

Net-Zero-CO₂ by 2050 is NOT Enough (!)

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Let's Talk About the “Elephant in the Room”

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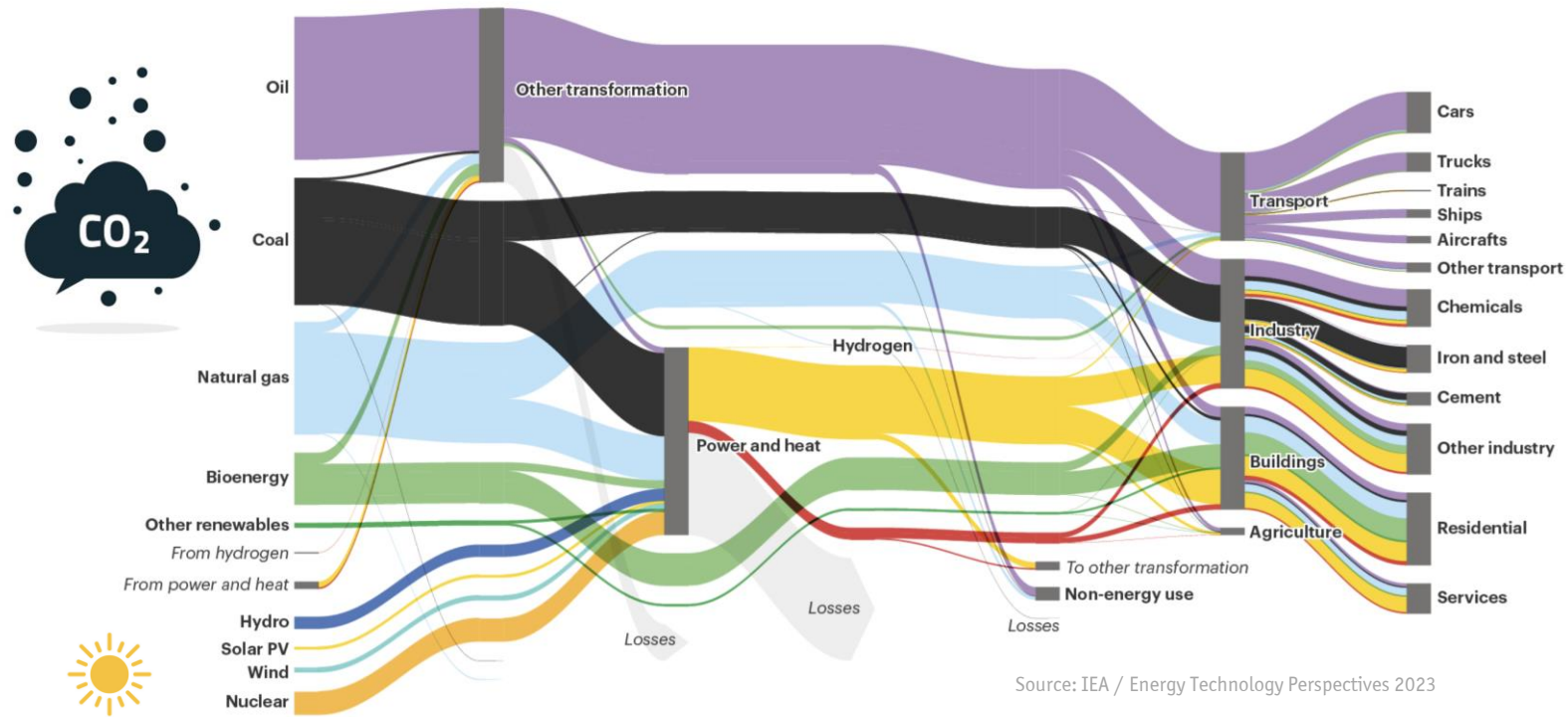
Outline



- ▶ *Decarbonization*
- ▶ *Internet of E-Energy*
- ▶ *The Elephant in the Room*
- ▶ *Design for Circularity*
- ▶ *Power Electronics 5.0*

The Challenge

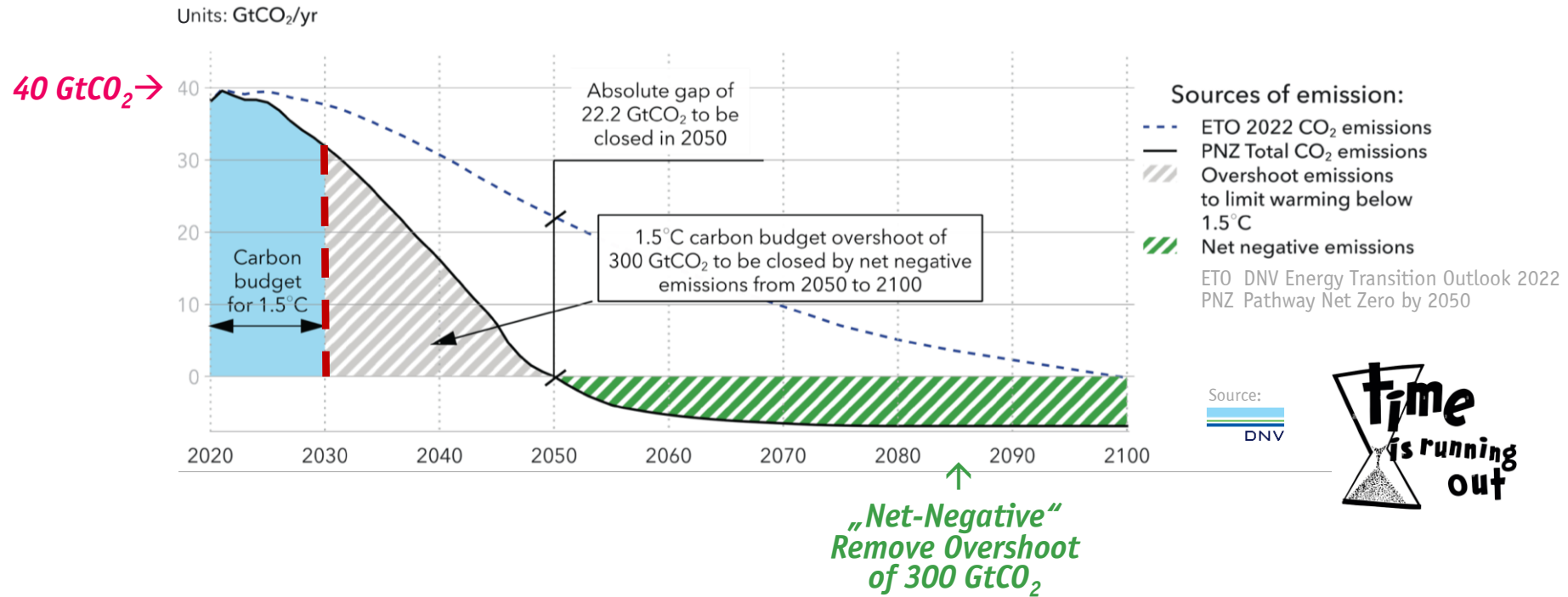
■ Global Energy Flows — 2021



■ Large Share of Fossil Fuels (!)

Decarbonization / Defossilization

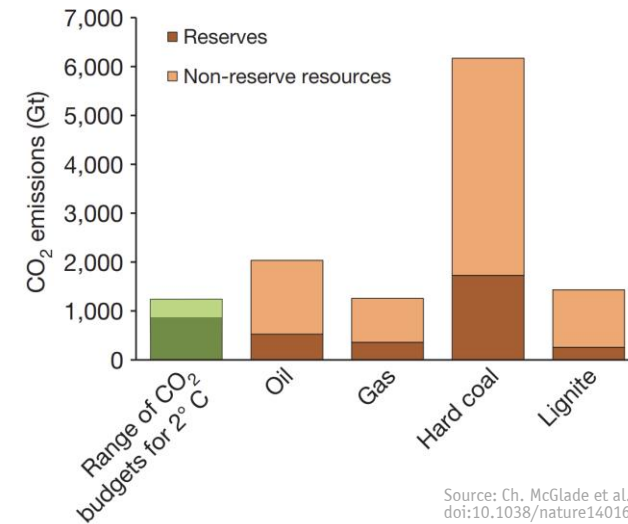
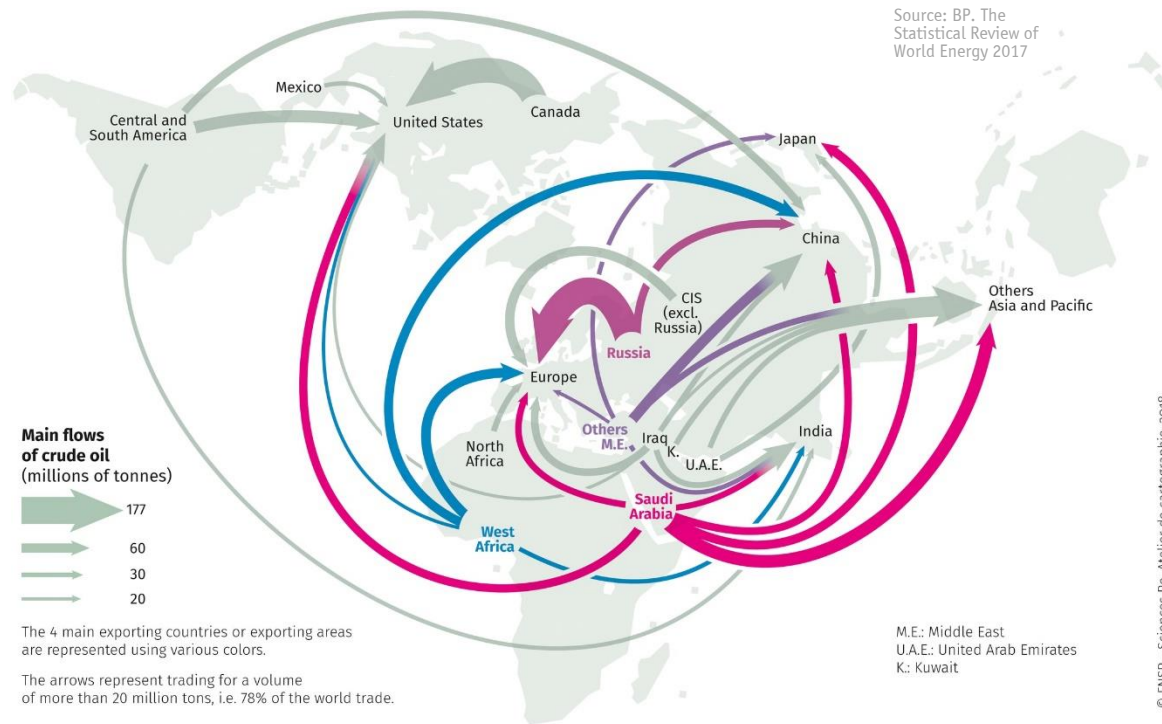
- "Net-Zero" Emissions by 2050 & Gap to be Closed
- 50 GtCO_{2eq} Global Greenhouse Gas Emissions / Year → 280 GtCO₂ Budget Left for 1.5°C Limit



