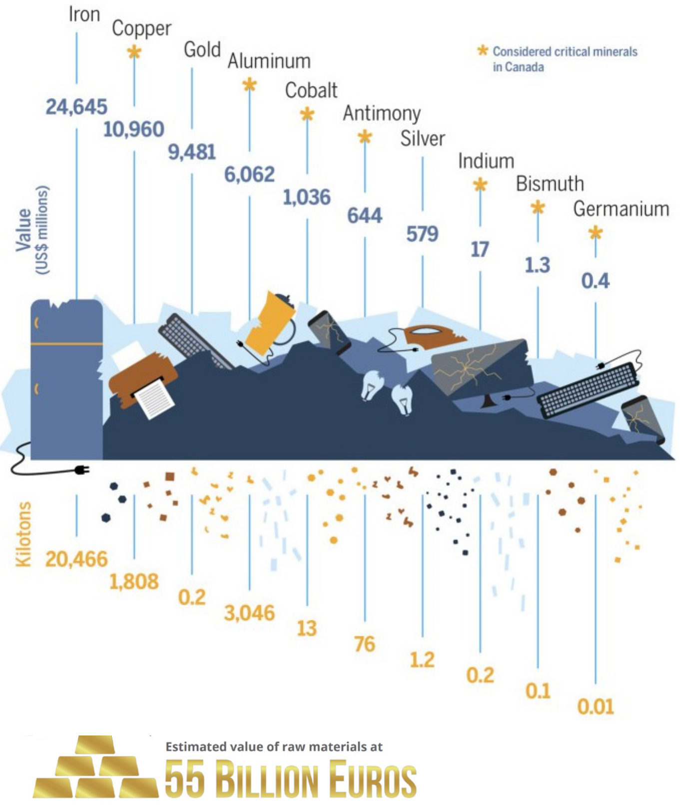
Source: www.e-waste-recyclers.co.in

- **$5'000\ GW_{eq} = 5'000'000'000\ kW_{eq}$** 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**





