Net-Zero-CO_2 by 2050 is NOT Enough (!)

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Let's Talk About the "Elephant in the Room"

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Source: www.ipu-berlin.de

Net-Zero-CO_2 by 2050 is NOT Enough!

Abstract – The transformation of the fossil-fuel-based energy system into a new Net-Zero-CO2 all-electric system will rely on a massive extension of the electric grid infrastructure and a massive installation of power electronic converters and energy storage systems. However, assuming a typ. 20 years lifetime, converter systems installed today will need to be replaced already by 2050, i.e., at the commonly accepted date for reaching the Net-Zero-CO2 target. Given the scale of the future Internet of Energy, the maintenance or replacement effort at some point will potentially run into depletion of scarce raw materials and large volumes of waste and associated environmental problems. This clearly indicates that “Net-Zero-CO2 by 2050 is NOT Enough” and underlines the urgency of a transition from a Linear Economy to a Circular Economy, which ensures that the Net-Zero-CO2 target is reached on a sustainable basis, i.e., with minimized environmental impact in all aspects.

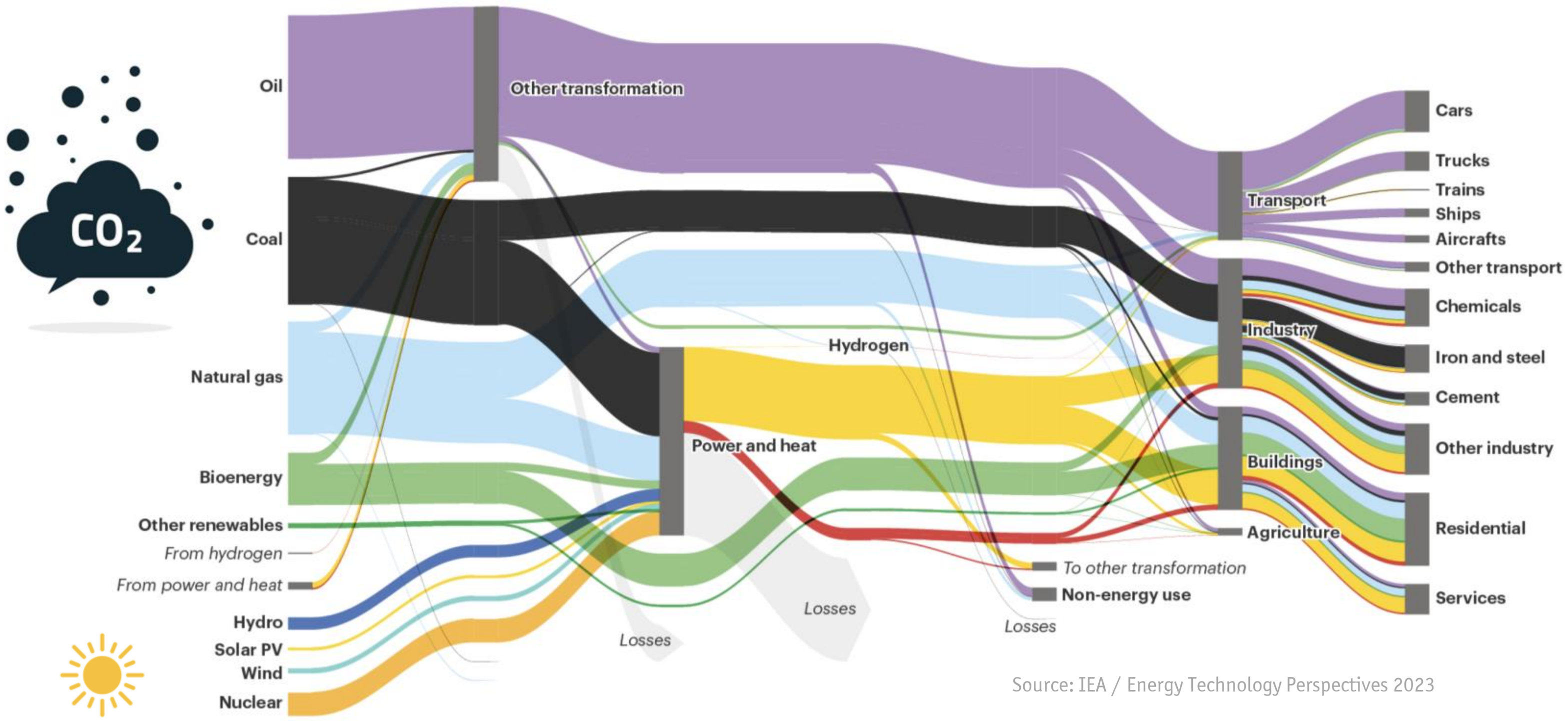
The talk will first introduce metrics for measuring the environmental impact of power electronic converters and explain the concepts of Life Cycle Analysis of systems and of a Circular Economy in contrast to the Linear Economy dominating today. Next, the utilization of degrees of freedom of the design of power electronic converters for maximizing repairability, reusability, and recyclability while minimizing the use of critical materials, toxic substances, and ultimately waste will be shown at the example of EV chargers and PV inverters employing different power semiconductor technologies and circuit topologies. Finally, a roadmap for the introduction of environmental awareness into the power electronics design process will be proposed in order to ensure that power electronics as the main enabler of a Net-Zero-CO2 society reaches full compatibility with a Circular Economy at the earliest point in time possible.