- Challenge of Stepping Back from Oil & Gas
- Human History — Transition from Lower to Higher Energy Density Fuel — Wood → Coal → Oil & Gas

Energy Independence / Security of Supply

■ Global Oil Trade (2016) — High Import Dependency of Leading Economies

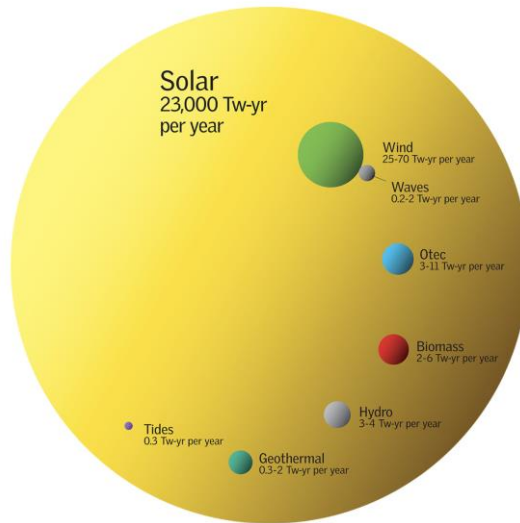


- **2°C Target → Globally, 30% of Oil Reserves | 50% Gas Reserves | > 80% Coal Reserves Should Remain Unused (!)**
- **“The Stone Age Didn't End for Lack of Stone — The Oil Age will End Long Before the World Runs Out of Oil”**

The Opportunity

(2009) 16 TW-yr  16 TW-yr per year  27 TW-yr (2050)

Renewable energy resources per year



100% Conv. Efficiency
Excl. Oceans

Note: Graphical Representation Assumes Spheres Not Circles

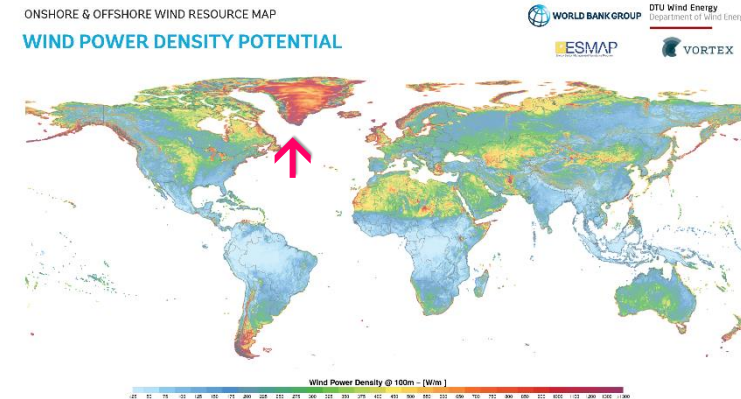
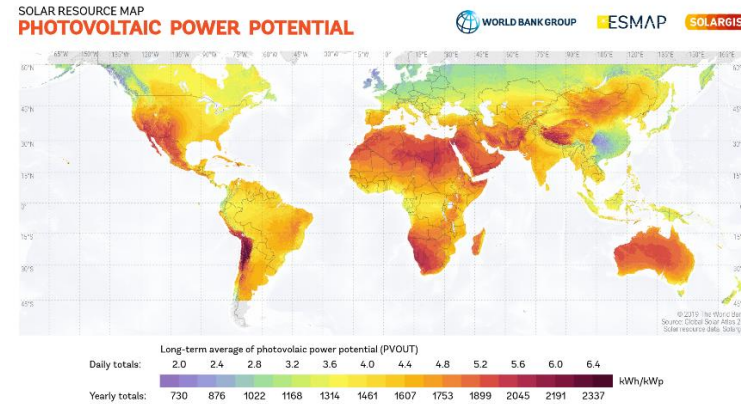
Primary Consumption: 16 TW-yr → 27 TW-yr
Final Consumption: 11 TW-yr → 15 TW-yr

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

Fossil energy resources - total reserve left on earth

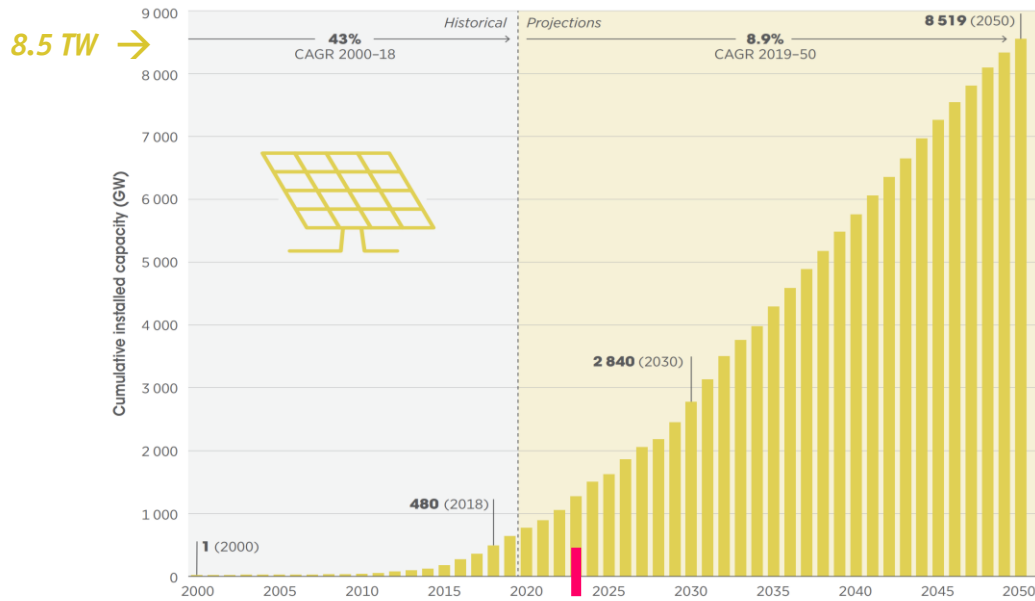


Global Distribution of Solar & Wind Resources



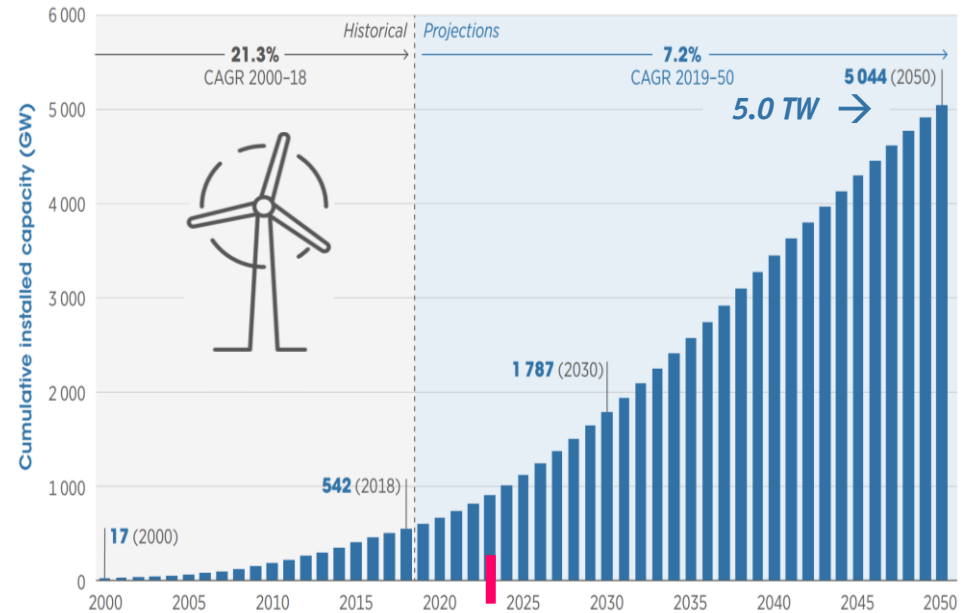
The Approach

- Outlook of Global Cumulative Installations Until 2050 / Add. 1000 GW Off-Shore Wind Power
- In 2050 Deployment of 370 GW/Year (PV) & 200 GW/Year (On-Shore Wind) incl. Replacements



Sources: Historical values based on IRENA's renewable energy statistics (IRENA, 2019c) and future projections based on IRENA's analysis (2019a).