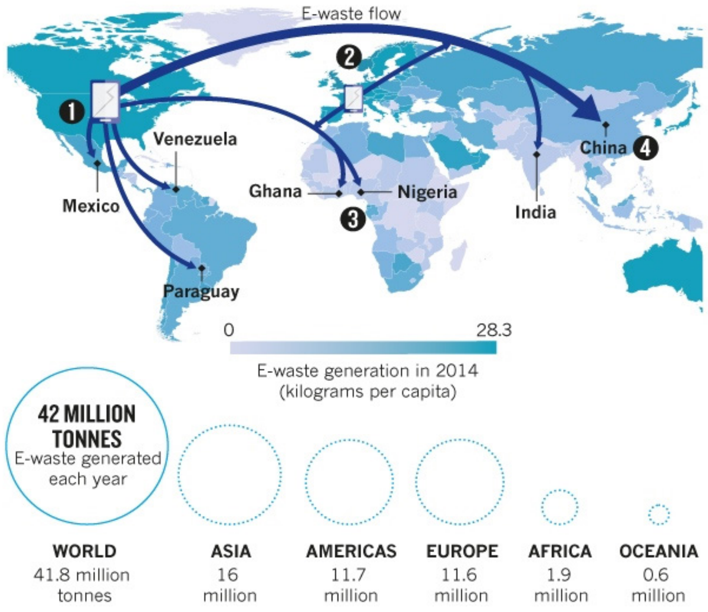
Global, 2019

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



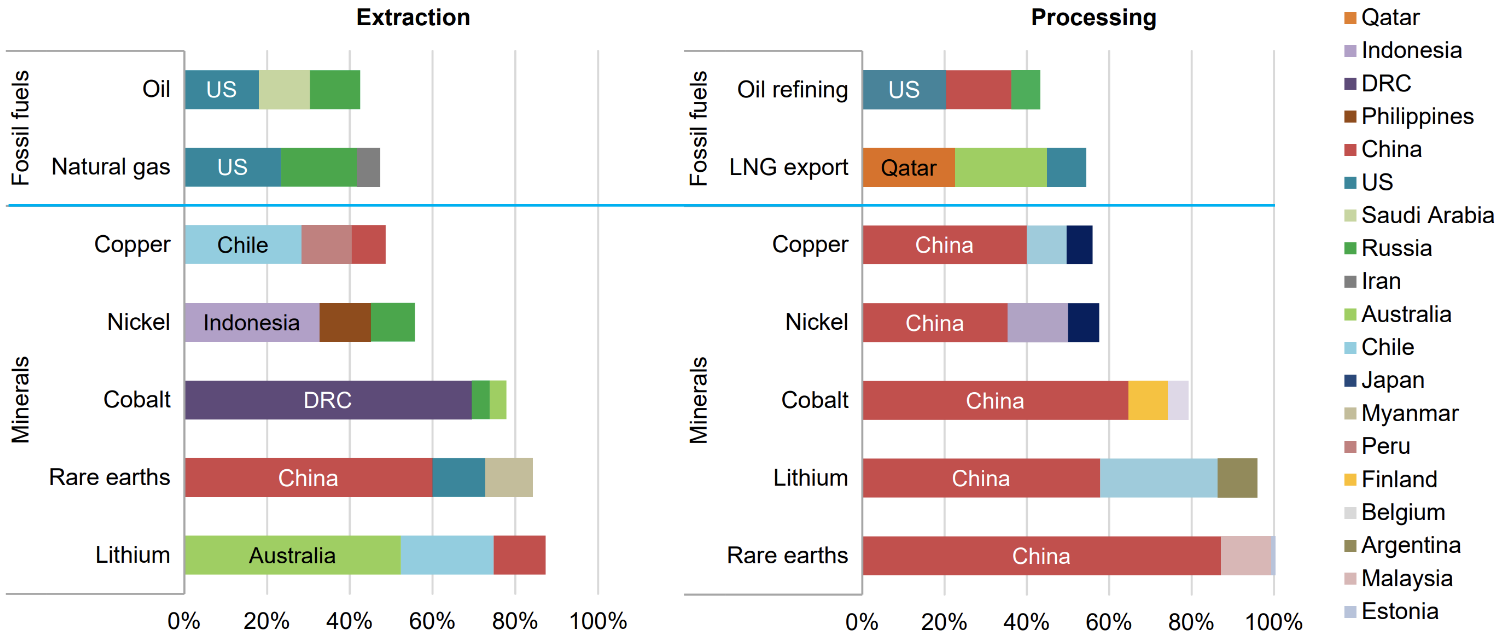
Source: nature

Source: Green IT Solution

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

Remark: Critical Minerals

- Production of selected minerals critical for the clean energy transition

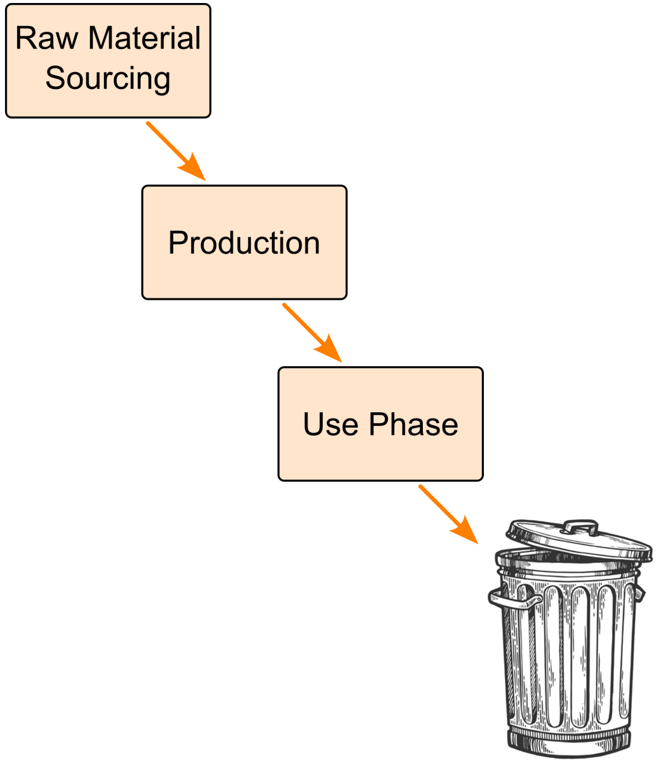


Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

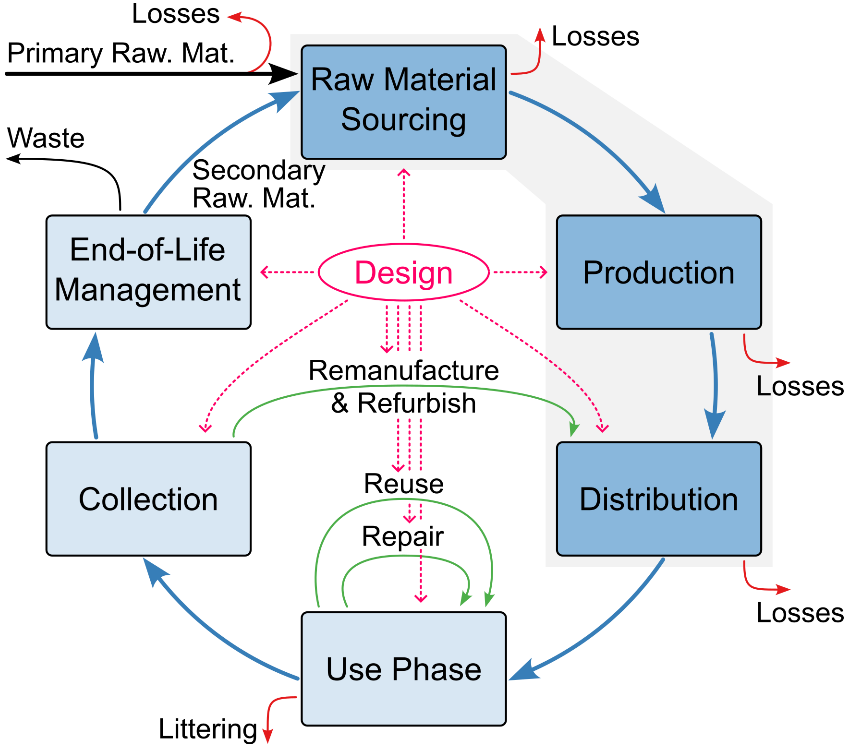
- Extraction & processing more geographically concentrated than for oil & gas (!)

The Paradigm Shift

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



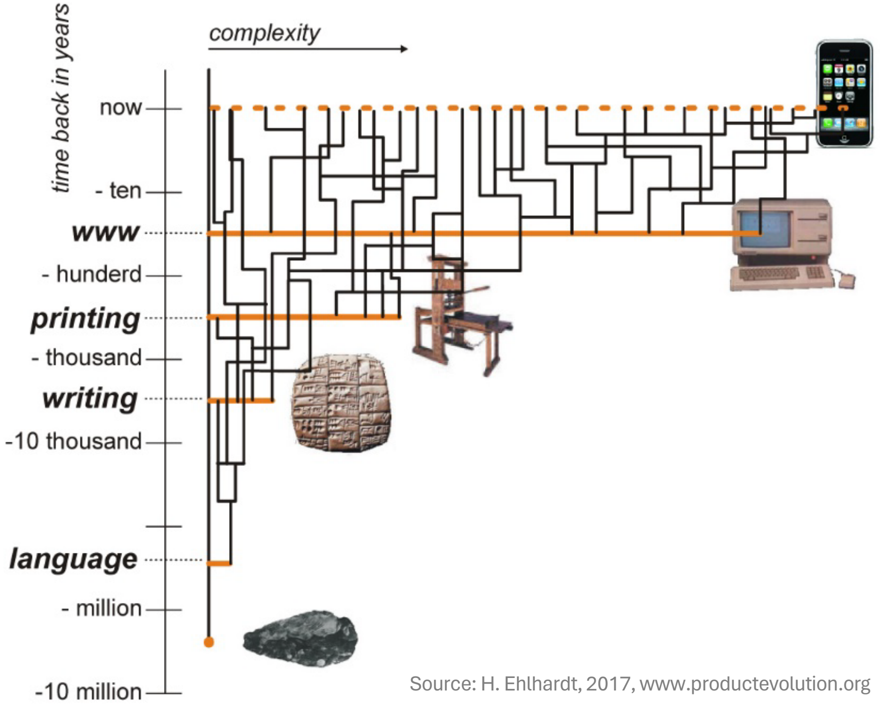
- **Circular Economy**
  - Perpetual flow of resources



- Resources returned into the product cycle at end of life

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!?