Outline

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

The Challenge

- *Global Energy Flows — 2021*

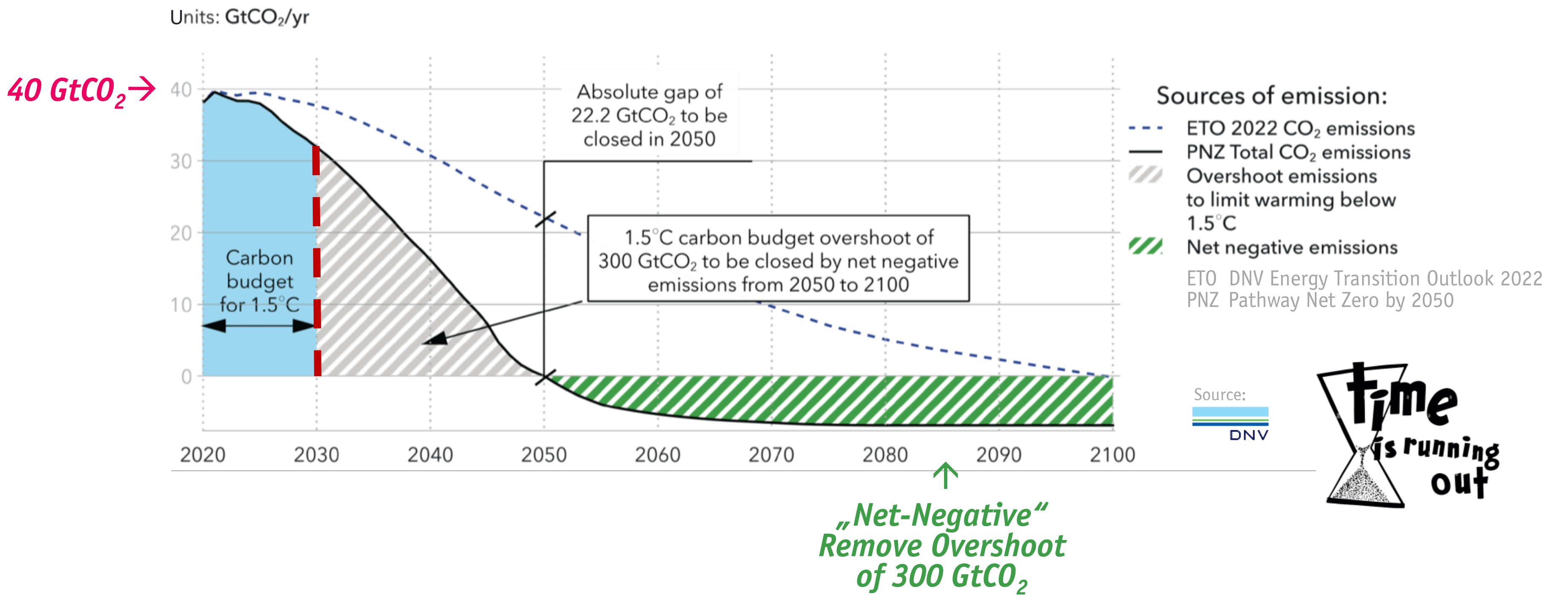


Source: IEA / Energy Technology Perspectives 2023

- *Large Share of Fossil Fuels (!)*

Decarbonization / Defossilization

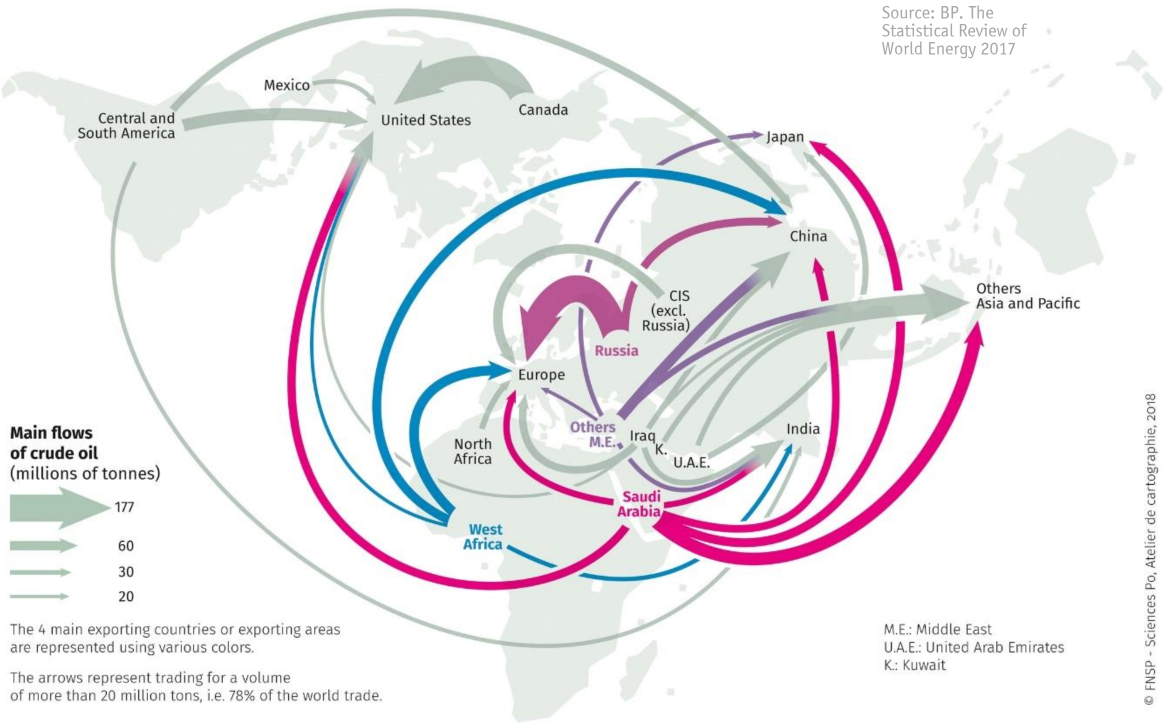
- *"Net-Zero" Emissions by 2050 & Gap to be Closed*
- *50 $GtCO_{2eq}$ Global Greenhouse Gas Emissions / Year → 280 $GtCO_2$ Budget Left for 1.5°C Limit*

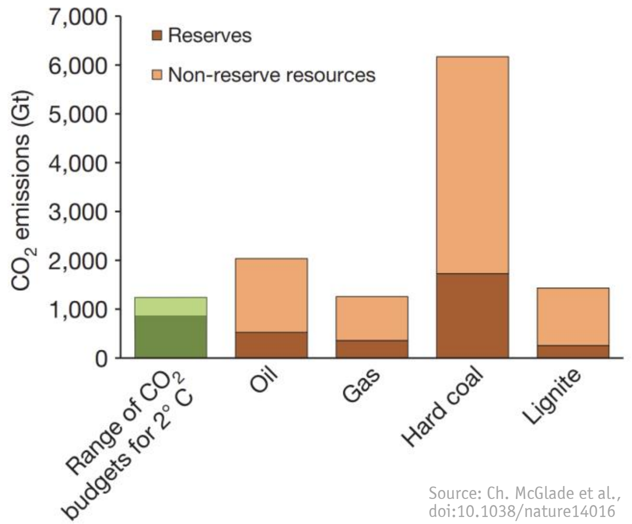


- *Challenge of Stepping Back from Oil & Gas*
- *Human History — Transition from Lower to Higher Energy Density Fuel — Wood → Coal → Oil & Gas*

Energy Independence / Security of Supply

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



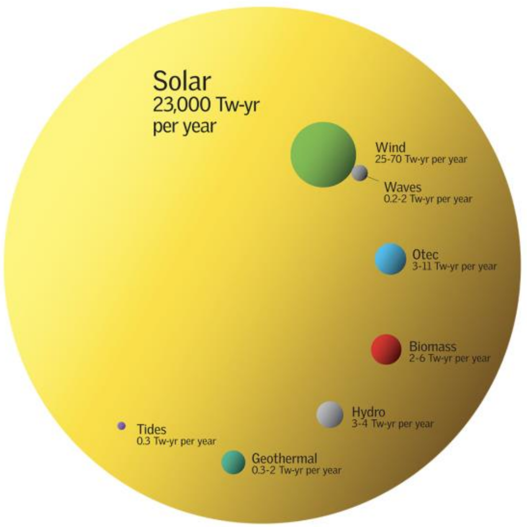


- *2°C Target → Globally, 30% of Oil Reserves | 50% Gas Reserves | > 80% Coal Reserves Should Remain Unused (!)*
- *"The Stone Age Didn't End for Lack of Stone — The Oil Age will End Long Before the World Runs Out of Oil"*

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

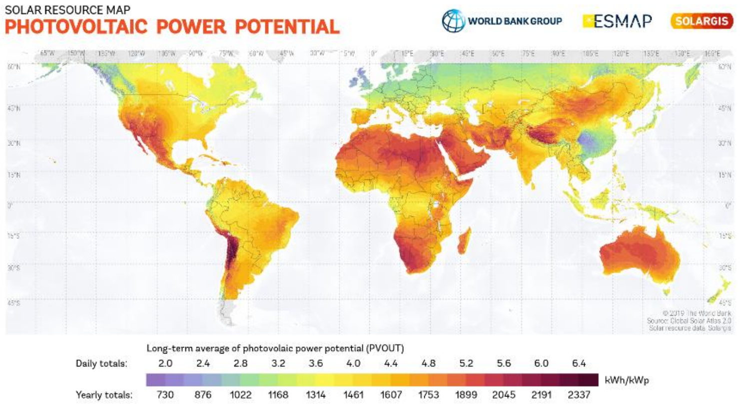
Note: Graphical Representation Assumes Spheres Not Circles

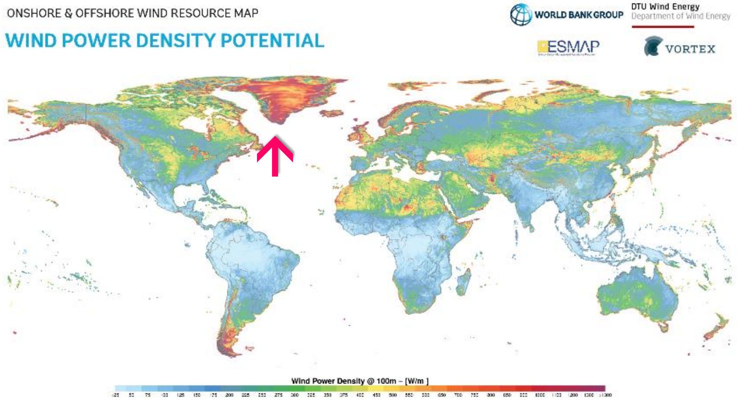
Primary Consumption:
16 TW-yr → 27 TW-yr
Final Consumption:
11 TW-yr → 15 TW-yr

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

Fossil energy resources - total reserve left on earth

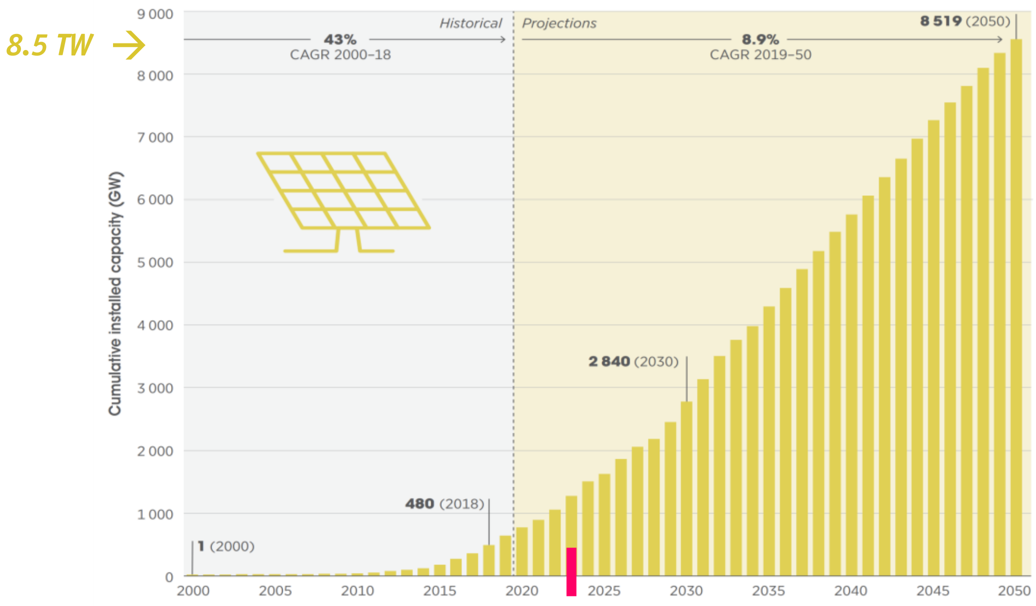
- ***Global Distribution of Solar & Wind Resources***



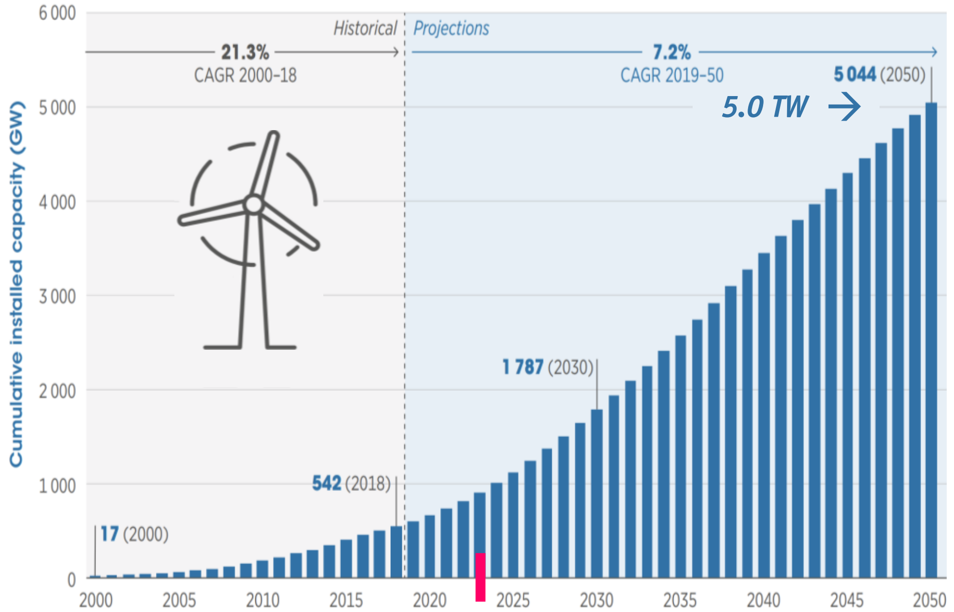


The Approach

- *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).