- CAGR of $\approx 9\%$ up to 2050 → 8500 GW

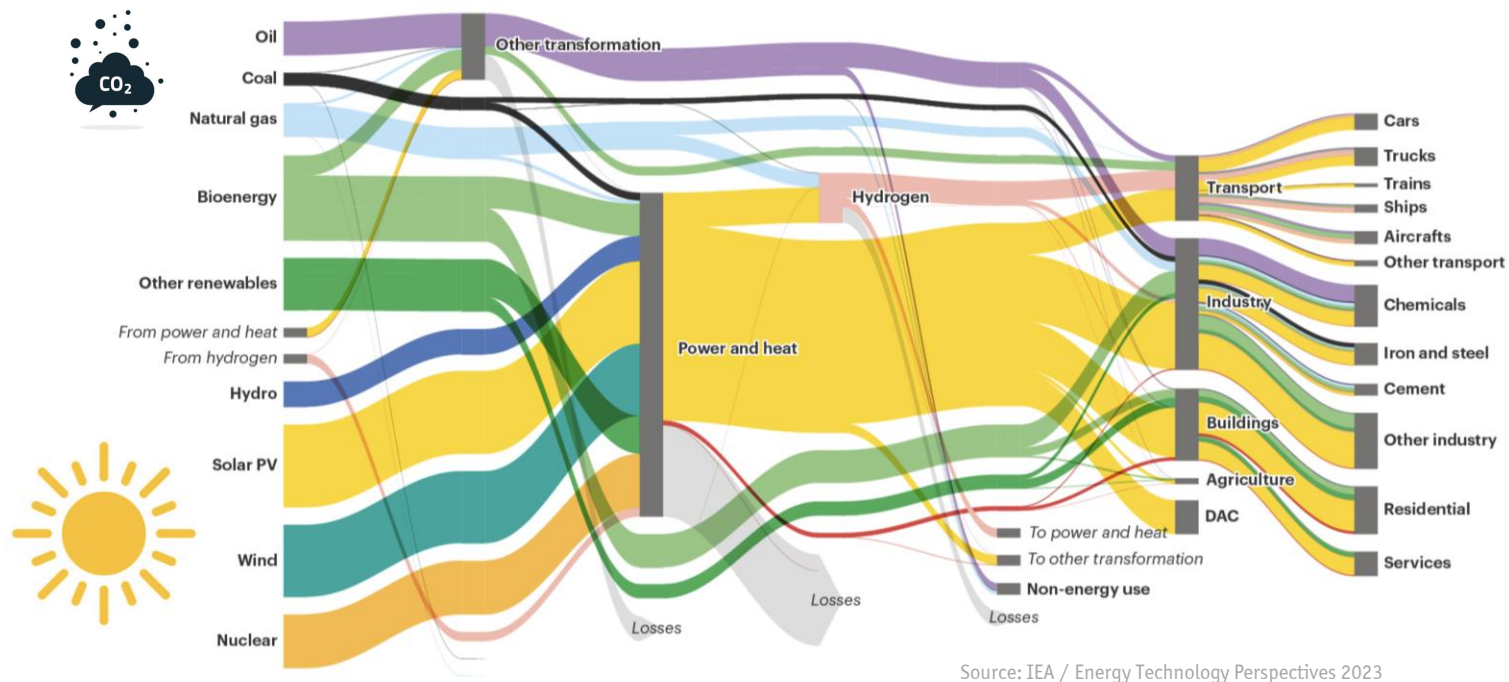


Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

- CAGR of $\approx 7\%$ up to 2050 → 5000 GW

Net-Zero CO₂ by 2050

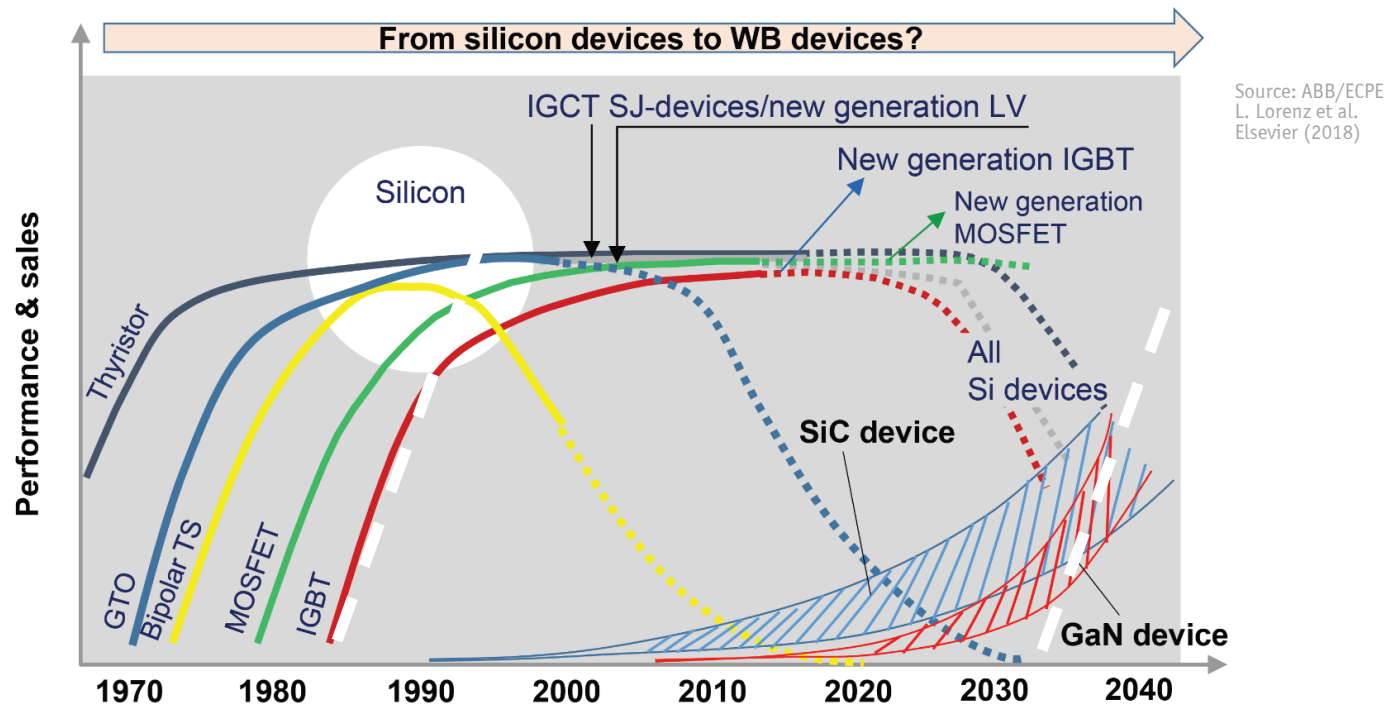
Global Energy Flows — 2050 / Net-Zero Scenario



Dominant Share of Electric Energy — Power Electronics as Key Technology (!)

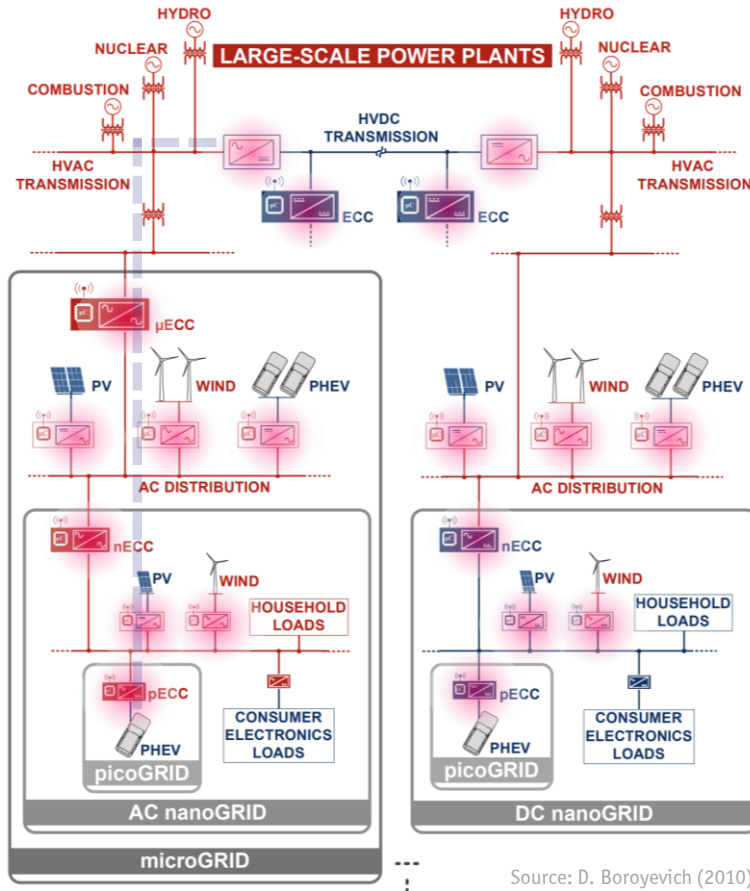
Remark New Disruptive Technologies (?)

- 2050 → No Fundamentally New Concepts Product-Ready in 20+ Years Time Frame (!)
- Main Barriers to Net-Zero Multi-Carrier Energy Systems Deployment are Social & Political & Institutional



- E.g. 10...20 Years Introduction Phase of New Power Semiconductor Technologies

The in the Room — WHAT WE'RE NOT TALKING ABOUT



Source: D. Boroyevich (2010)

- 25'000 GW Installed Ren. Generation in 2050
- 15'000 GWh Batt. Storage
- 4x Power Electr. Conversion btw Generation & Load
- 100'000 GW of Installed Converter Power
- 20 Years of Useful Life



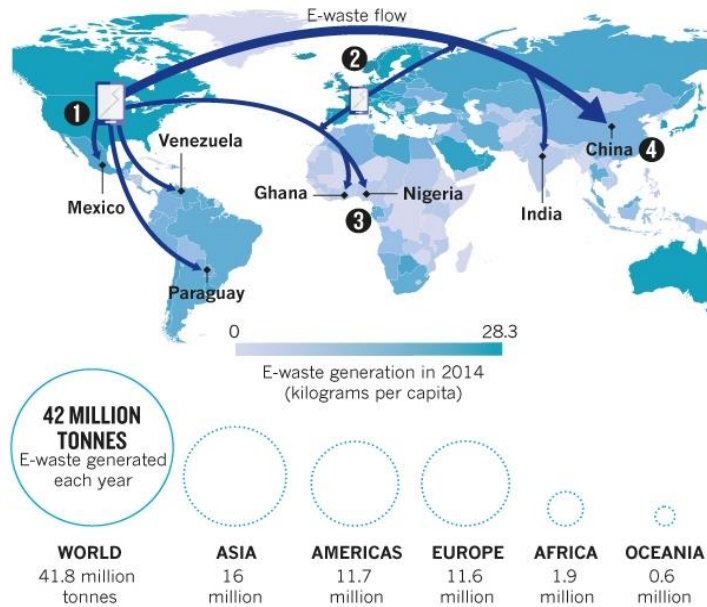
Source: www.e-waste-recyclers.co.in

- 5'000 GW_{eq} = 5'000'000'000 kW_{eq} of E-Waste / Year (!)
- 10'000'000'000 \$ of Potential Value

The in the Room — WHAT WE NEED TO TALK ABOUT !