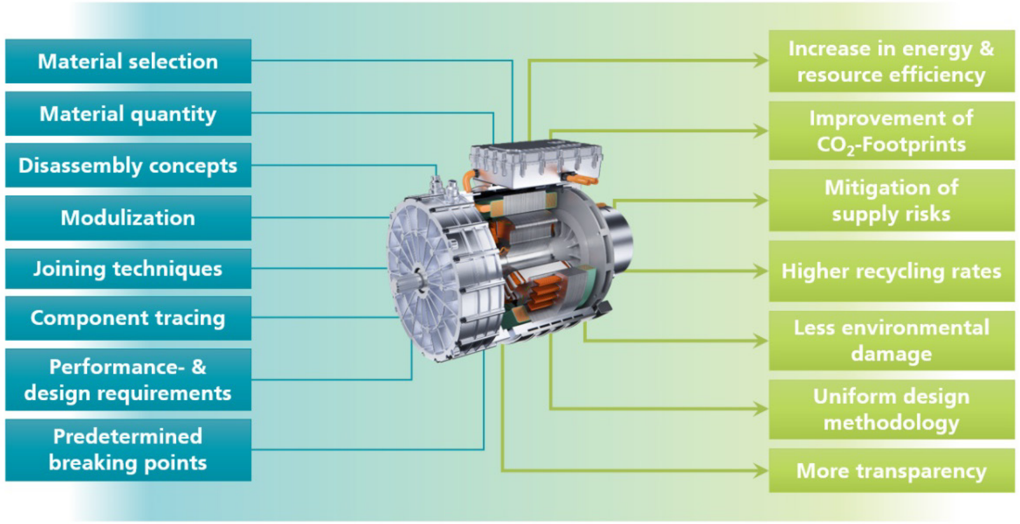
Design for Repairability & Circularity

- **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: www.ligman.com/

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

Source: DLR



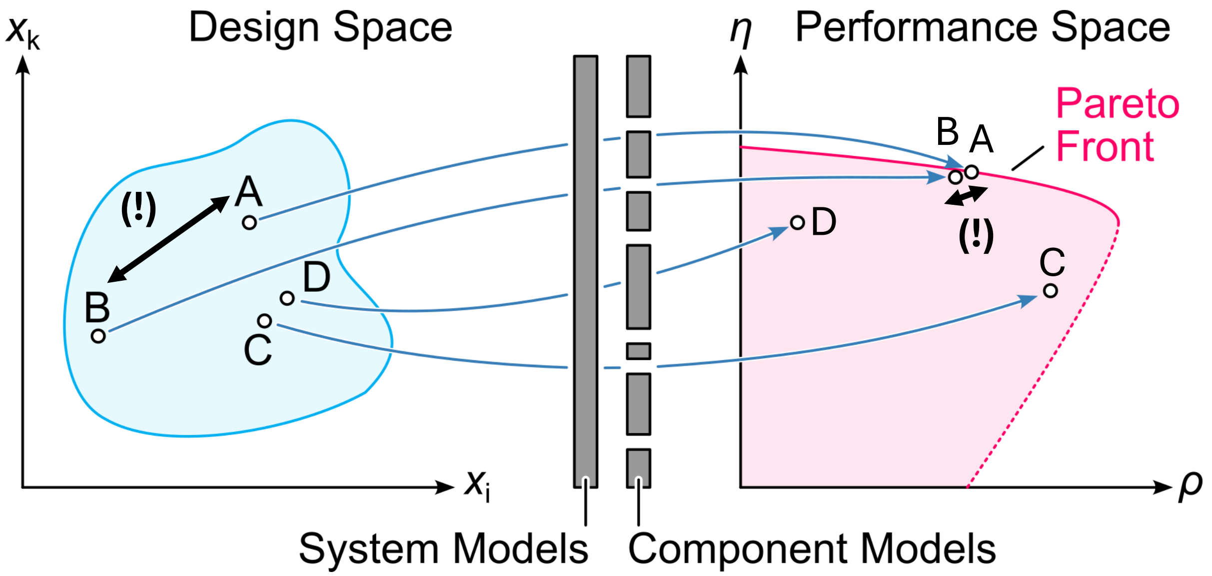
- ***FAIRPHONE*** — Modular design / man. replaceable parts / 100% recycl. of sold products / fairtrade materials
- **"80% of environmental impact** of products are **locked-in at the design stage"** — J. Thackara, 2006

New Holistic Design Procedure

Multi-Objective Optimization with Environmental Impacts as New Performance Indicators

Multi-Objective Optimization

- **Typ. performance indices — Efficiency η [%] | Power density ρ [kW/dm^3] | Rel. Cost σ [kW/$]**
- **Consideration of specific operating points or mission profile (power loss → energy loss / life-cycle cost)**



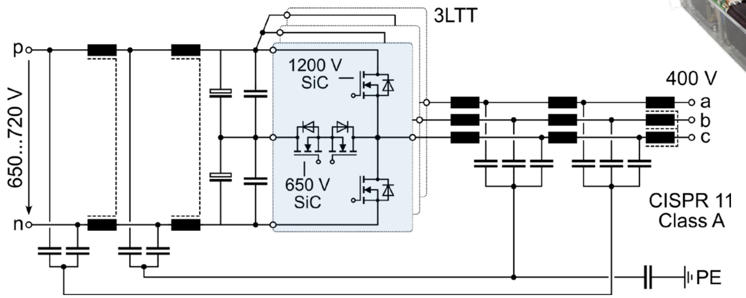
- **Design space diversity: Very different design-space coord. map to very similar performance-space coord.**

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%)**

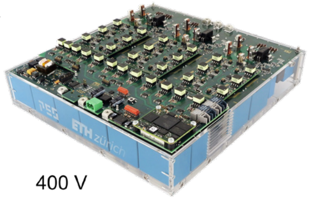
3-Level All-SiC T-Type PV Inverter

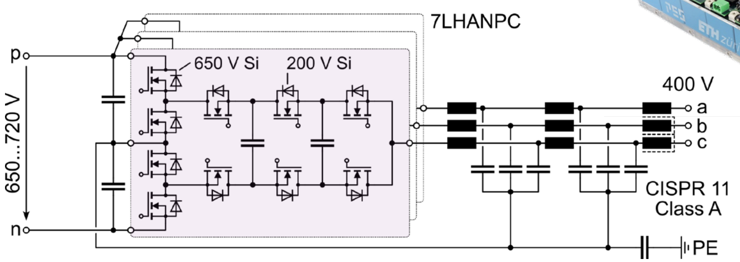
99.4%, 2.4 kW/dm³

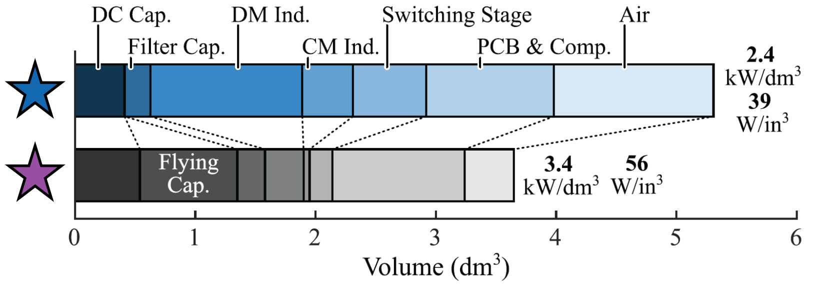


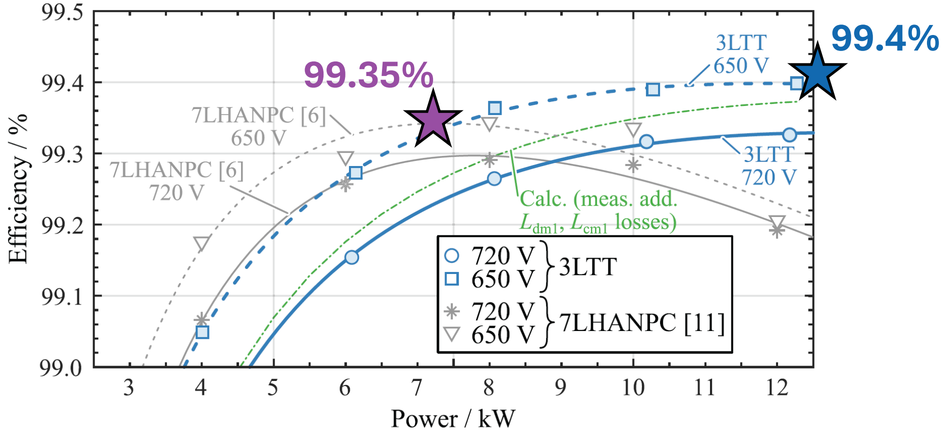
7-Level All-Si HANPC PV Inverter

99.35%, 3.4 kW/dm³









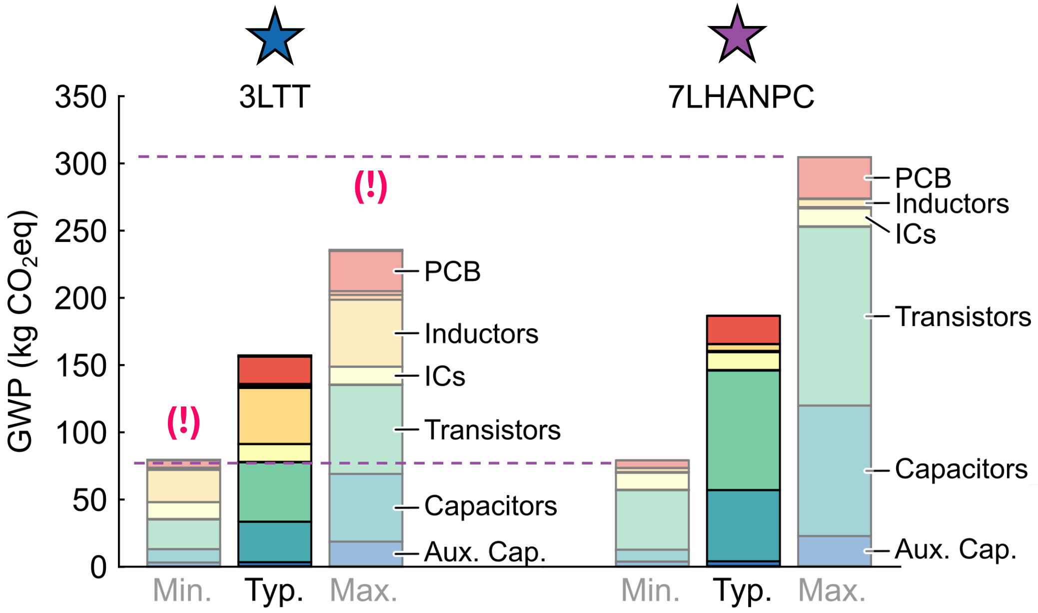
Source: Anderson et al., *Electron Lett.*, 2023.