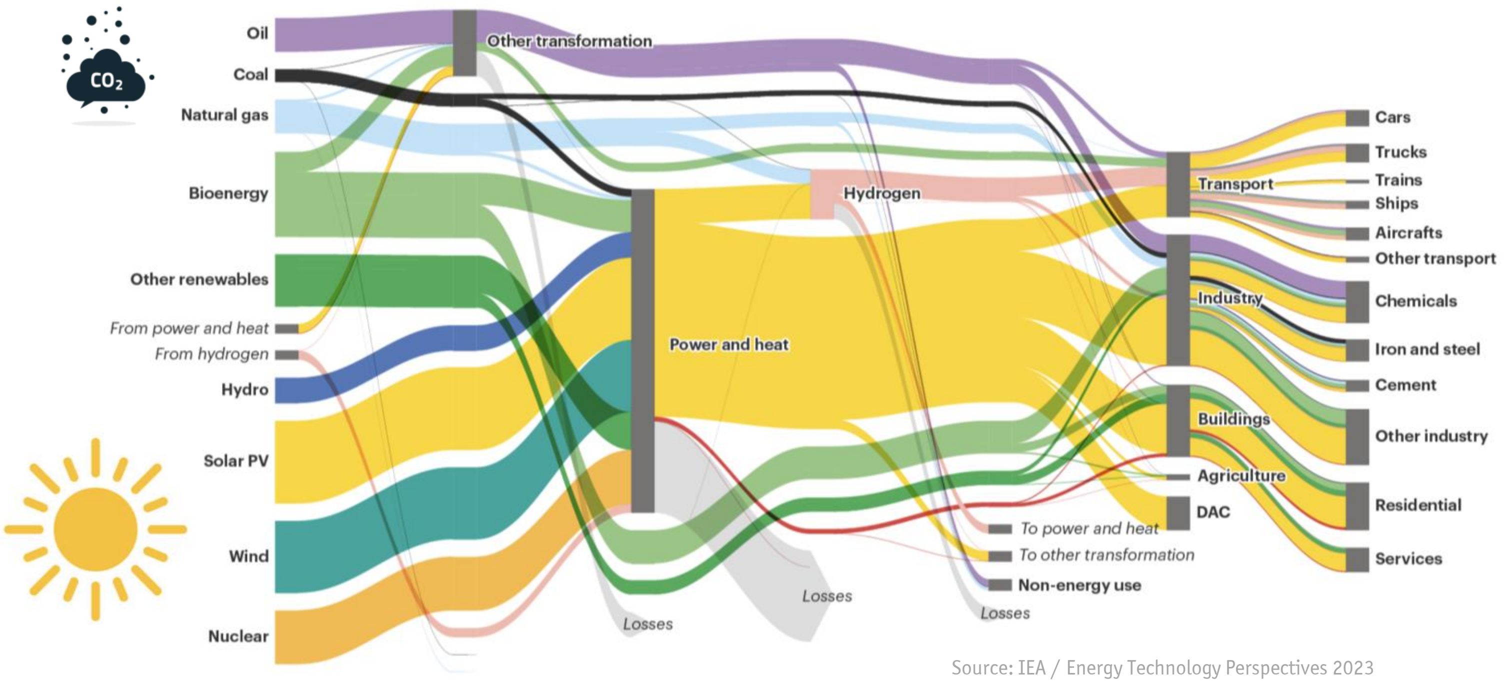


Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

- *CAGR of ≈9% up to 2050 → 8500 GW*
- *CAGR of ≈7% up to 2050 → 5000 GW*

Net-Zero CO_2 by 2050

- *Global Energy Flows — 2050 / Net-Zero Scenario*

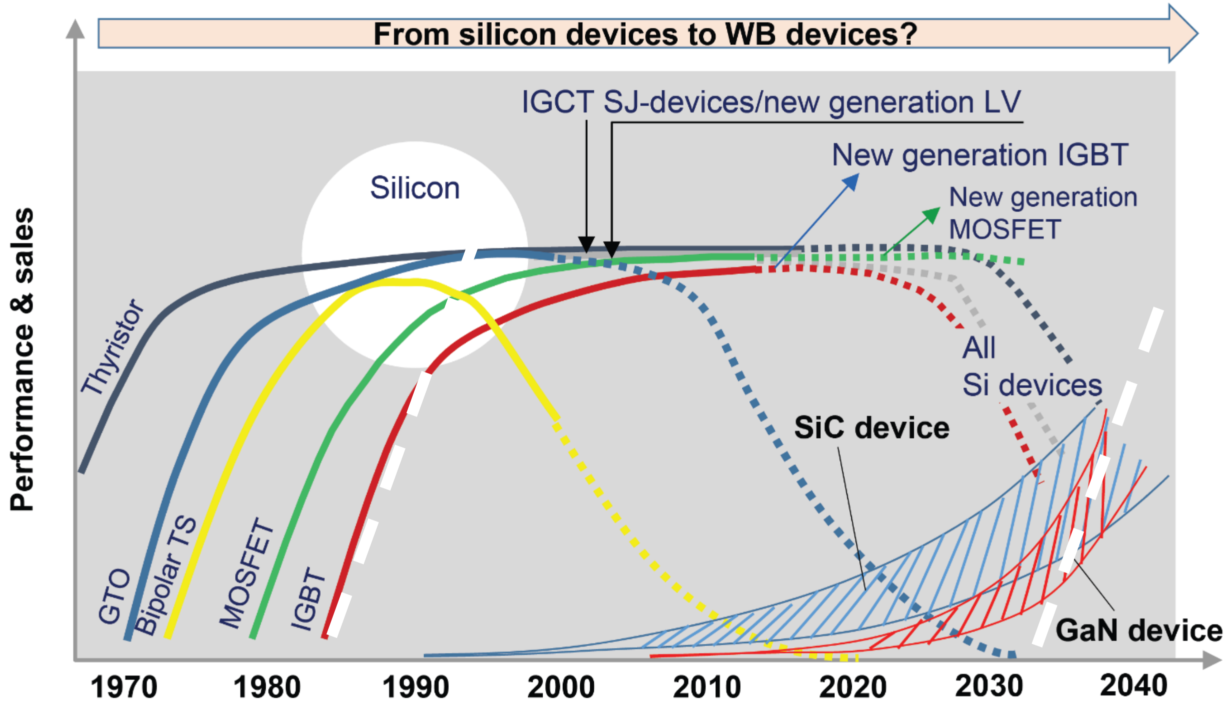


Source: IEA / Energy Technology Perspectives 2023

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

Remark New Disruptive Technologies (?)

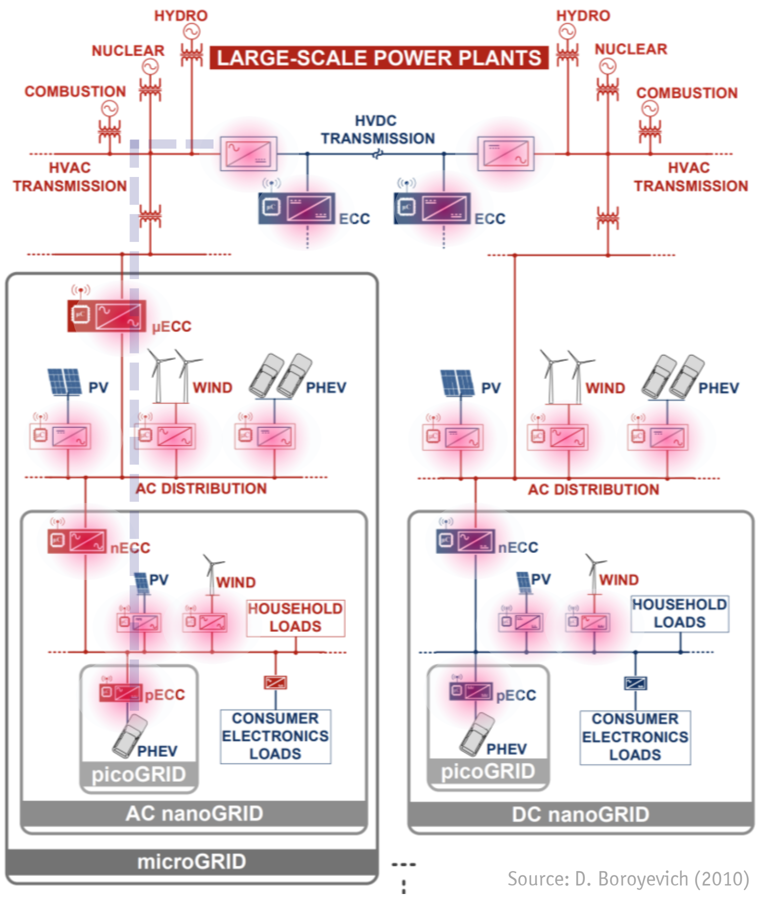
- *2050 → No Fundamentally New Concepts Product-Ready in 20+ Years Time Frame (!)*
- *Main Barriers to Net-Zero Multi-Carrier Energy Systems Deployment are Social & Political & Institutional*