- 52'000'000 Tons of Electronic Waste Produced Worldwide in 2021 → 74'000'000 Tons in 2030
- Increasingly Complex Constructions → No Repair or Recycling

Source: Green IT Solution

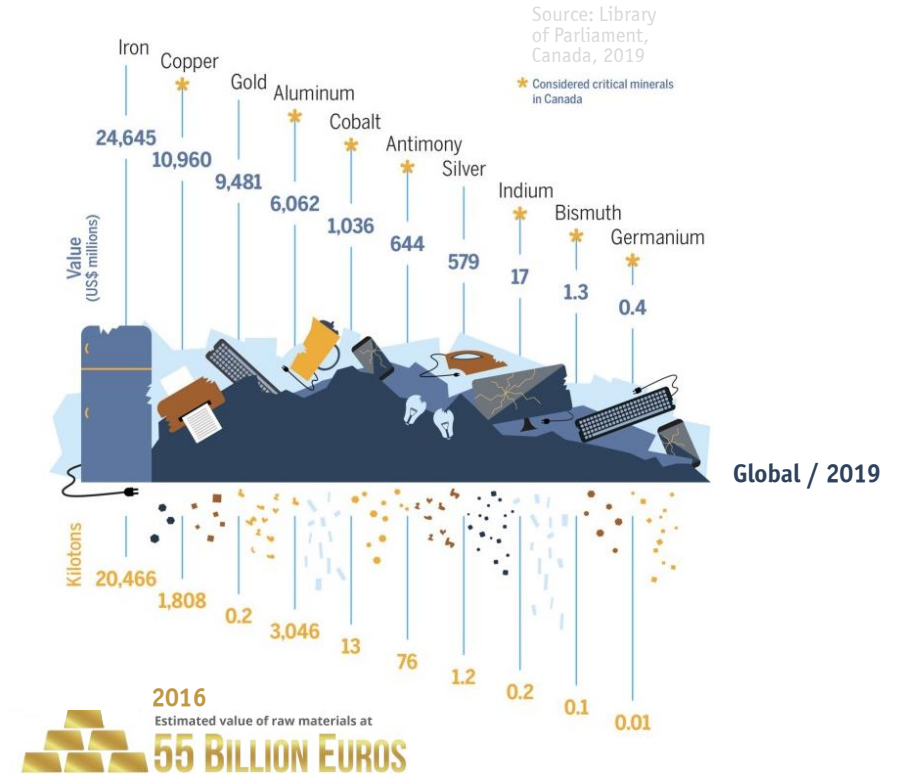


Source: nature

- Growing Global E-Waste Streams → Regulations Mandatory (!)

The Paradigm Shift (1)

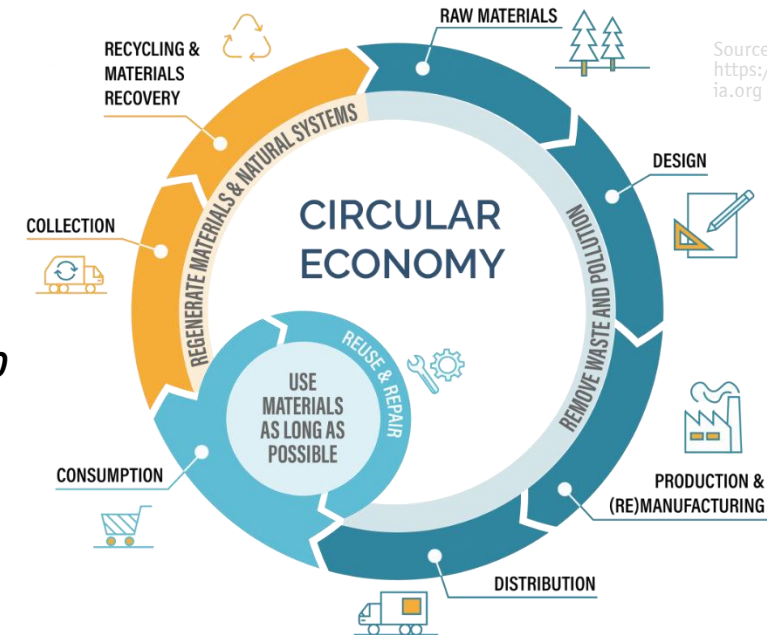
- **Growing Global E-Waste Streams / < 20% Recycled**
- **120'000'000 Tons of Global E-Waste in 2050**



- **“Linear” Economy / Take-Make-Dispose → “Circular” Economy / Perpetual Flow of Resources**
- **Resources Returned into the Product Cycle at the End of Use**
- **E-Waste is an “Urban Mine” w/ Great Economic Potential**

The Paradigm Shift (2)

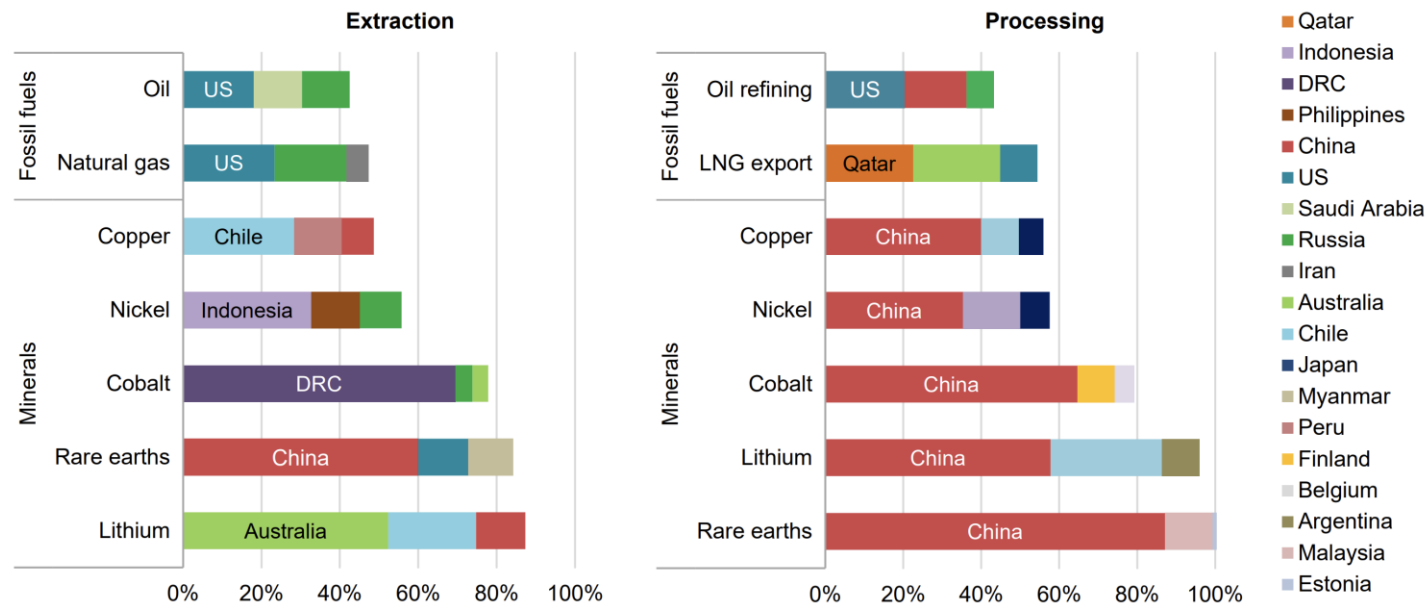
- Growing Global E-Waste Streams / < 20% Recycled
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- “Linear” Economy / Take-Make-Dispose → “Circular” Economy / Perpetual Flow of Resources
- Resources Returned into the Product Cycle at the End of Use

Critical Minerals

■ Production of Selected Minerals Critical for the Clean Energy Transition



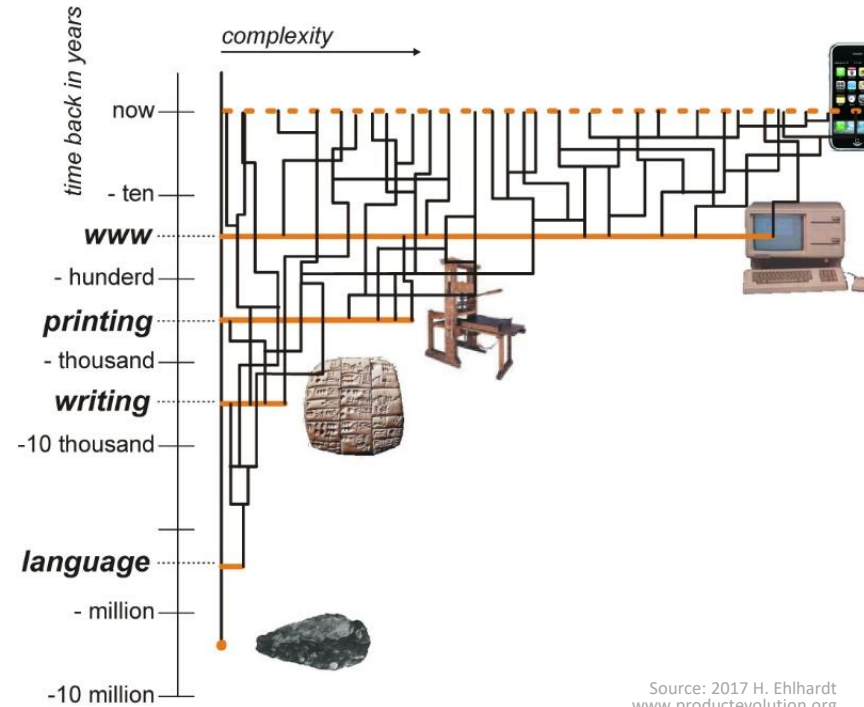
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

Shares of top three producing countries, 2019

■ Extraction & Processing More Geographically Concentrated than for Oil & Nat. Gas (!)