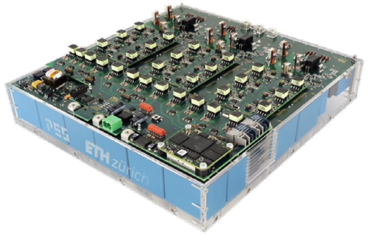
- **Differences in environmental impact?**

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/dm^3, 11.8 kg





3.4 kW/dm^3, 4.6 kg

- **Generic comp. models / ecoinvent database & lit. → Widely varying Global Warming Pot. (GWP) results (!)**
- **Data availability / quality as key challenge!**

CO_2 is Not Enough!

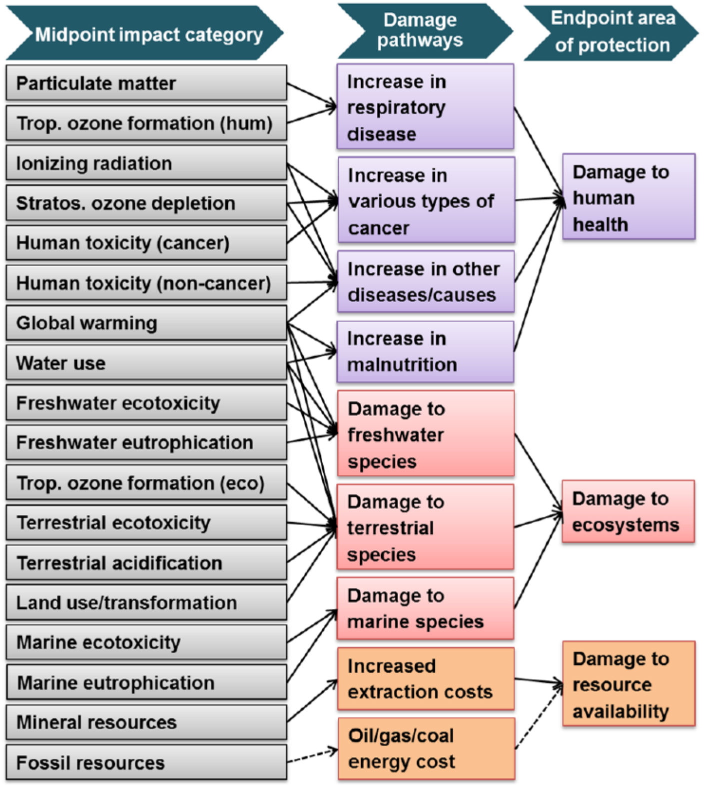
- Life cycle impact assessment (LCIA) phase of LCA — Environmental profile w. wide range of perf. indicators

- 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 ($)

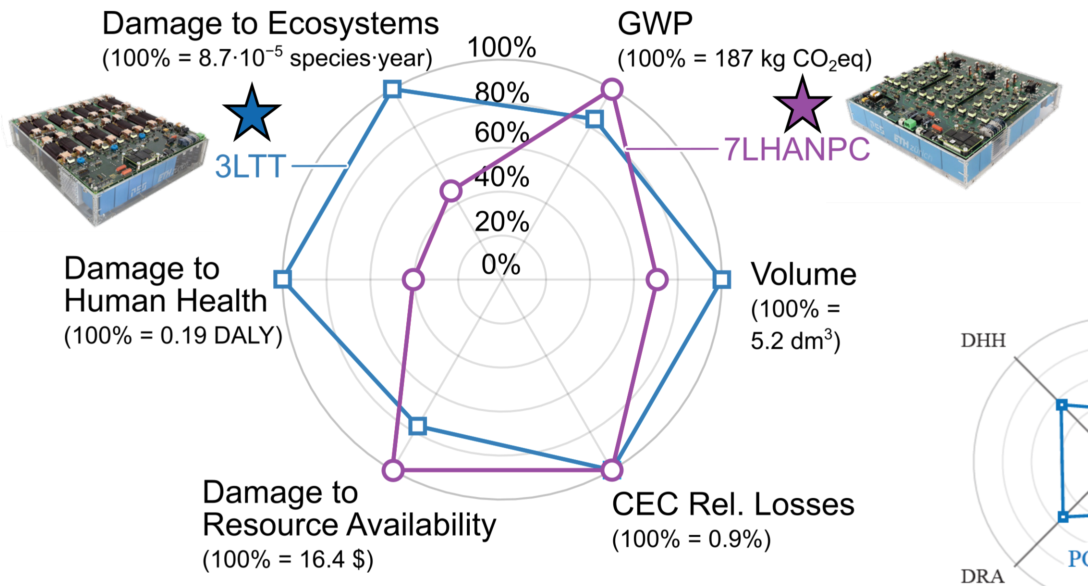


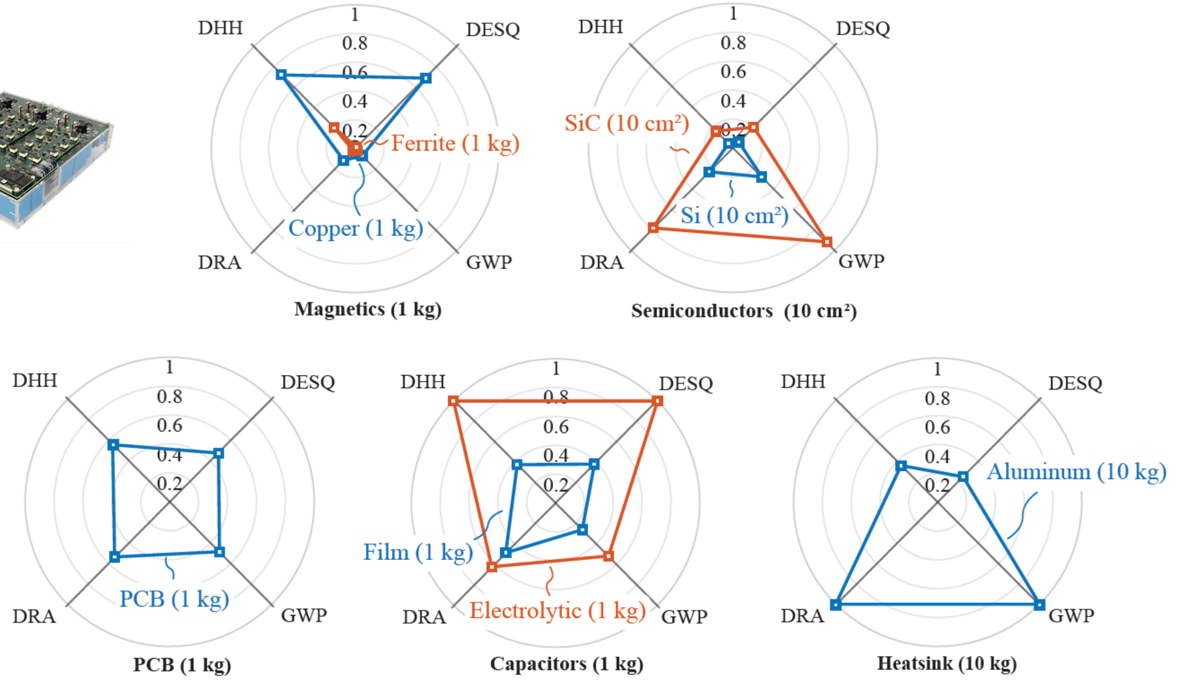
Source: Huijbregts et al., ReCiPe 2016 v1.1 Report

- Value choices (individualist / hierarchist / egalitarian) affect time horizon, included effects, etc.