Source: ABB/ECPE
L. Lorenz et al.
Elsevier (2018)

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

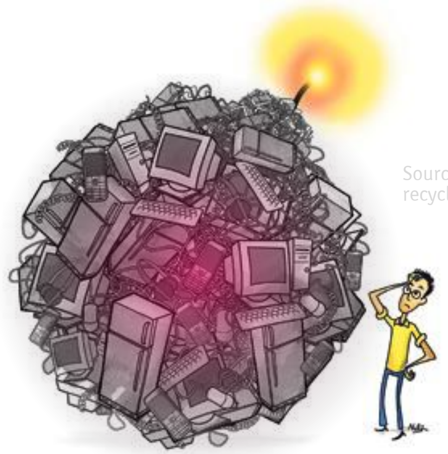
The [elephant] in the Room — WHAT WE´RE NOT TALKING ABOUT



Source: D. Boroyevich (2010)

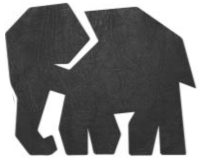
- *25´000 GW Installed Ren. Generation in 2050*
- *15´000 GWh Batt. Storage*

- *4x Power Electr. Conversion btw Generation & Load*
- *100´000 GW of Installed Converter Power*
- *20 Years of Useful Life*

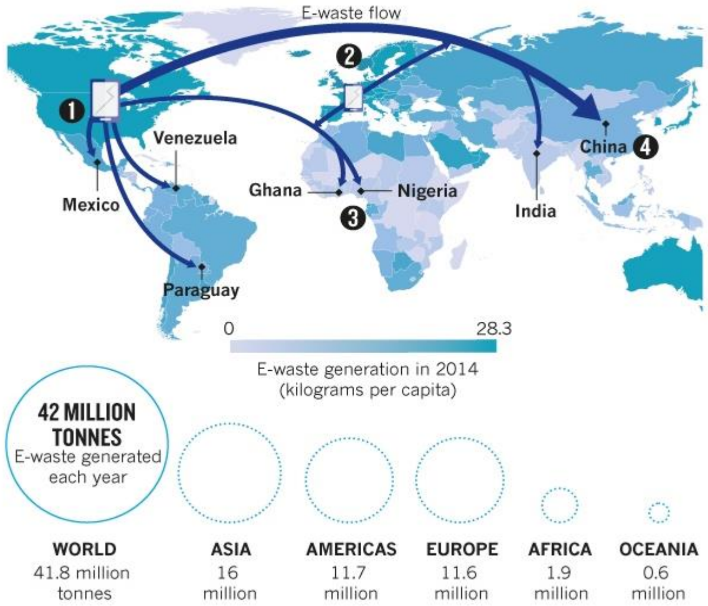


Source: www.e-waste-recyclers.co.in

- *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*



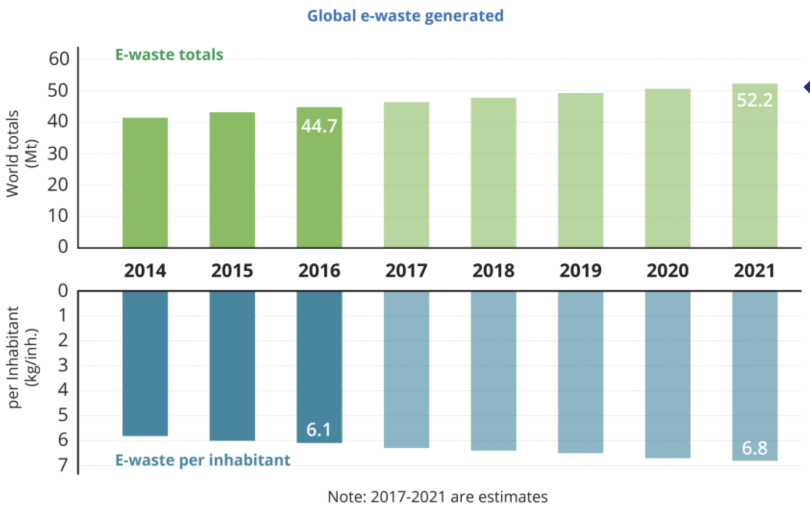
Source: nature

Source: Green IT Solution

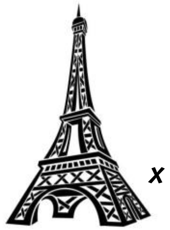
- *Growing Global E-Waste Streams → Regulations Mandatory (!)*

The Paradigm Shift (1)

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

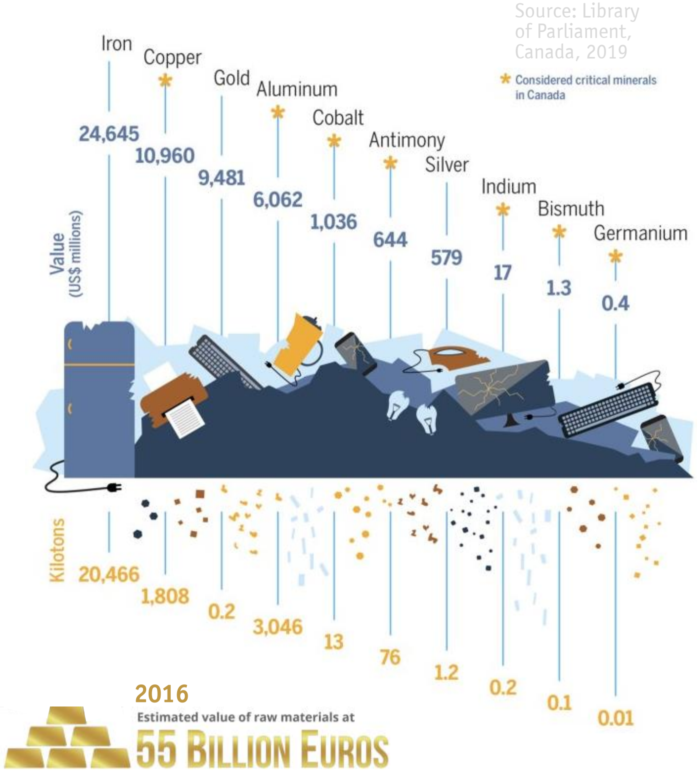


← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

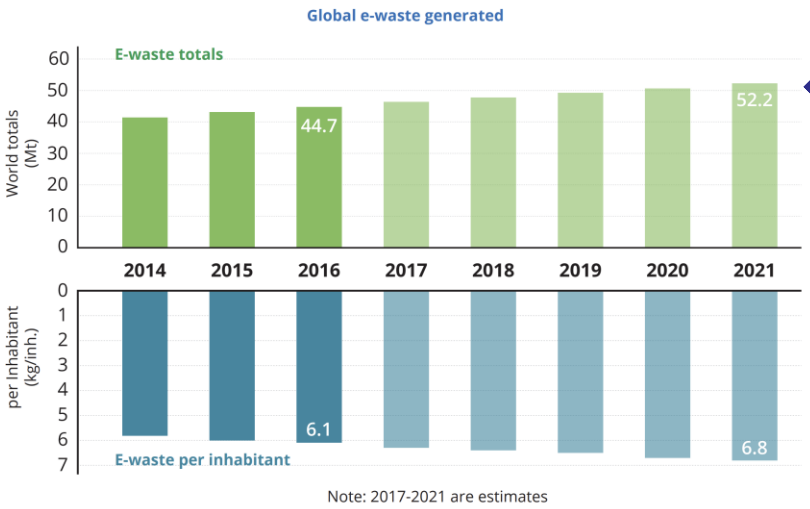


Global / 2019

- *"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*
- *120´000´000 Tons of Global E-Waste in 2050*



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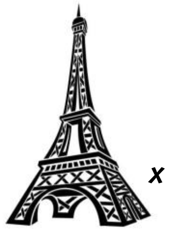
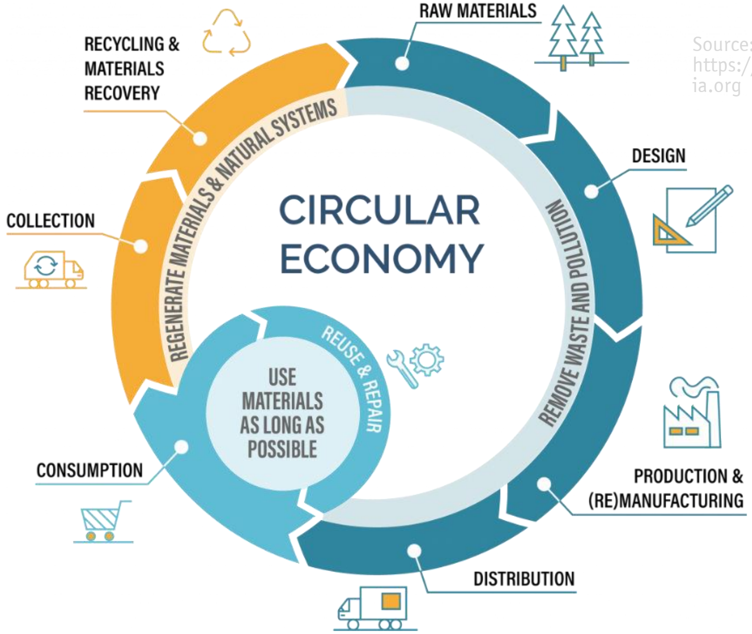