Complexity Challenge

- Technological Innovation — **Increasing Level of Complexity & Diversity of Modern Products**
- Exp. Accelerating Technological Advancement (R. Kurzweil)

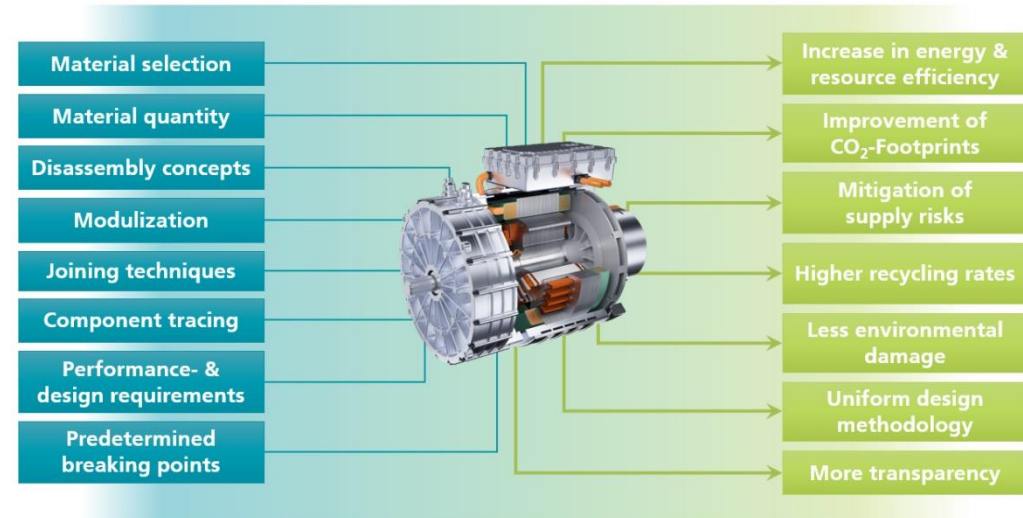


- **Ultra-Compact Systems / Functional Integration — Main Obstacle for Material Separation**

Design for Repairability & Circularity

- **Eco-Design** — Reduce Environmental Impact of Products, incl. Energy Consumption Over Life Cycle
- **Re-Pair / Re-Use / Disassembly / Sorting & Max. Material Recovery**, etc. Considered
- **EU Eco-Design Guidelines (!)**

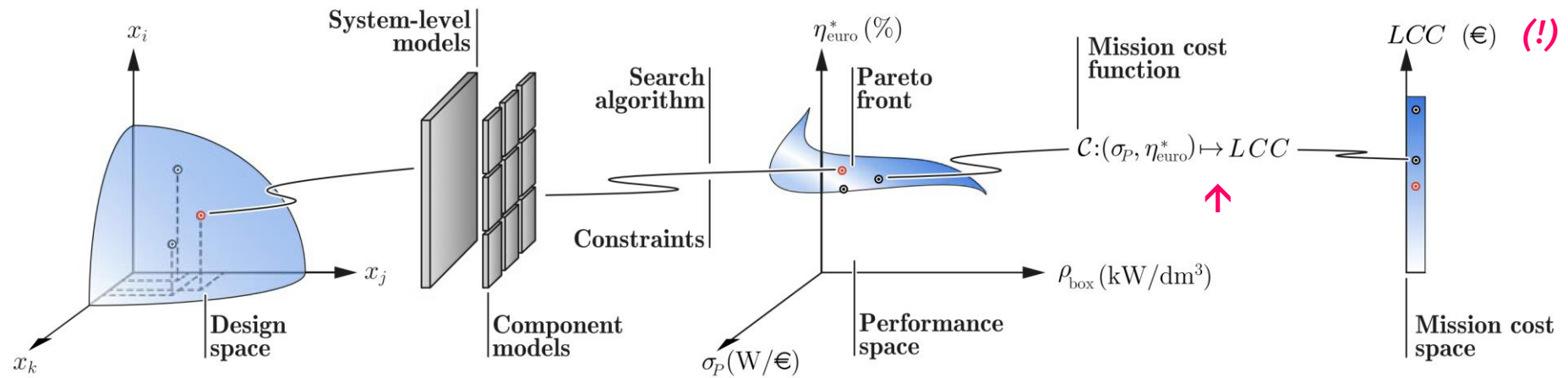
Source: 



- **FAIRPHONE** — Modular Design | Man. Replaceable Parts | 100% Recycl. of Sold Products | Fairtrade Materials
- **80% of Sustainability / Environmental Impact of Products are Locked-In at the Design Phase**

Multi-Objective Optimization

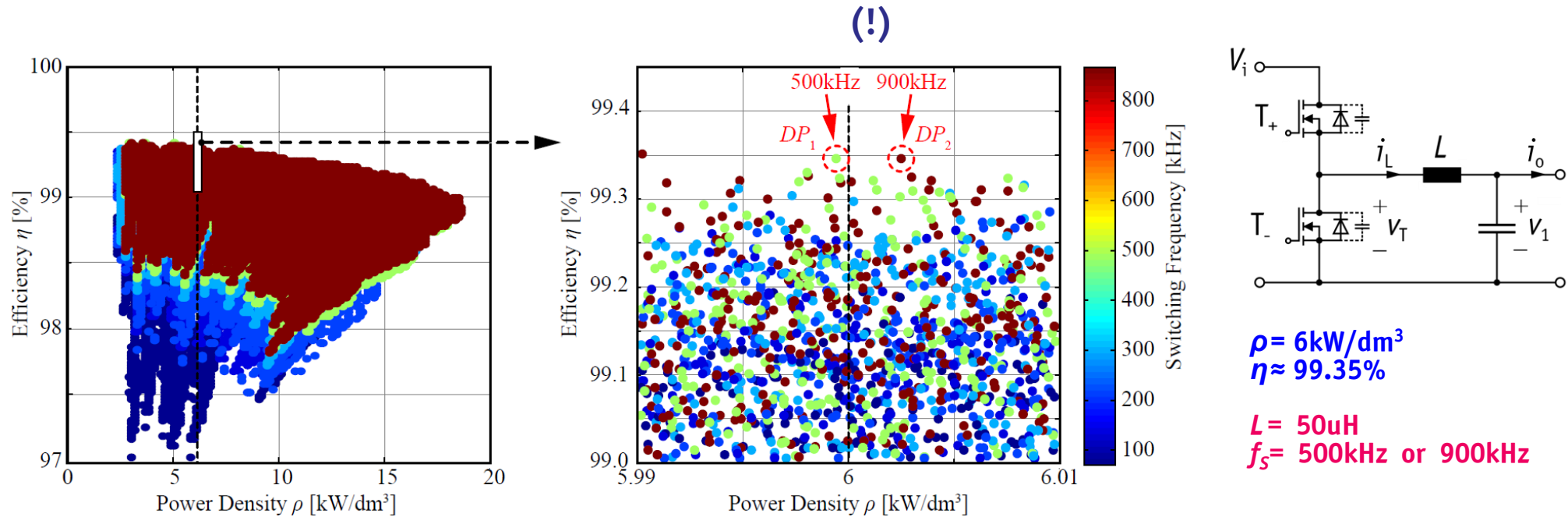
- *Typ. Performance Indices* — Efficiency η [%] | Power Density ρ [kW/dm³] | Rel. Cost σ [kW/\$]
- *Consideration of Specific Operating Points OR Mission Profile*



- *Mission Profile* — Power Loss \rightarrow Energy Loss / **Life-Cycle Cost (!)**

Design Space Diversity (1)

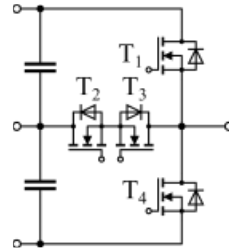
- Very Different Design Space Coordinates Map to Very Similar Performance Space Coordinates



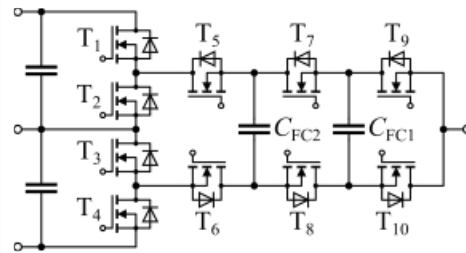
- Example of GOOGLE Littlebox Challenge 1.0 Design Optimization w/ PWM Operation & Ideal Switches
- Mutual Compensation of HF and LF Loss Contributions

Design Space Diversity (2)

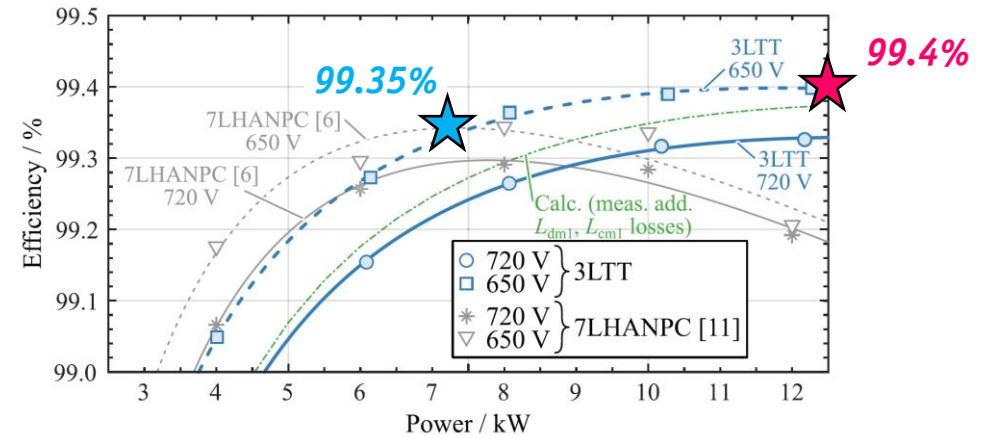
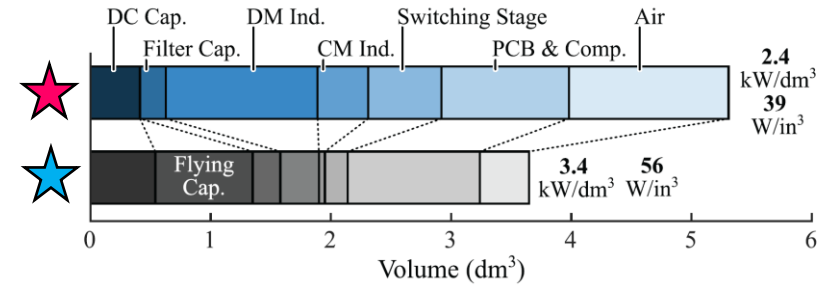
- **Two Concepts / Similar Specs** — 12.5 kW, 650...720V_{DC}, CISPR 11 Class A — **Similar Performance ($\eta_{CEC} = 99.1\%$)**
- **Differences in Environmental Impact (?)**