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)





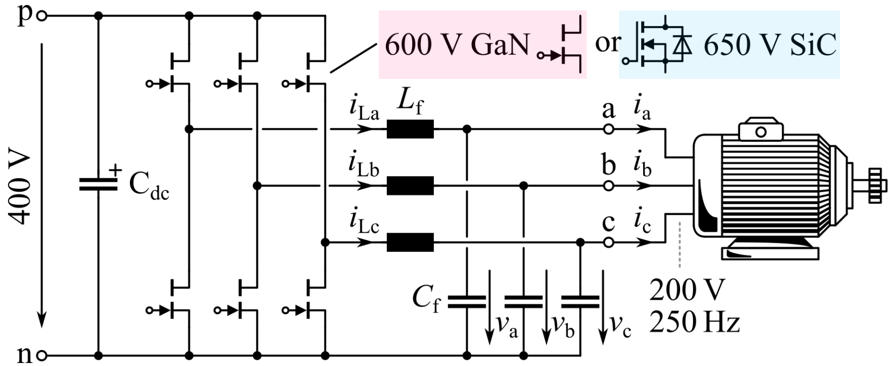
Normalized scales due to ecoinvent licensing restrictions.

- **Environmental footprint of converter as aggregate of components' env. footprints**

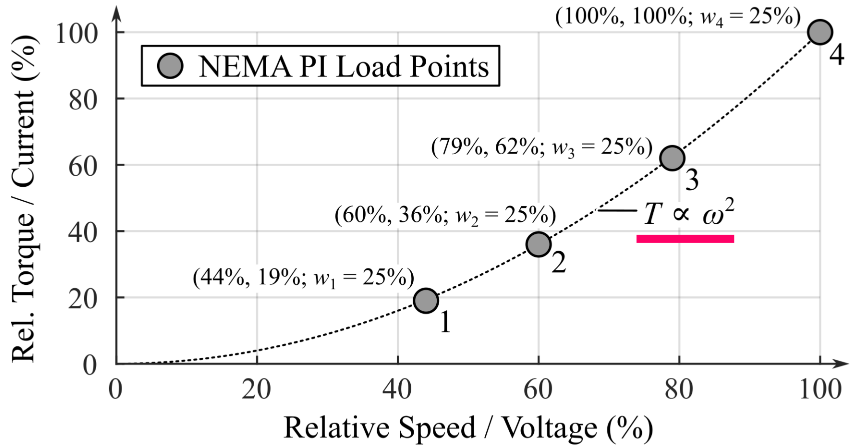
A Priori Consideration of Environmental Impacts in the Design Process?

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

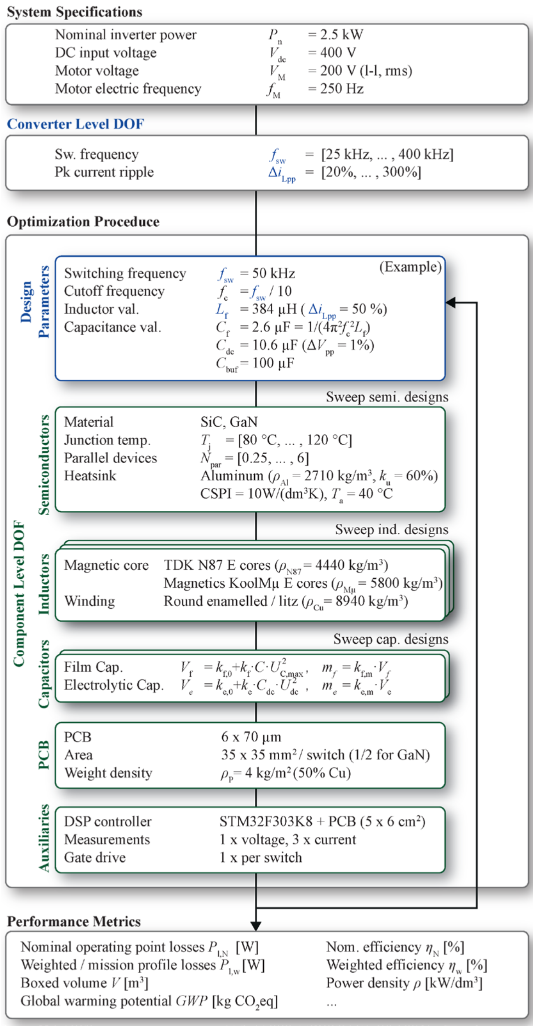


Specs: 2.5 kW inverter / 3-hp motor		
Input dc volt.	400	V
Motor volt.	0...200	V
Motor el. freq.	0...250	Hz

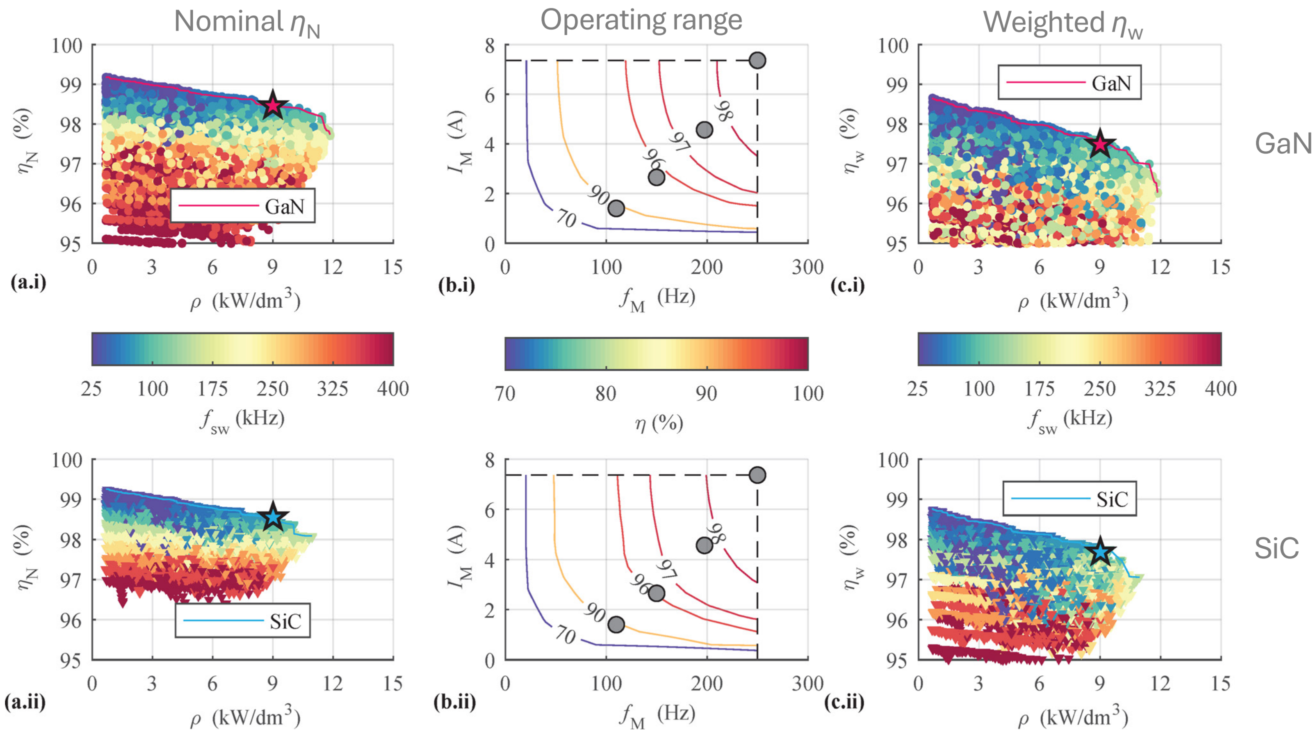


- **LV VSD inverter w. WBG and dc-bus-referenced LC output filter w. DM & CM attenuation (smooth mot. volt.)**
- **Mitigation of dv/dt issues (reflections, bearing currents, ...) | Standard motors | No harmonic motor losses**