x 5´200

Source: The Global E-waste Monitor 2020

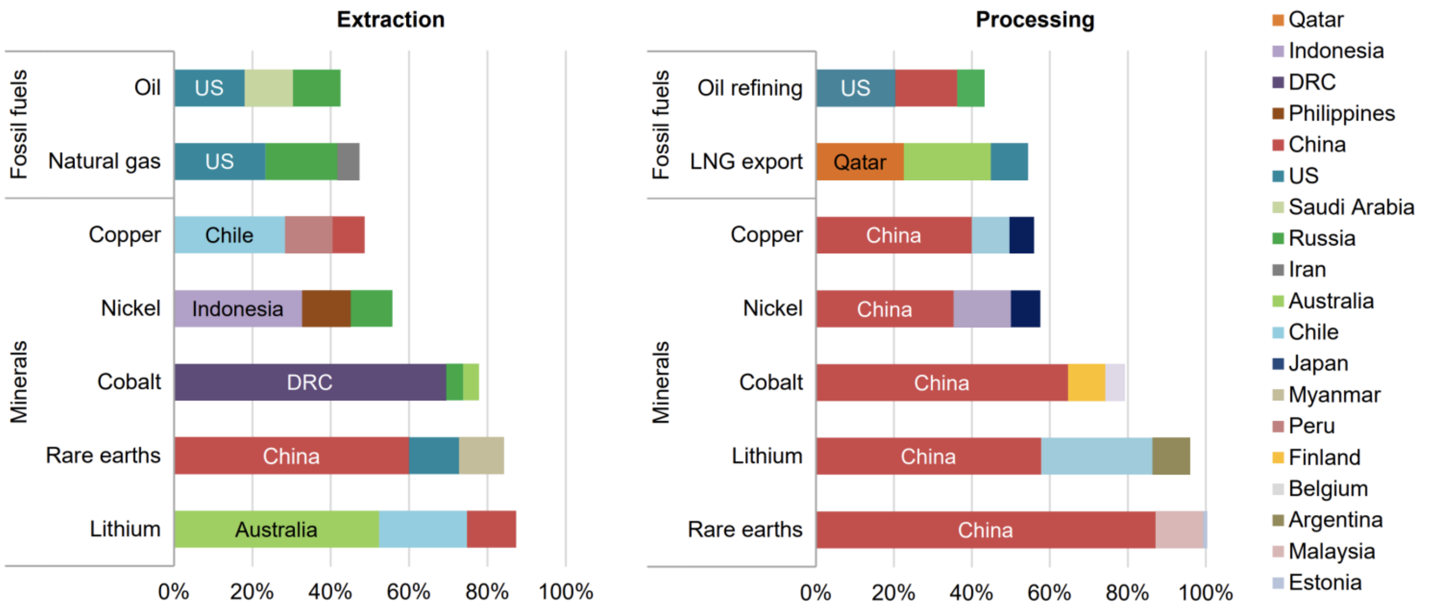


Source: https://circularphiladelphia.org

- *"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*



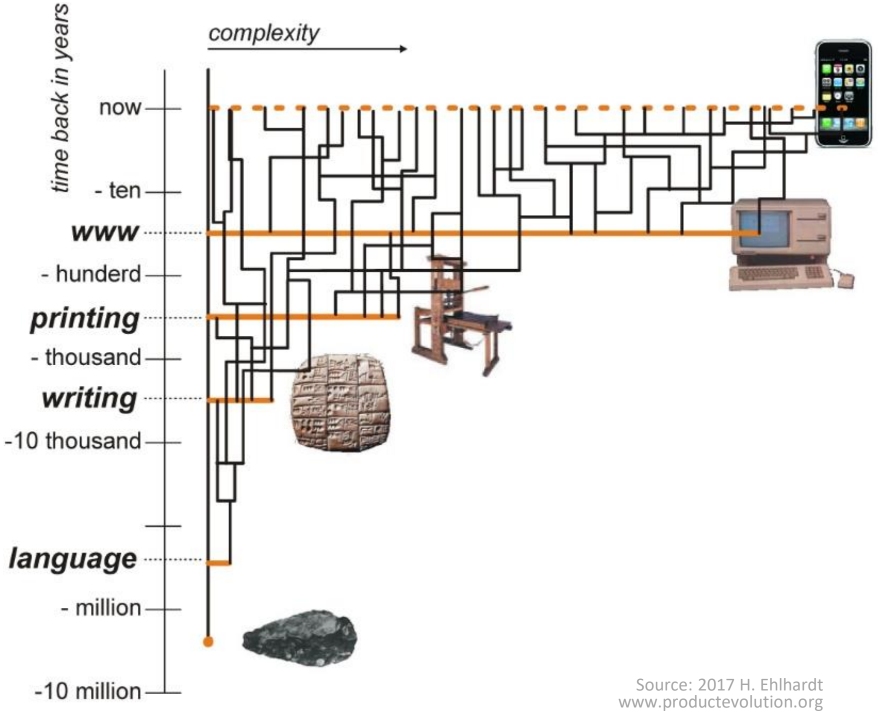
Shares of top three producing countries, 2019

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

- *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)*



Source: 2017 H. Ehlhardt
www.productevolution.org

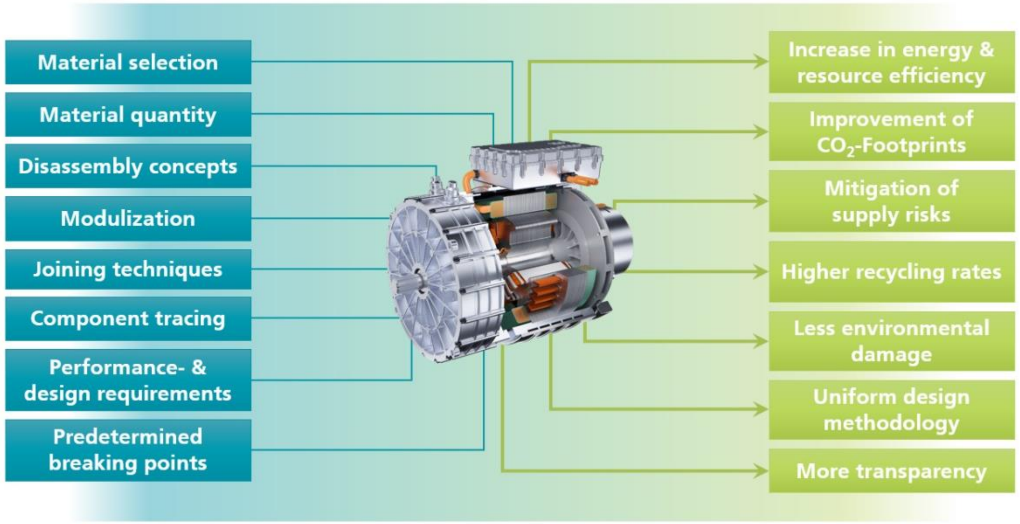
- *Ultra-Compact Systems / Functional Integration — Main Obstacle for Material Separation*