★ **3-Level All-SiC T-Type PV Inverter**
99.4% @ 2.4 kW/dm³

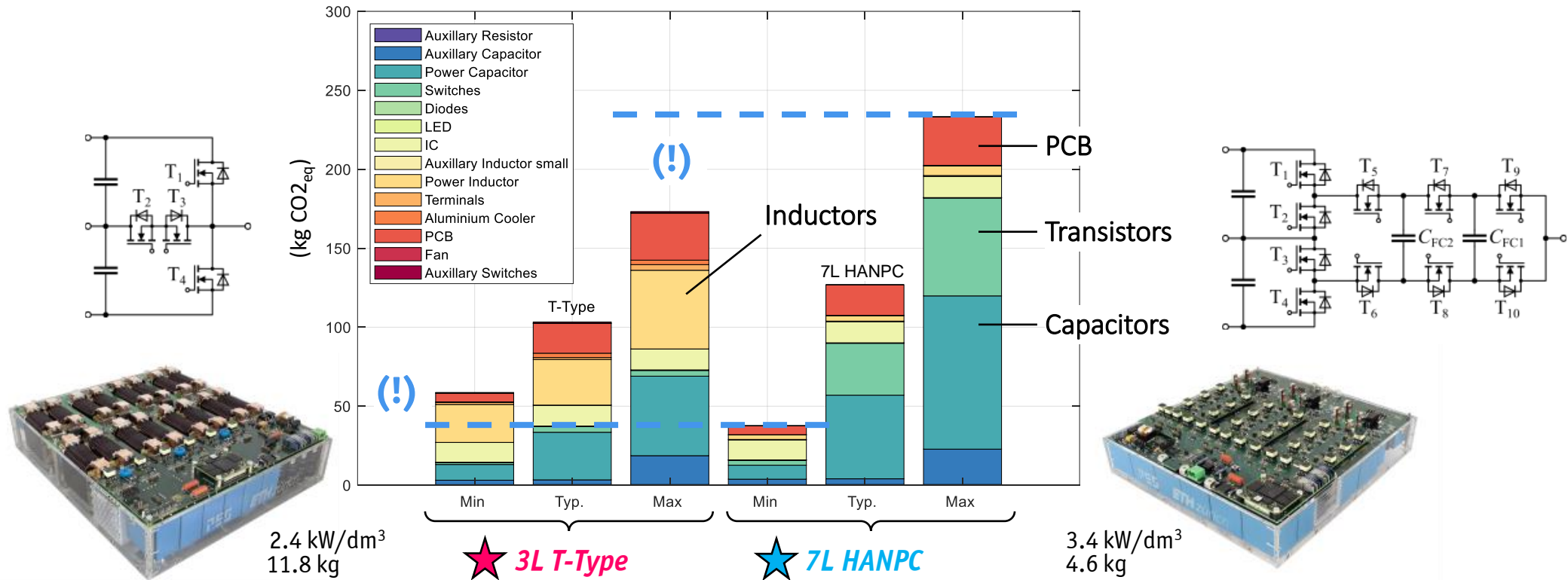


★ **7-Level All-Si HANPC PV Inverter**
99.35% @ 3.4 kW/dm³



A-Posteriori LCA of 3L & 7L PV Inverters

- Two Concepts / *Similar Specs* — 12.5 kW, 650...720V_{DC}, CISPR 11 Class A — *Similar Performance* ($\eta_{CEC} = 99.1\%$)



- Generic Compon. Models / *ecoinvent & Literature as Data Sources* → *Widely Varying Parameter Values / CO_{2eq}-Results*

New Holistic (!) Design Approach

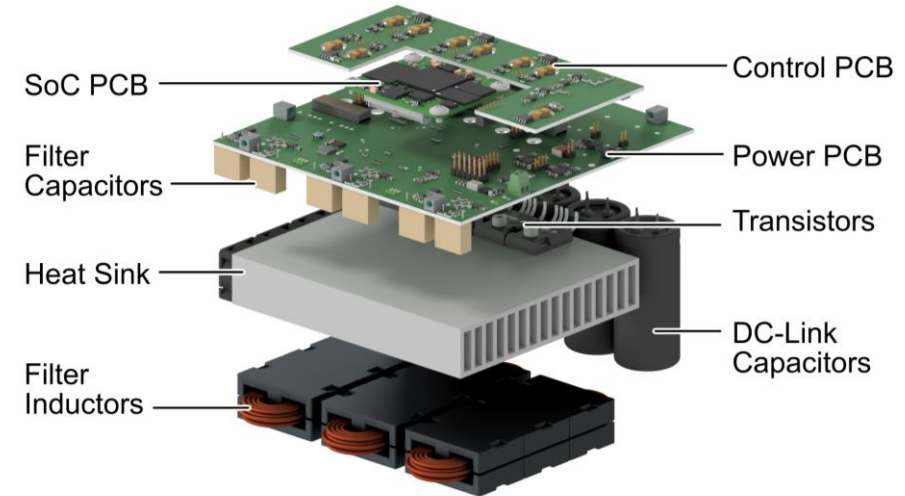
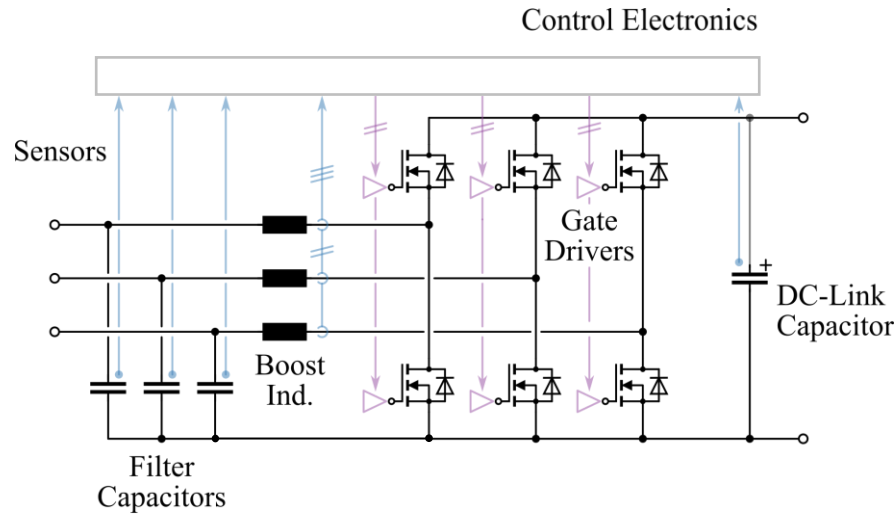
*Multi-Objective Optimization w/
Environmental Impacts as New
Performance Indicators*



Example — Three-Phase AC/DC PEBB

- **Key Power Electronics Building Block (PEBB) for Three-Phase PFC Rectifiers & Inverters**

10 kW
 400 V_{AC} Mains
 800 V_{DC} Output
 1200 V SiC

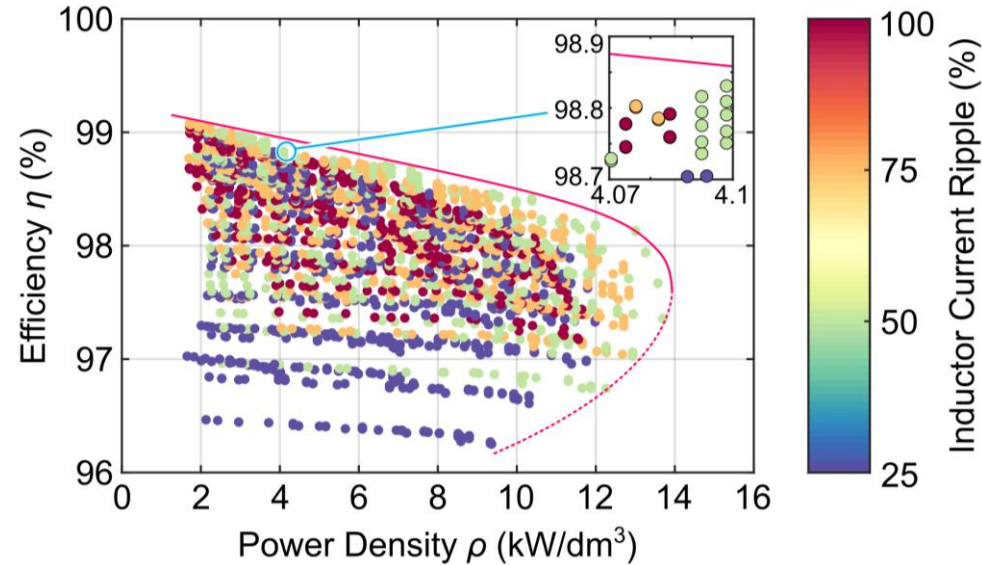


- **Main Components Considered (Losses, Volume, CO_{2eq})**
- **Power Trans., Heat Sink, Boost Ind., DC-Link Cap., Filter Cap., Gate Drivers, Sensors, Contr. Electr., PCBs**

η - ρ -Multi-Objective Optimization

- *Design Space Diversity — Optimiz. for Min. Environmental Impact w/o Compromising Eff. or Power Density (!)*
- *Example of a Three-Phase Two-Level AC-DC PEBB w/ LC-Input Filter*