Multi-Objective Optimization Procedure



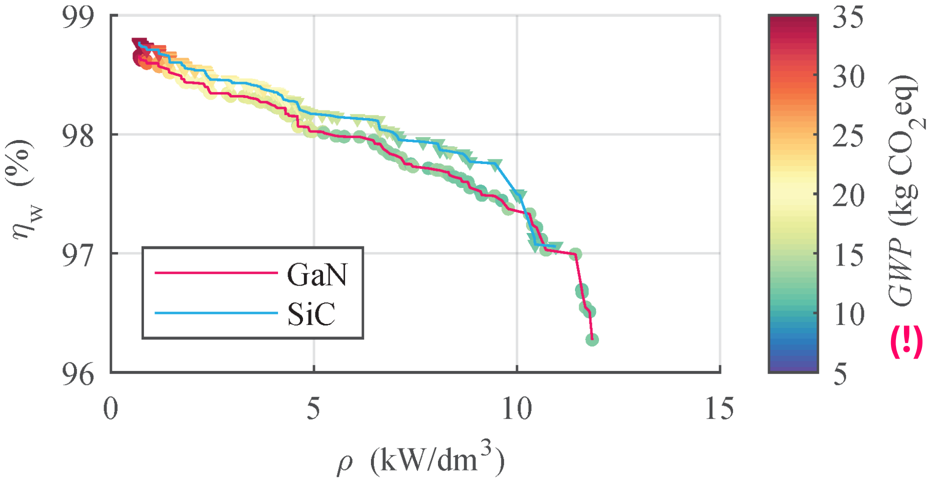
- DoFs: Sw. freq. | Ind. cur. ripple | Var. chip area | Var. inductor designs
- Nominal eff. η_N & weighted eff. η_w (NEMA PI load profile)

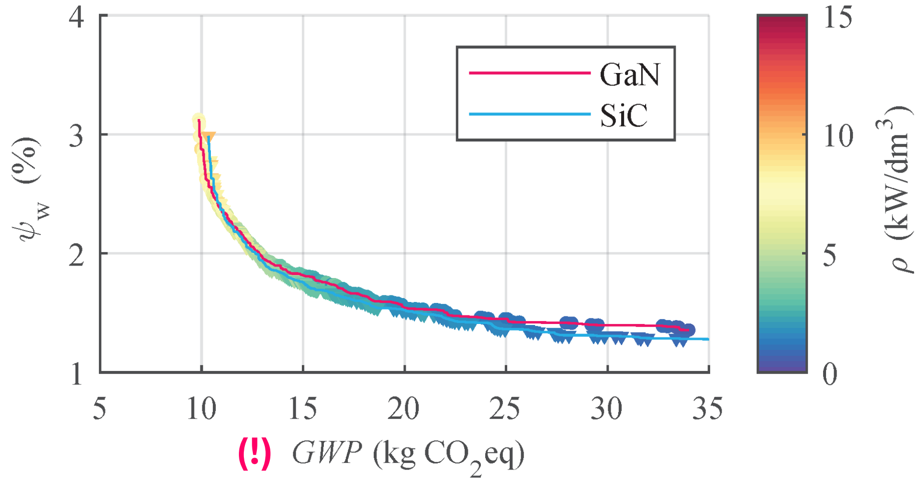


- GaN/SiC losses via scaling exemplary devices / Calorimetric meas. sw. loss.

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**



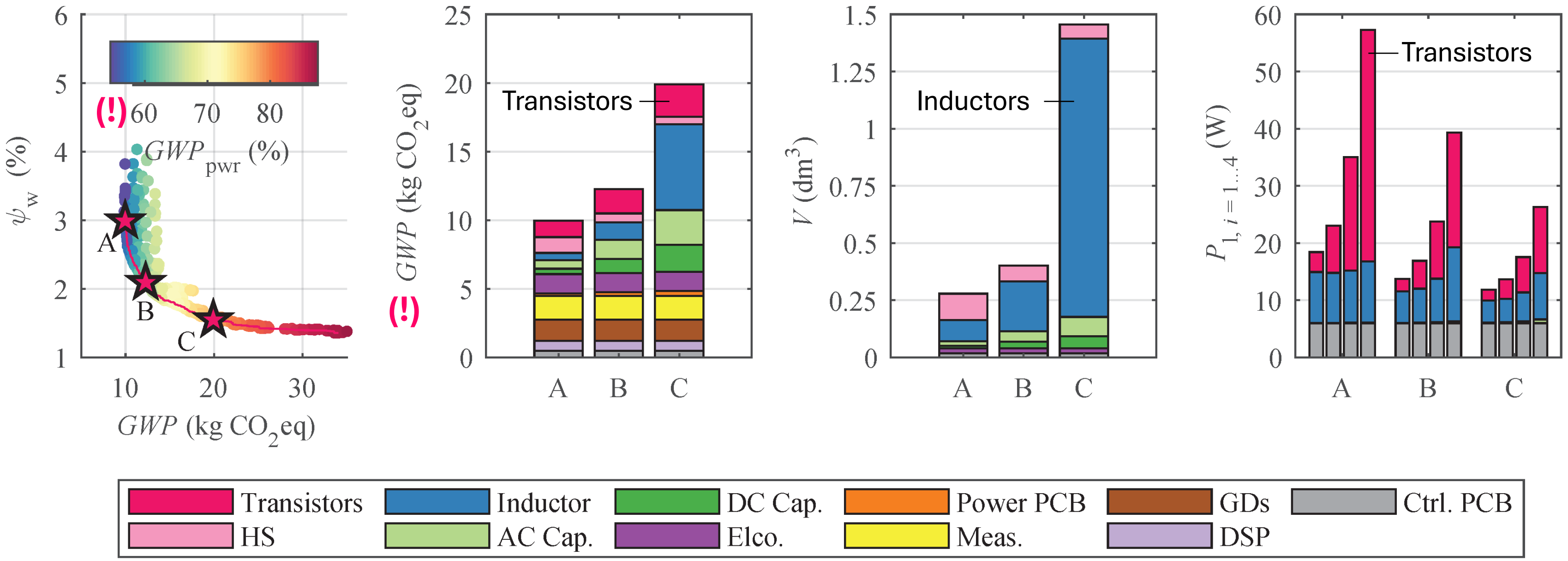


- **Very similar performance of GaN-based & SiC-based designs | Limited accuracy of generalized comp. mod.**
- **"Snapshot in time" — Outcome dep. on available data & technological developments**

Details of Exemplary Pareto-Optimal Designs

- **Three exemplary GaN designs — GWP breakdown | Volume breakdown | Loss breakdown**

NEMA PI load profile op. pts.