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: DLR

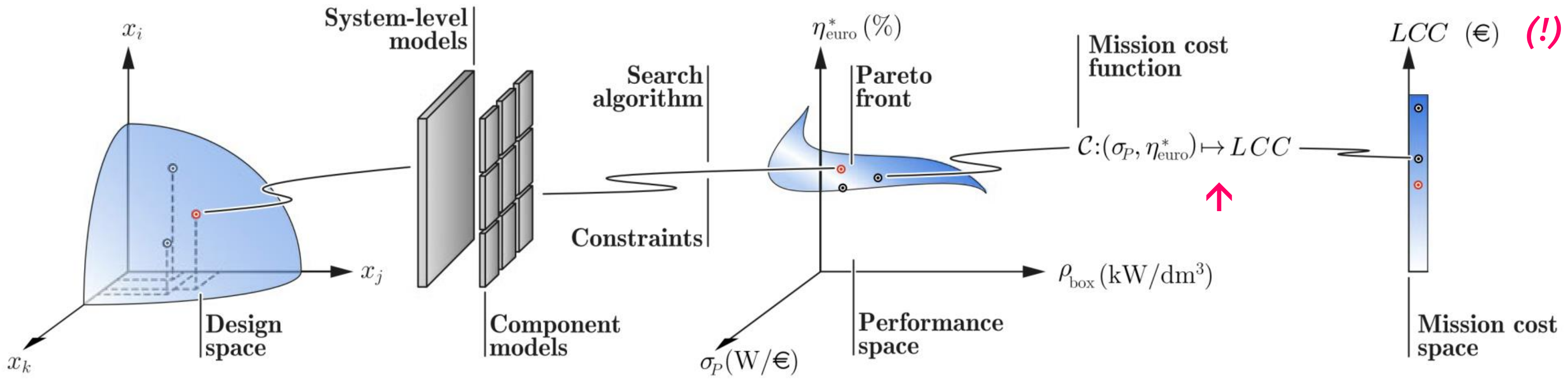
Source: https://de.ifixit.com/



- **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*

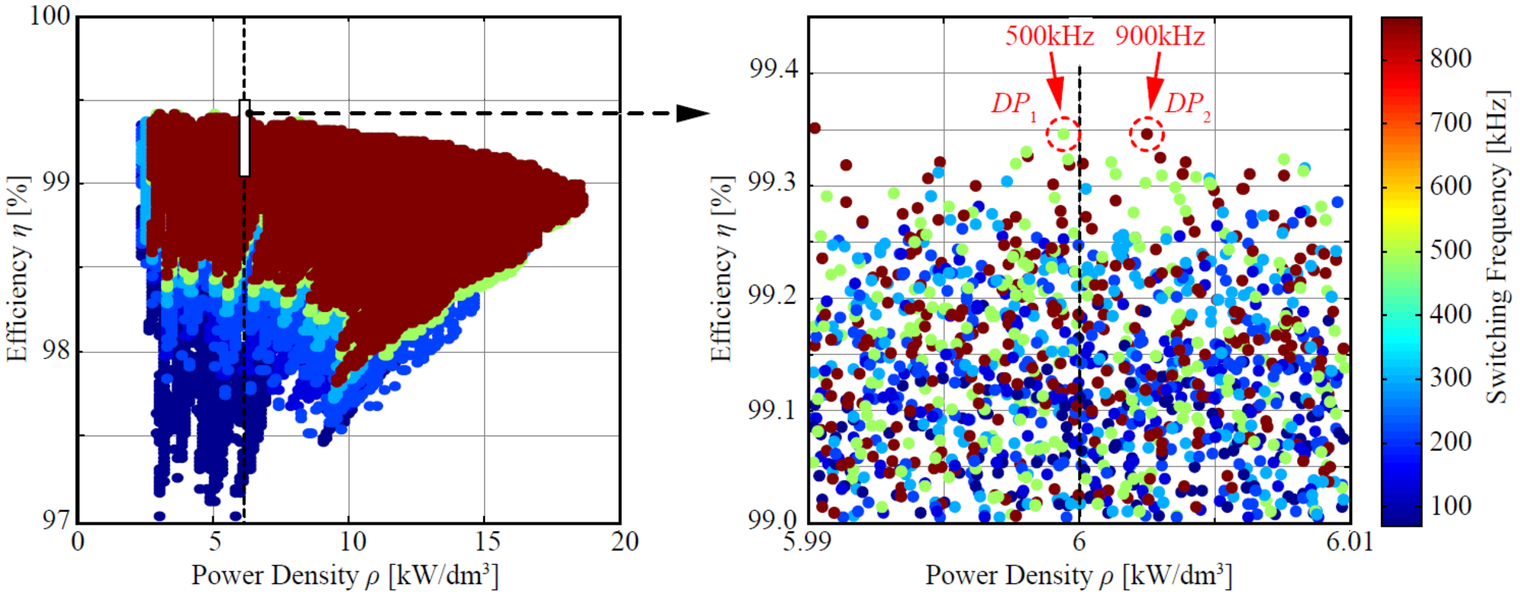


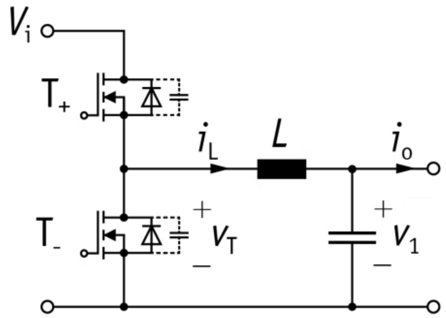
- *Mission Profile — Power Loss → Energy Loss / Life-Cycle Cost (!)*

Design Space Diversity (1)

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

(!)





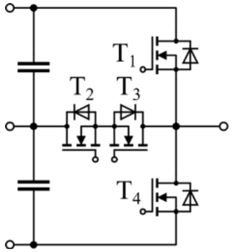
ρ = 6kW/dm^3
$\eta \approx$ 99.35%

L = 50uH
f_S = 500kHz or 900kHz

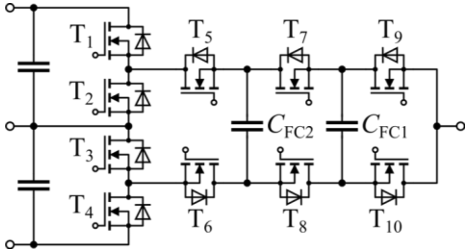
- *Example of GOOGLE Littlebox Challenge 1.0 Design Optimization w/ PWM Operation & Ideal Switches*
- *Mutual Compensation of HF and LF Loss Contributions*

Design Space Diversity (2)

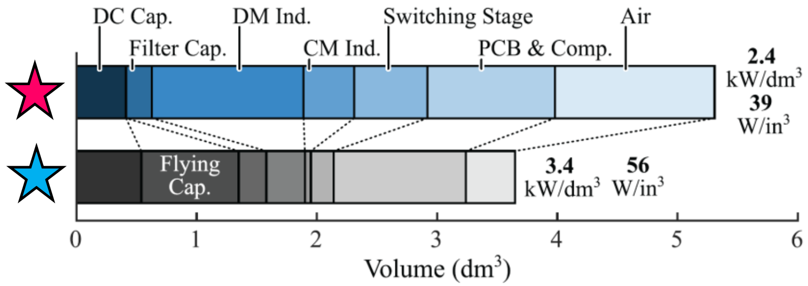
- *Two Concepts / Similar Specs — 12.5 kW, 650...720 V_{DC}, CISPR 11 Class A — Similar Performance (η_{CEC} = 99.1%)*
- *Differences in Environmental Impact (?)*

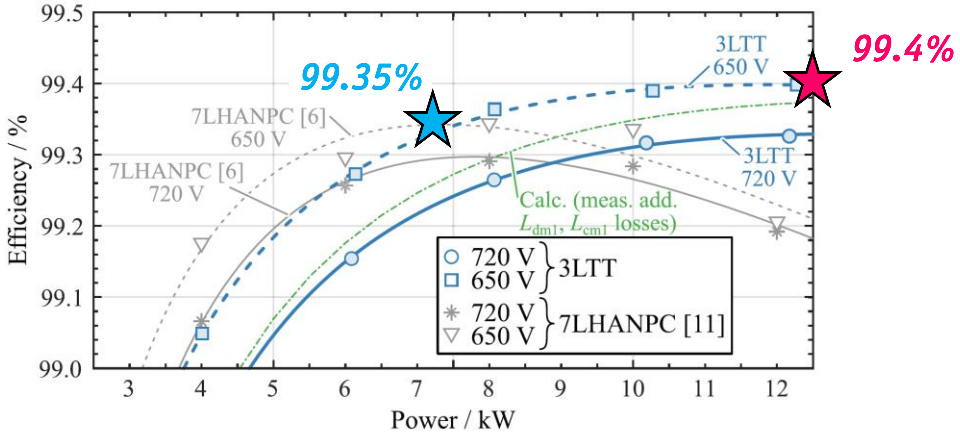


3-Level All-SiC T-Type PV Inverter
99.4% @ 2.4 kW/dm³



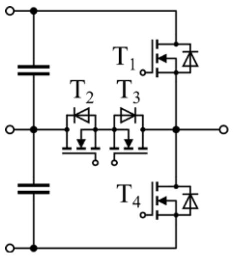
7-Level All-Si HANPC PV Inverter
99.35% @ 3.4 kW/dm³

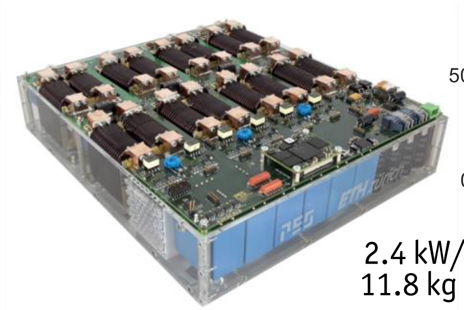




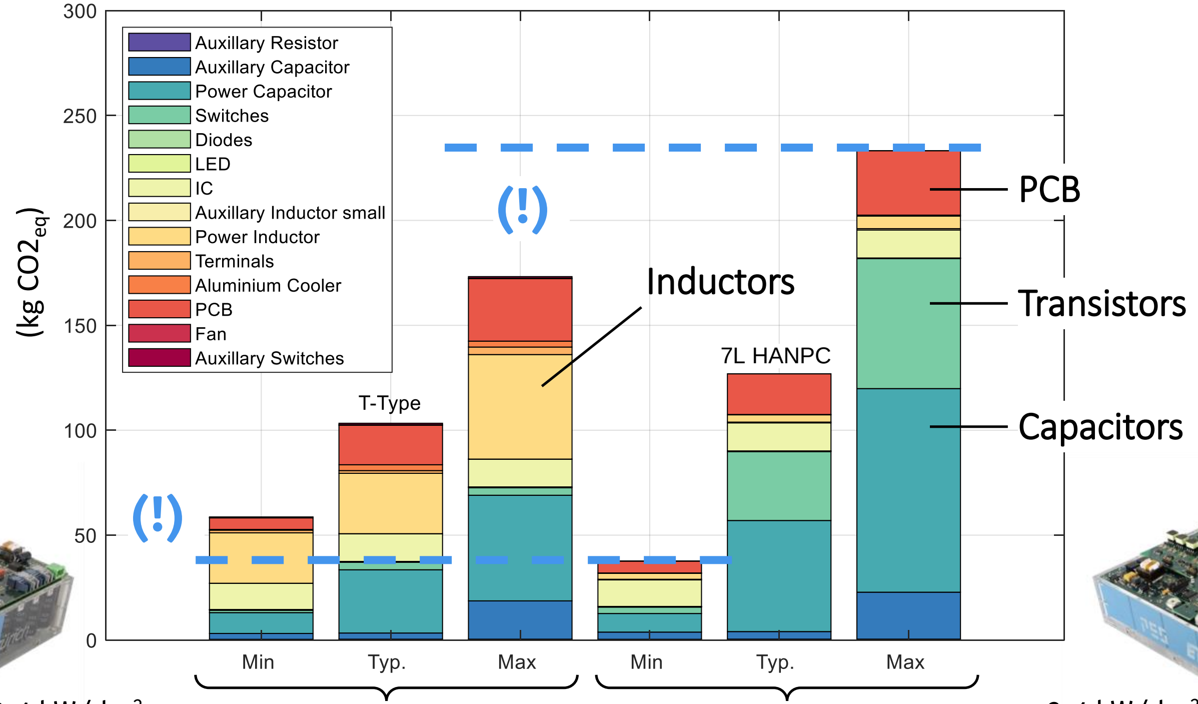
A-Posteriori LCA of 3L & 7L PV Inverters