10 kW
400 V_{AC} Mains
800 V_{DC} Output
1200 V SiC



■ *Degrees of Freedom*

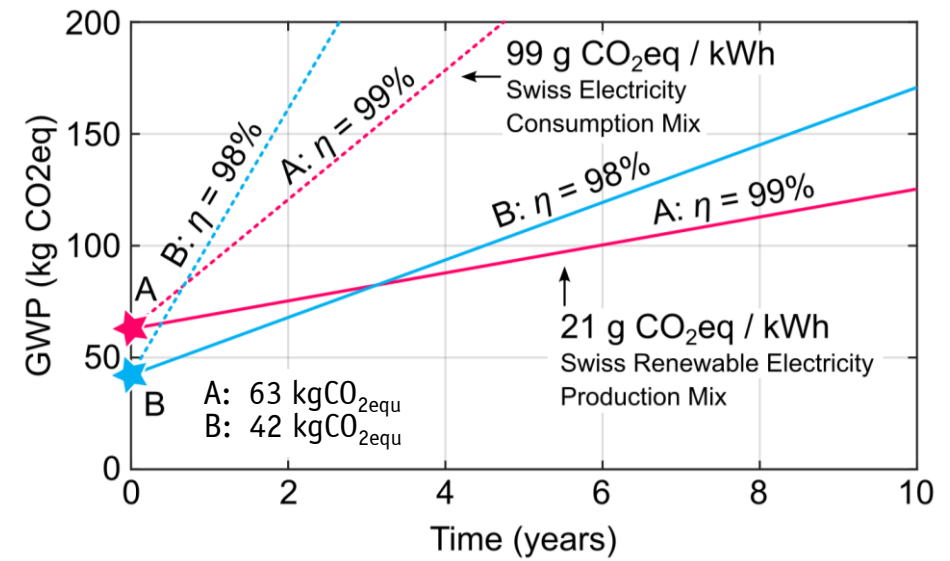
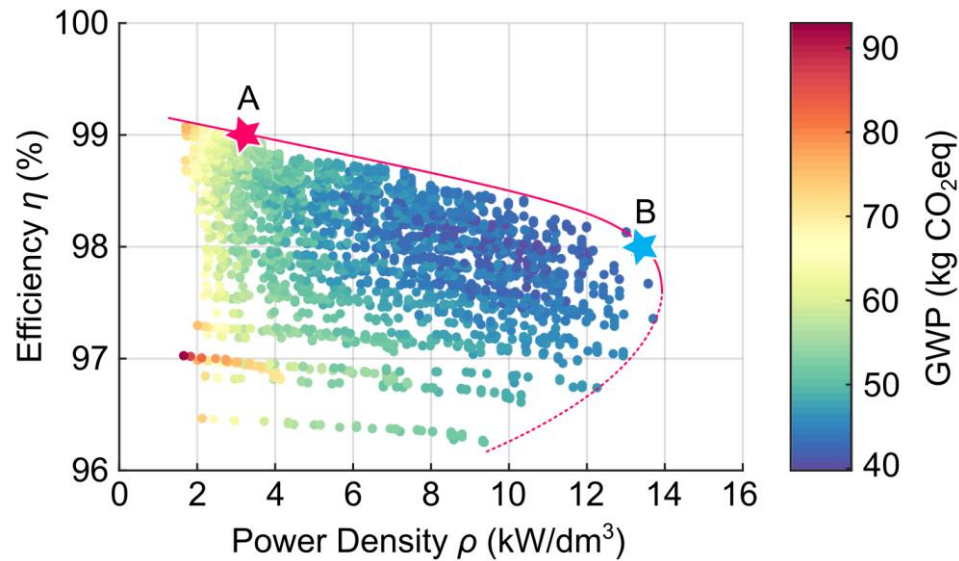
- *Switching Frequency [25...200 kHz]*
- *Rel. Ind. Peak Current Ripple [0.25...1]*
- *Variable Transistor Chip Area*
- *Variable Ind. Size (N87; Solid/Litz Wire)*

■ *Assumptions*

- *Junction Temp. @ 120 °C*
- *Ambient Temp. 40 °C*
- *Necessary Heat Sink Volume via CSPI = 25 W/(K·dm³)*

Efficiency vs. Operating Time Carbon Footprint

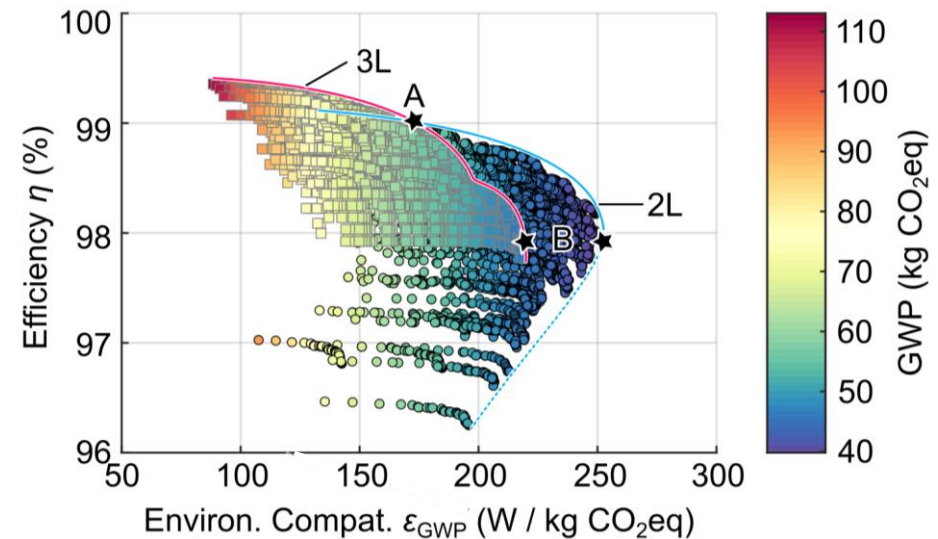
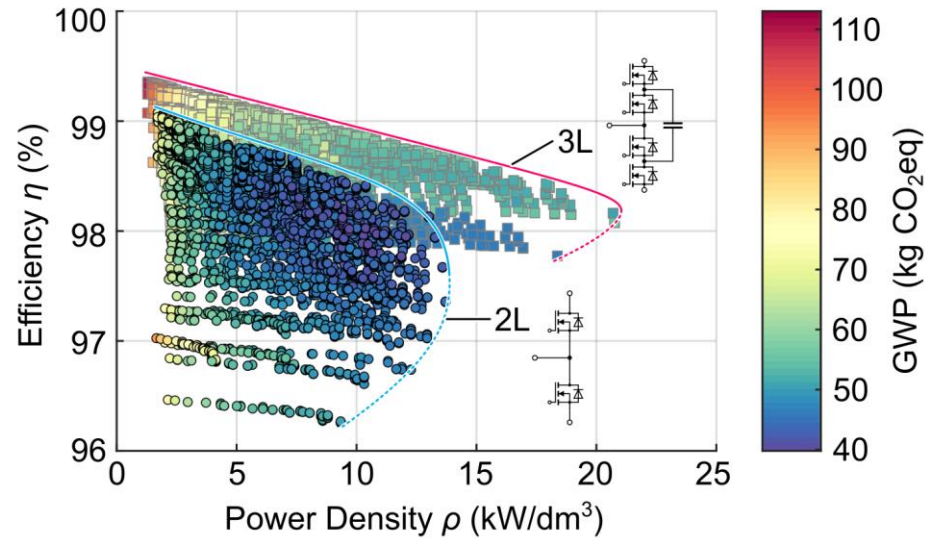
- **Global Warming Potential GWP [kg CO_{2eq}] as Add. Performance Indicator**
- **Mission Matters — Example 8 Hours Full Load per Day Over 10 Years**
- **Electricity Mix Matters — Carbon Intensity**



- **Energy Losses During Use Phase Contribute to Overall GWP**
- **More Eff. Designs w/ Higher Initial GWP Outperform Less Eff. Designs for Longer Operating Times**

2-Level vs. 3-Level PEBB Evaluation

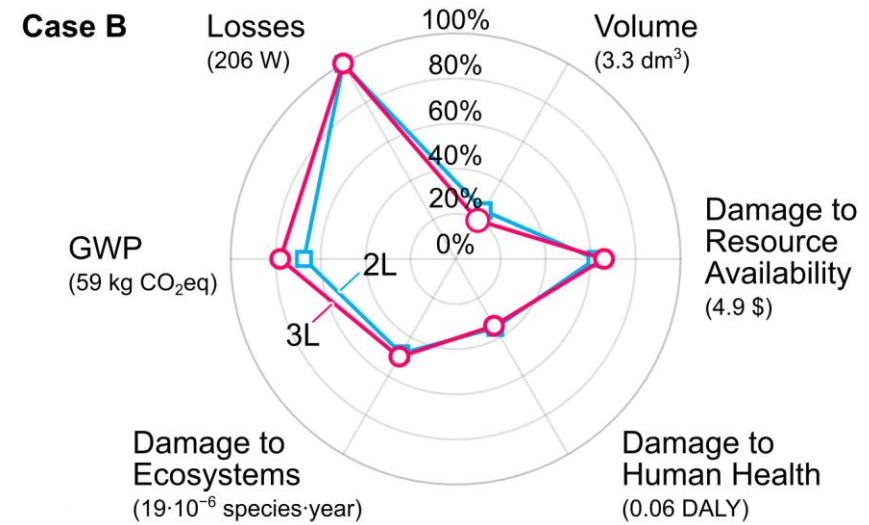
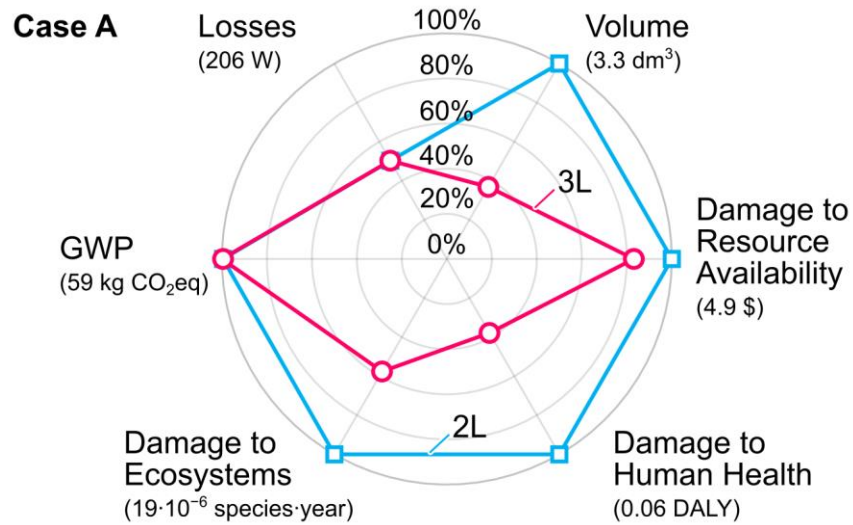
- **3-Level Flying-Capacitor Bridge-Legs** w/ 650 V SiC MOSFETS / **2-Level Bridge-Legs** w/ 1200 V SiC MOSFETS
- 400 V_{AC} Mains | 800 V_{DC} | 10 kW | LC-Filter w/ Same Capacitor Voltage Ripple