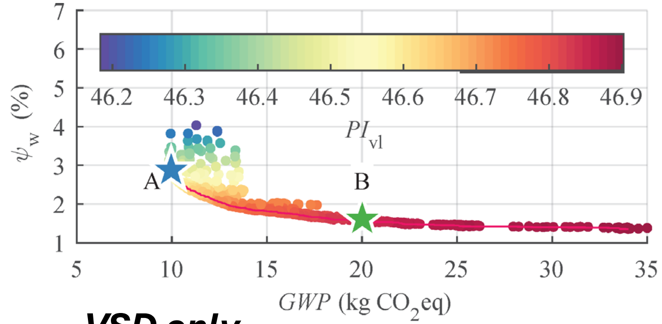


- **Auxiliary electronics limit min. GWP (!) — Similar: housing, etc. (not considered) — Dep. on rated power!**

Use Phase & Life-Cycle Carbon Footprints

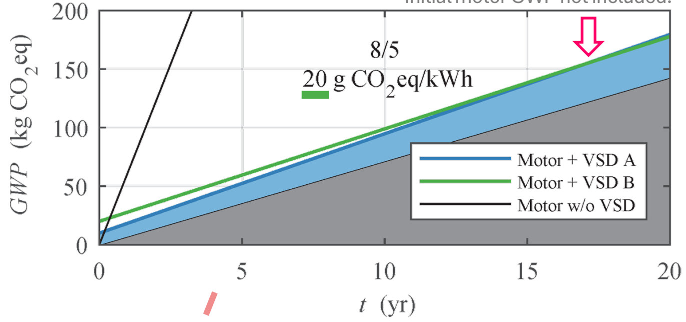
- Two Pareto-optimal exemplary GaN designs A & B | NEMA PI default motor
- Mission matters — 24 h on 7 d or 8 h on 5 d per week | NEMA PI load profile
- Electricity mix matters — Carbon intensity of wasted electricity (losses)

Fixed-Freq.
Motor w/o VSD



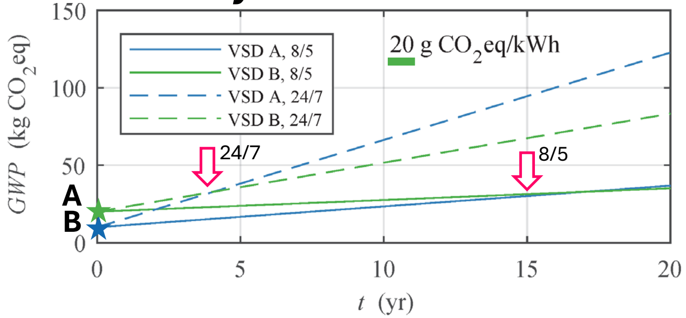
VSD + Motor

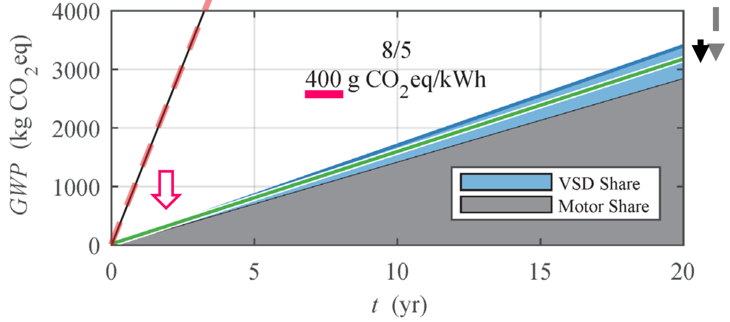
Initial motor GWP not included.



w. VSD vs. w/o VSD:
− 21’000 kg CO_2eq (!)

VSD only



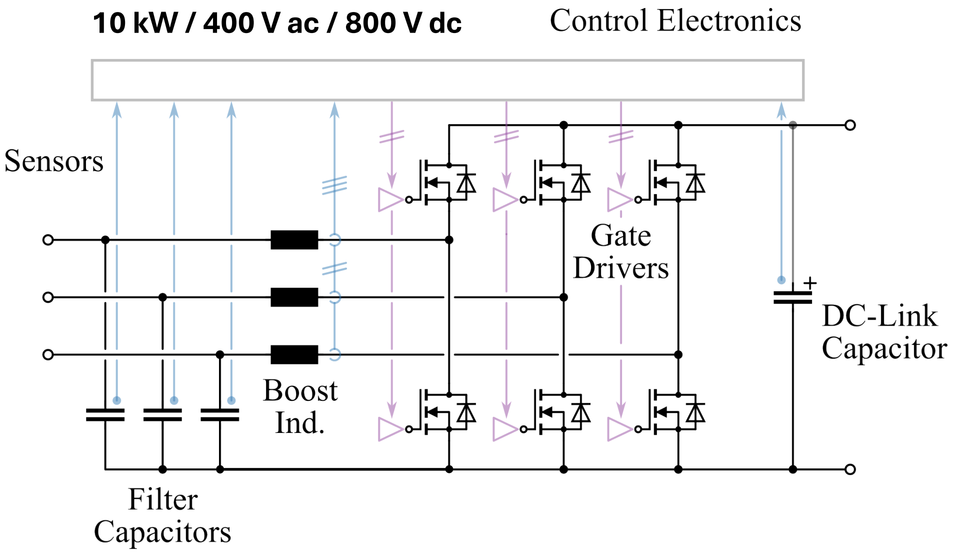


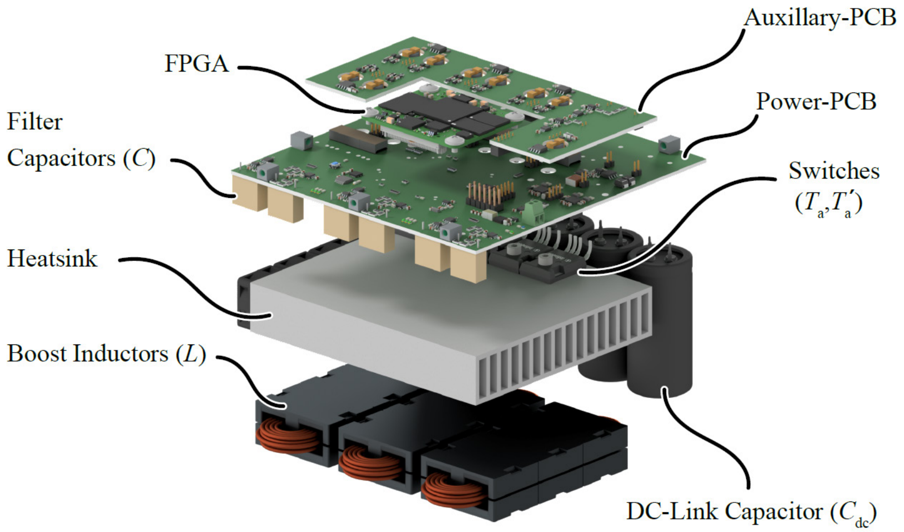
VSD A vs. B:
−230 kg CO_2eq

- More eff. designs w. higher initial GWP outperform less eff. designs for longer operating times
- VSD B vs. VSD A saves 230 kg CO_2eq (7%) after 20 years with electricity mix with high carbon intensity
- **21’000 kg CO_2eq (87%) savings with VSD (B) vs. fixed-frequency motor w/o VSD!**