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

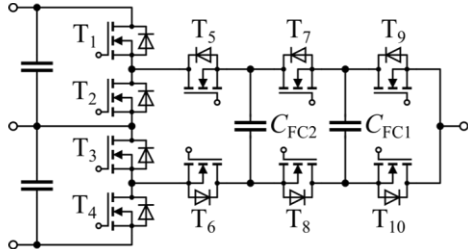




2.4 kW/dm³
11.8 kg



3L T-Type   *7L HANPC*



3.4 kW/dm³
4.6 kg

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

Power Electronic Systems
Laboratory

New Holistic (!) Design Approach

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

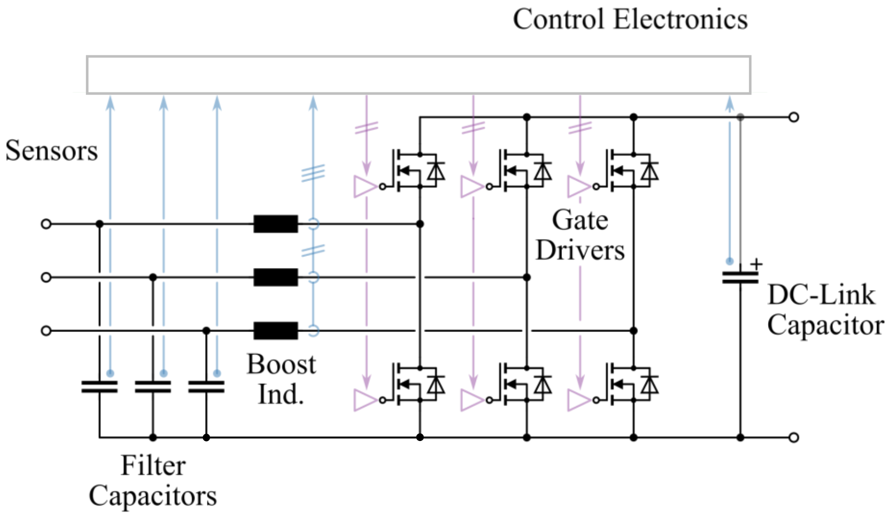
ETH zürich

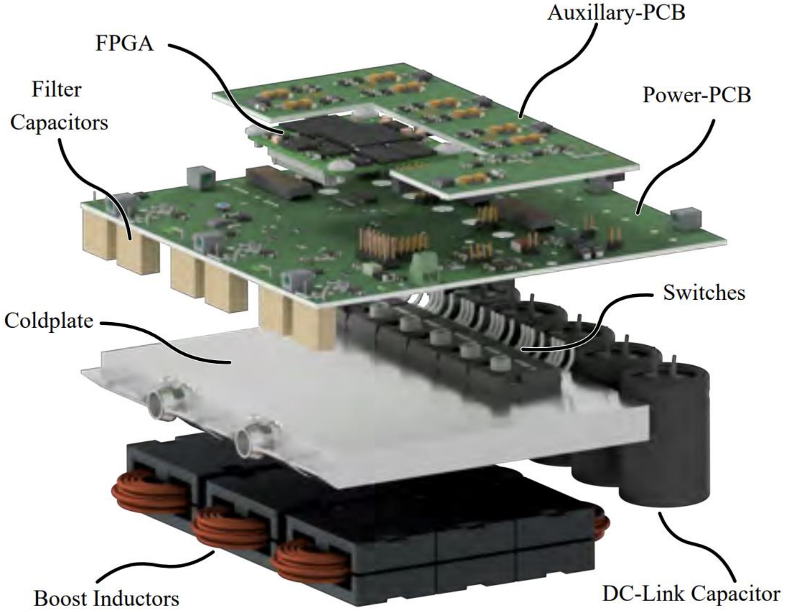
EPE' ECCE 23

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



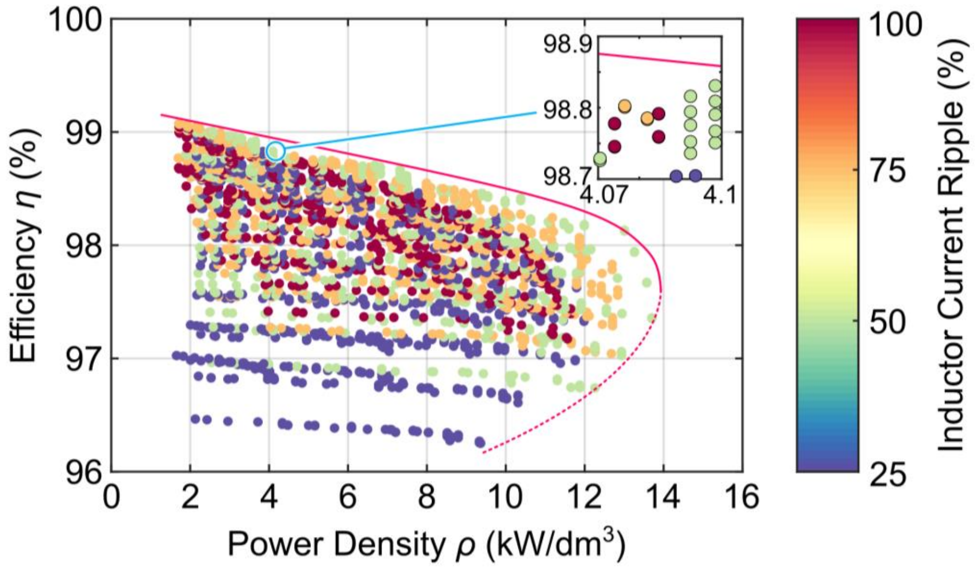


- *Main Components Considered (Losses, Volume, CO_{2eq})*
- *Power Trans., Heat Sink, Boost Ind., DC-Link Cap., Filter Cap., Gate Drivers, Sensors, Contr. Electr., PCBs*

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*

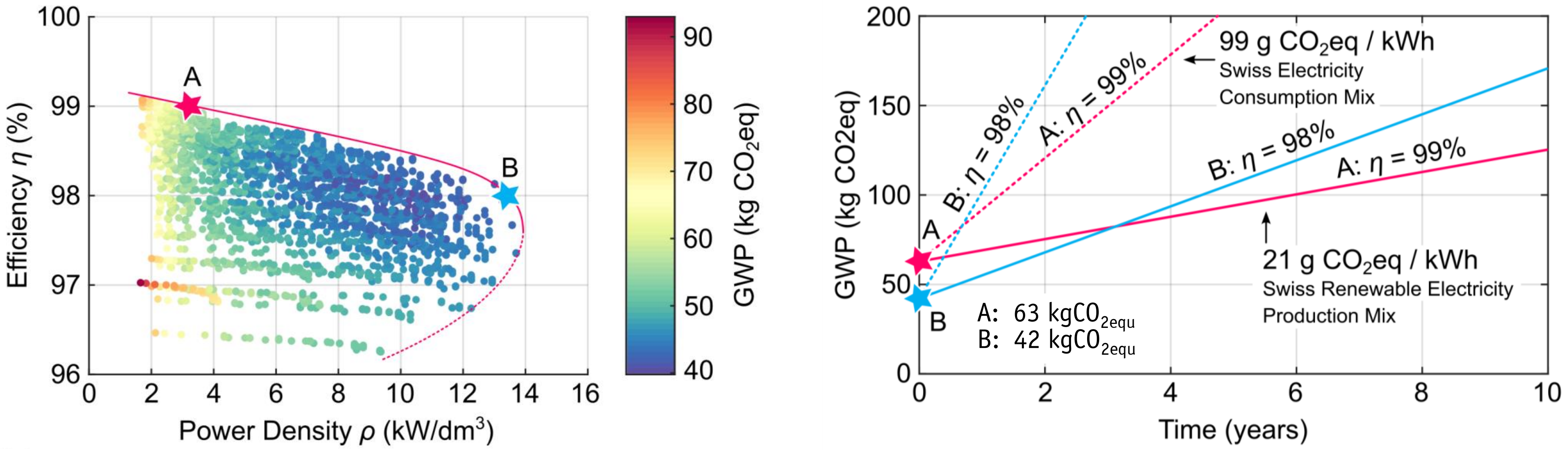
10 kW
400 V_{AC} Mains
800 V_{DC} Output
1200 V SiC



- *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

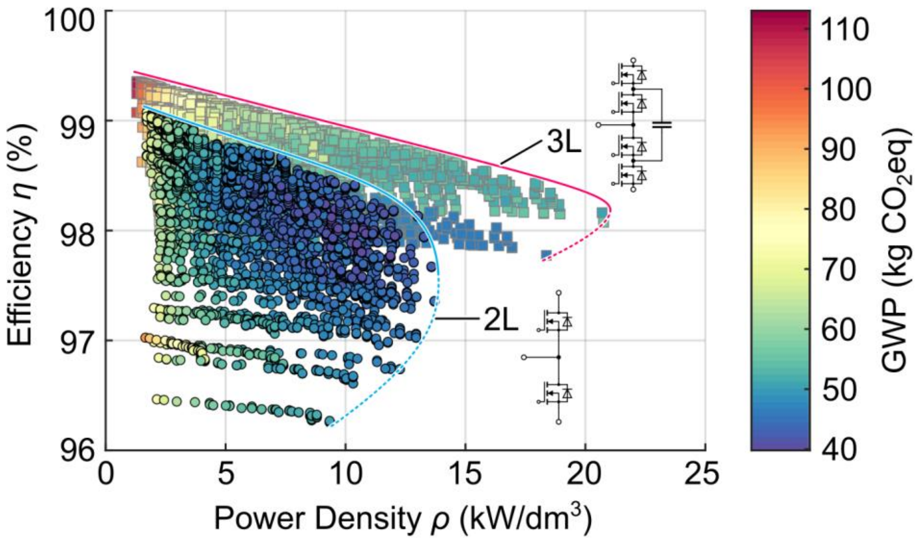
- *Global Warming Potential GWP [kg CO_{2eq}] as Add. Performance Indicator*
- *Mission Matters — Example 8 Hours Full Load per Day Over 10 Years*
- *Electricity Mix Matters — Carbon Intensity*