- **Higher 3L Inverter Eff. & Power Density BUT Lower Environm. Compatibility [W/kgCO_{2eq}]**
- **Higher 3L Initial GWP Due to Higher # of Power Semiconductors**

Comprehensive Environmental Impact Profile

- Further Environm. Impact Indicators / Volume & ReCiPe 2016 Areas of Protection
- Human Health | Ecosyst. Quality | Resource Scarcity
- Comparative Evaluation of 2L vs. 3L PEBB



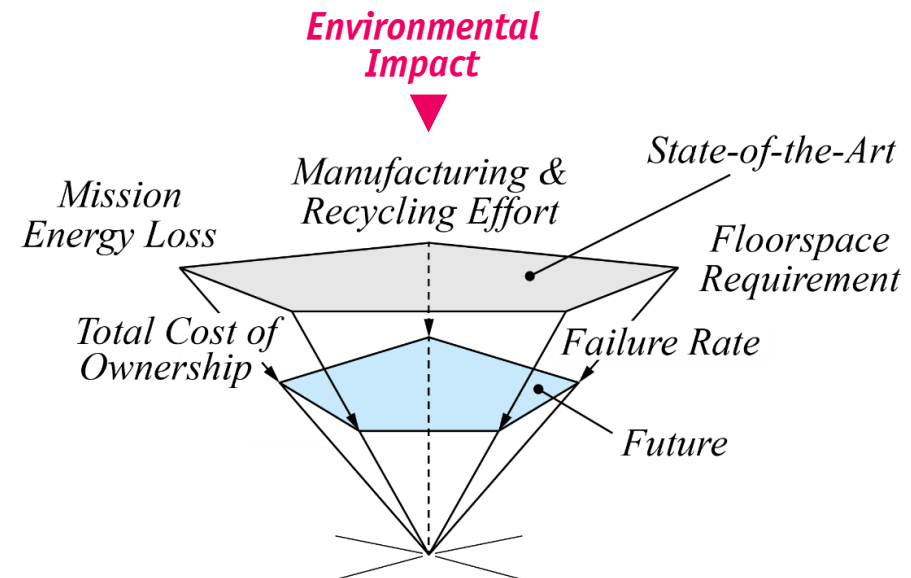
- Case A 99% Eff. @ Equal GWP — Significantly Diff. Volumes & Diff. ReCiPe Performance
- Case B 98% Eff. @ Highest Rel. Environm. Compatibility — Similar Volumes & Environm. Impacts

Future Performance Indicators

- Assuming 20+ Years Lifetime → Systems Installed Today Reach End-of-Life in 2050 (!)
- Life-Cycle Assessment (LCA) Mandatory for All Future System Designs

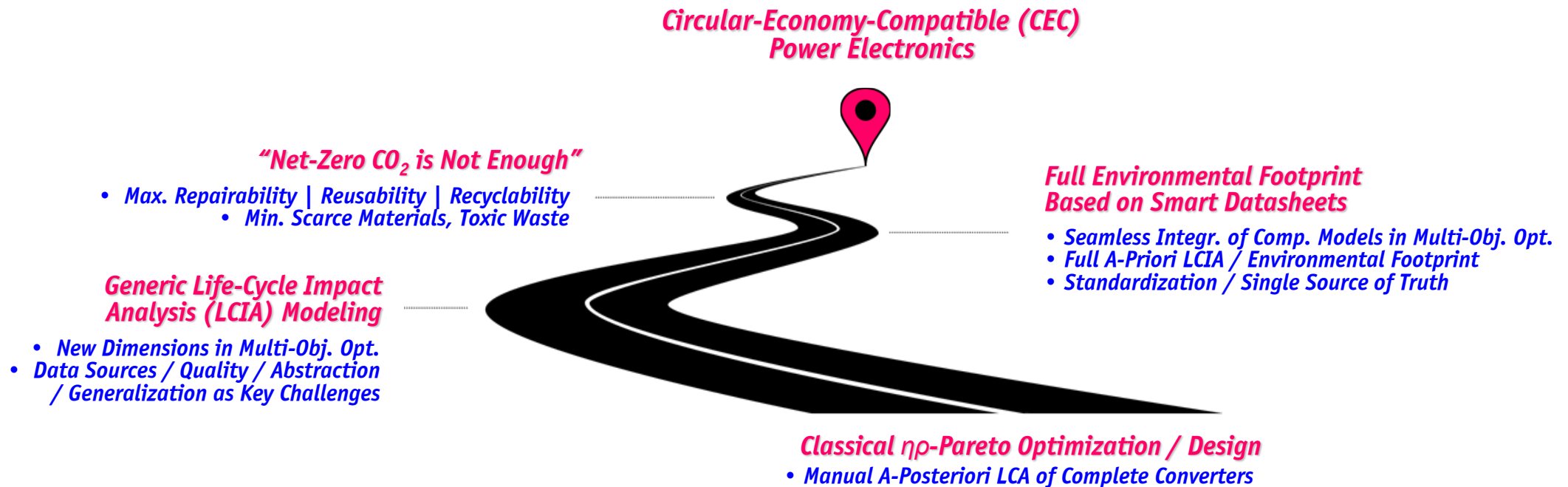
- Complete Set of New Performance Indicators

- Environmental Impact [kgCO₂eq/kW]
- Resource Efficiency [kg_{xx}/kW]
- Embodied Energy [kWh/kW]
- TCO [\$/kW]
- Power Density [kW/m²]
- Mission Efficiency [%]
- Failure Rate [h⁻¹]



CEC-Power Electronics Roadmap

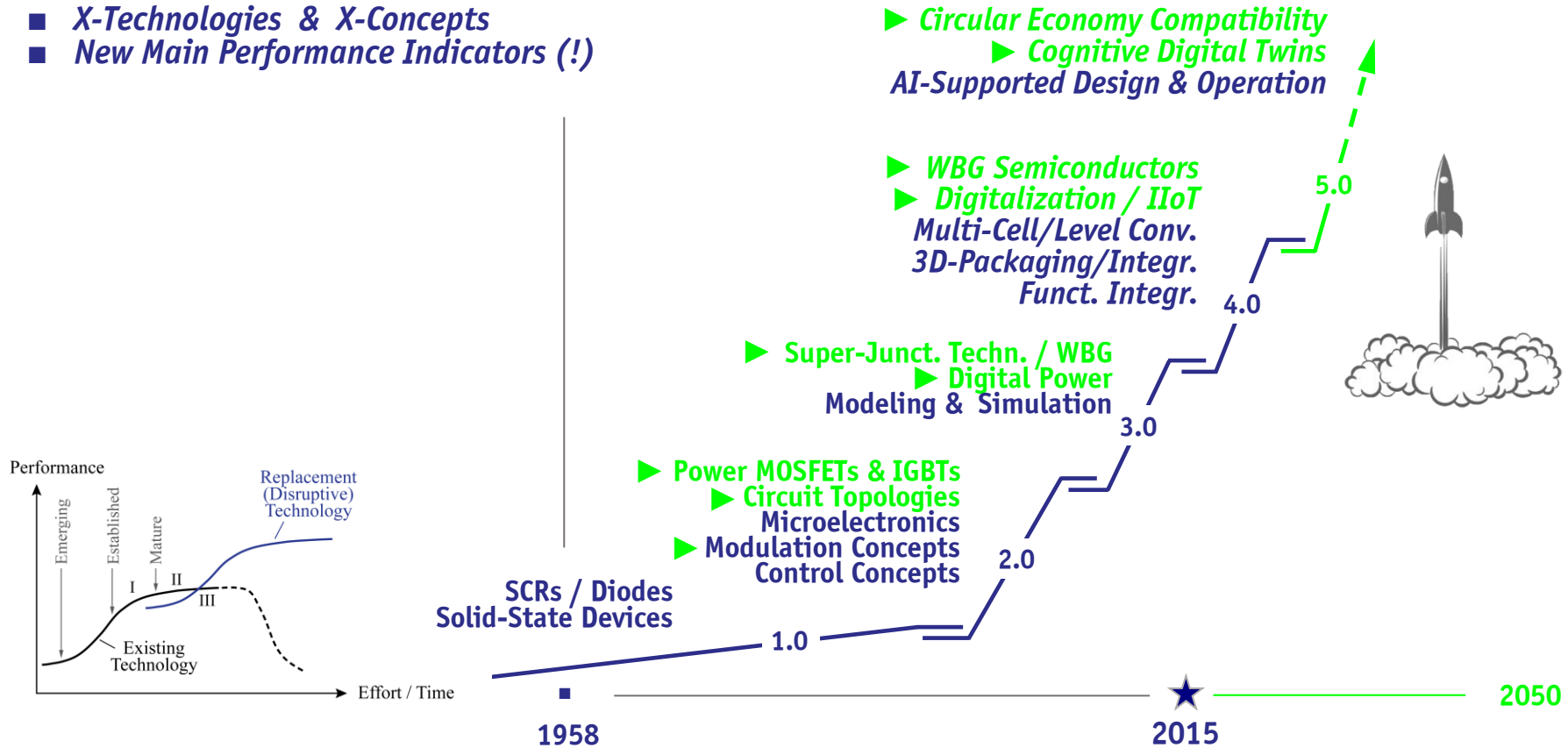
■ Environmental Awareness as Integral Part of Power Electronics Design



■ Automated Design | On-Line Monitoring | Prev. Maintenance | Digital Product Passport

Power Electronics 5.0

- Power Electronics 1.0 → Power Electronics 5.0
- X-Technologies & X-Concepts
- New Main Performance Indicators (!)



Thank You !