A Priori LCA Example 2: 10-kW Three-Phase AC-DC PEBB

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

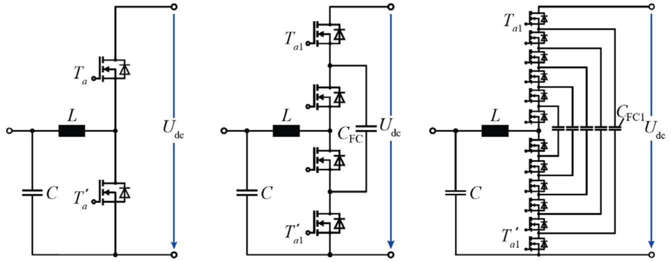


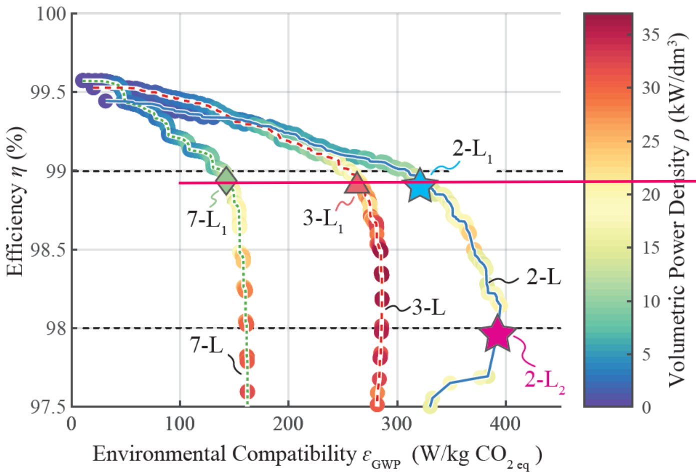


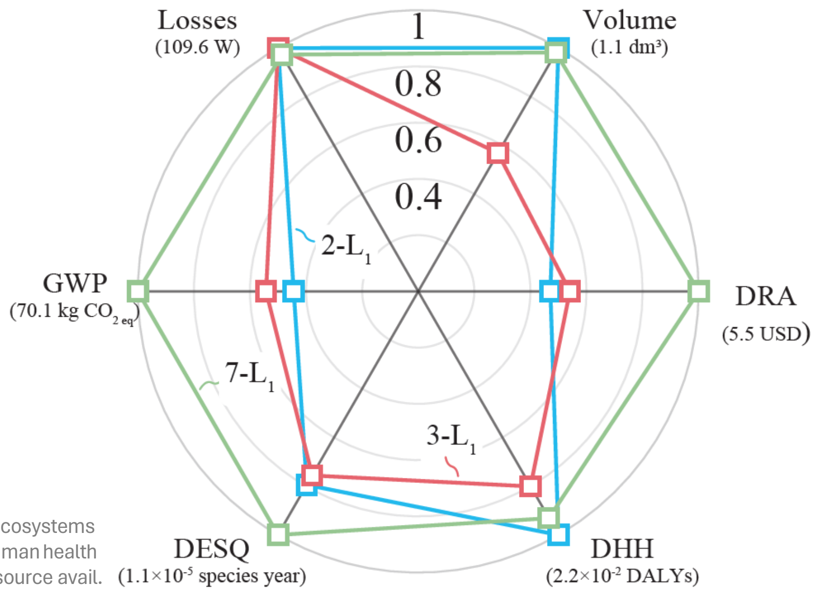
- **Degrees of freedom:**
  - Switching freq. [25…700 kHz]
  - Rel. Ind. Peak cur. ripple [0.25…1.5]
  - Var. transistor chip area
  - Variable ind. size (N87; solid/litz)
- **Assumptions:**
  - Junction temp. @ 120 °C
  - Ambient temp. 40 °C
  - Necessary heat sink vol. via CSPI = 25 W/(K dm^3)

Comprehensive Environmental Impact Profiles

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







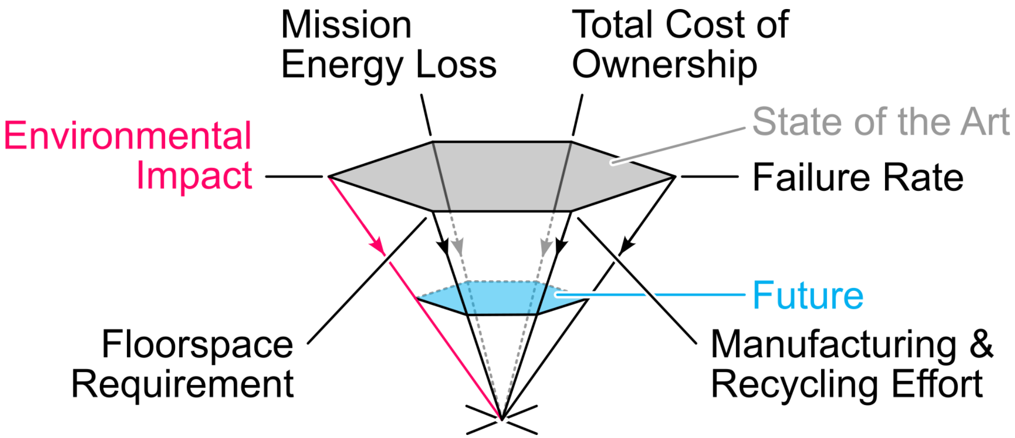
ReCiPe 2016:
DESQ—Damage to ecosystems
DHH—Damage to human health
DRA—Damage to resource avail.

- **Environmental 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!**

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}]

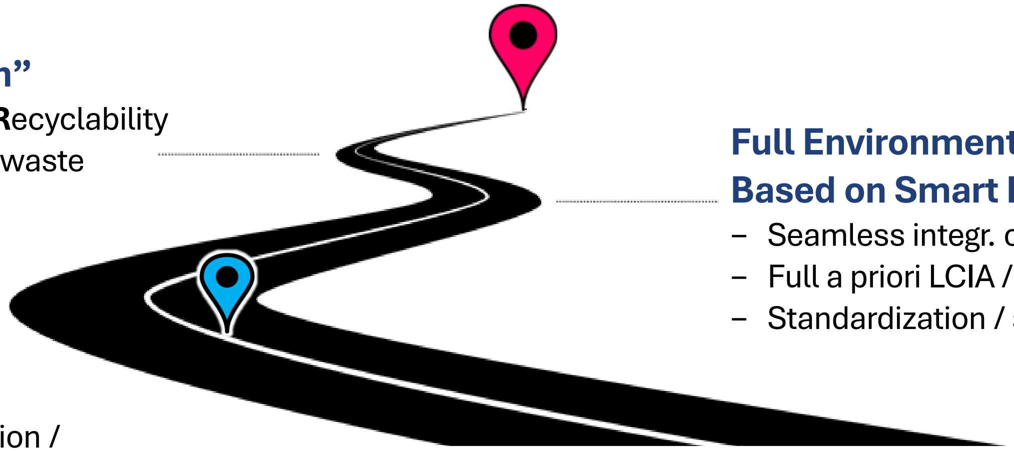


- **Mission/location-specific trade-off embod. vs. life-cycle environ. impact — Losses / Reliability / Lifetime**
- **Compatibility with a circular economy (!) — Repairability / Reusability / Recyclability**

CEC Power Electronics Roadmap

- **Environmental awareness as integral part of 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

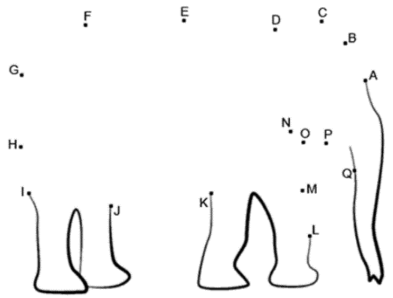
Full Environmental Footprint Based on Smart Datasheets
- Seamless integr. of comp. models in multi-obj. opt.
- Full a priori LCIA / environmental footprint
- Standardization / single source of truth

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!



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.