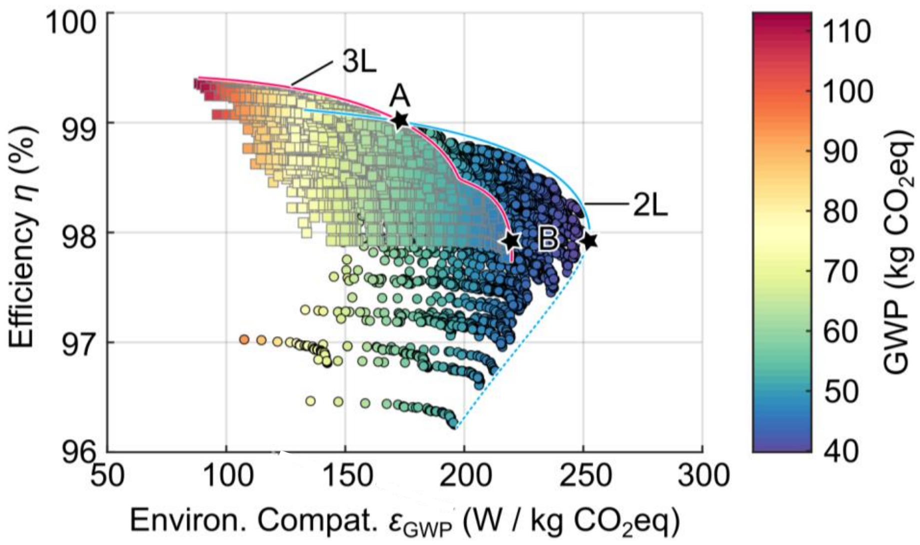


- *Energy Losses During Use Phase Contribute to Overall GWP*
- *More Eff. Designs w/ Higher Initial GWP Outperform Less Eff. Designs for Longer Operating Times*

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*

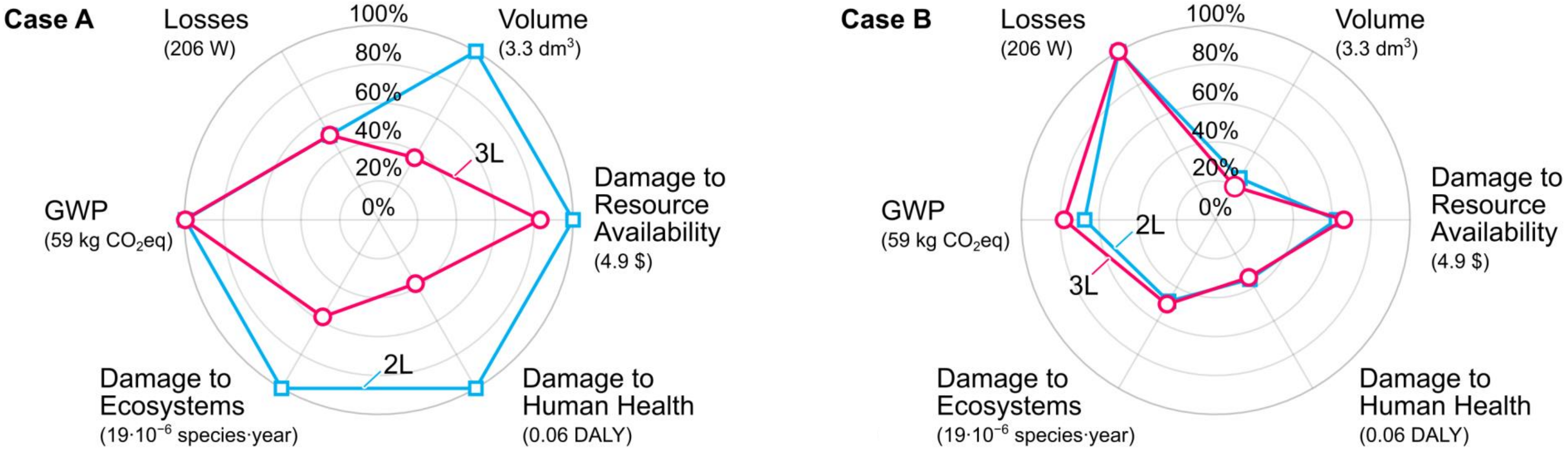




- *Higher 3L Inverter Eff. & Power Density BUT Lower Environm. Compatibility [W/kgCO$_{2eq}$]*
- *Higher 3L Initial GWP Due to Higher # of Power Semiconductors*

Comprehensive Environmental Impact Profile

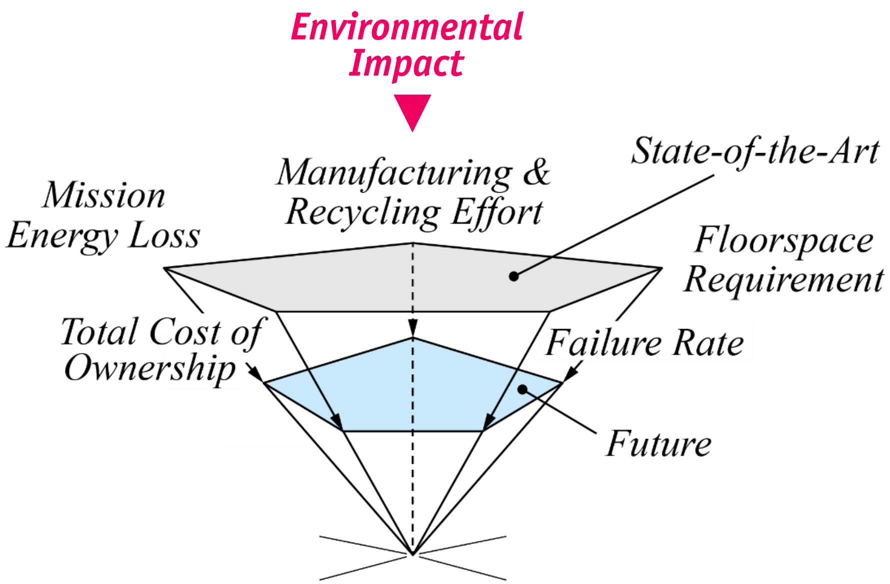
- *Further Environm. Impact Indicators / Volume & ReCiPe 2016 Areas of Protection*
- *Human Health | Ecosyst. Quality | Resource Scarcity*
- *Comparative Evaluation of 2L vs. 3L PEBB*



- *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 Analysis (LCA) Mandatory for All Future System Designs*



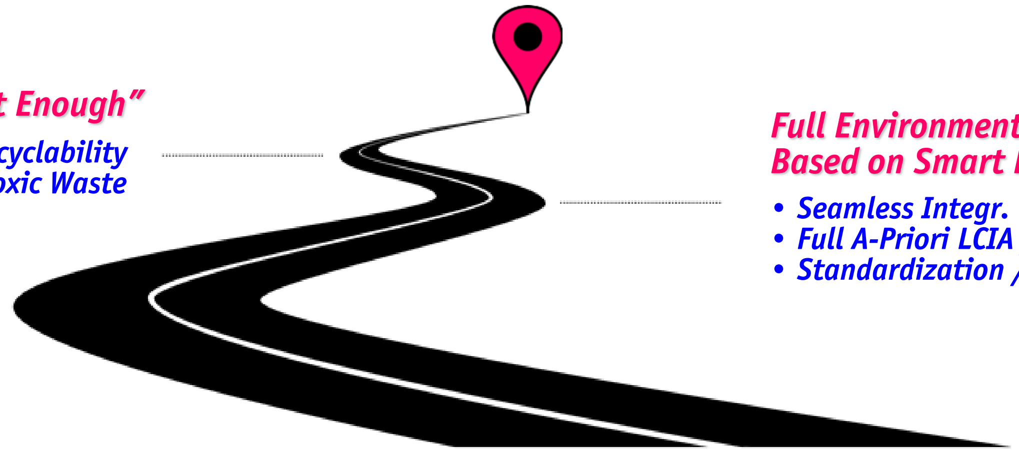
- *Complete Set of New Performance Indicators*

— Environmental Impact	[kgCO_2eq/kW]
— Resource Efficiency	[kg_{xx}/kW]
— Embodied Energy	[kWh/kW]
— TCO	[$/kW]
— Power Density	[kW/m^2]
— Mission Efficiency	[%]
— Failure Rate	[h^{-1}]

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. Repairability | Reusability | Recyclability*
- *Min. Scarce Materials, 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) Modeling

- *New Dimensions in Multi-Obj. Opt.*
- *Data Sources / Quality / Abstraction / Generalization as Key Challenges*

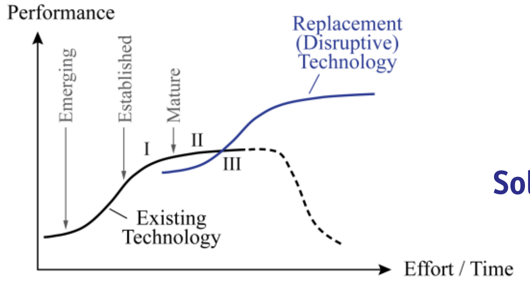
Classical $\eta\rho$-Pareto Optimization / Design

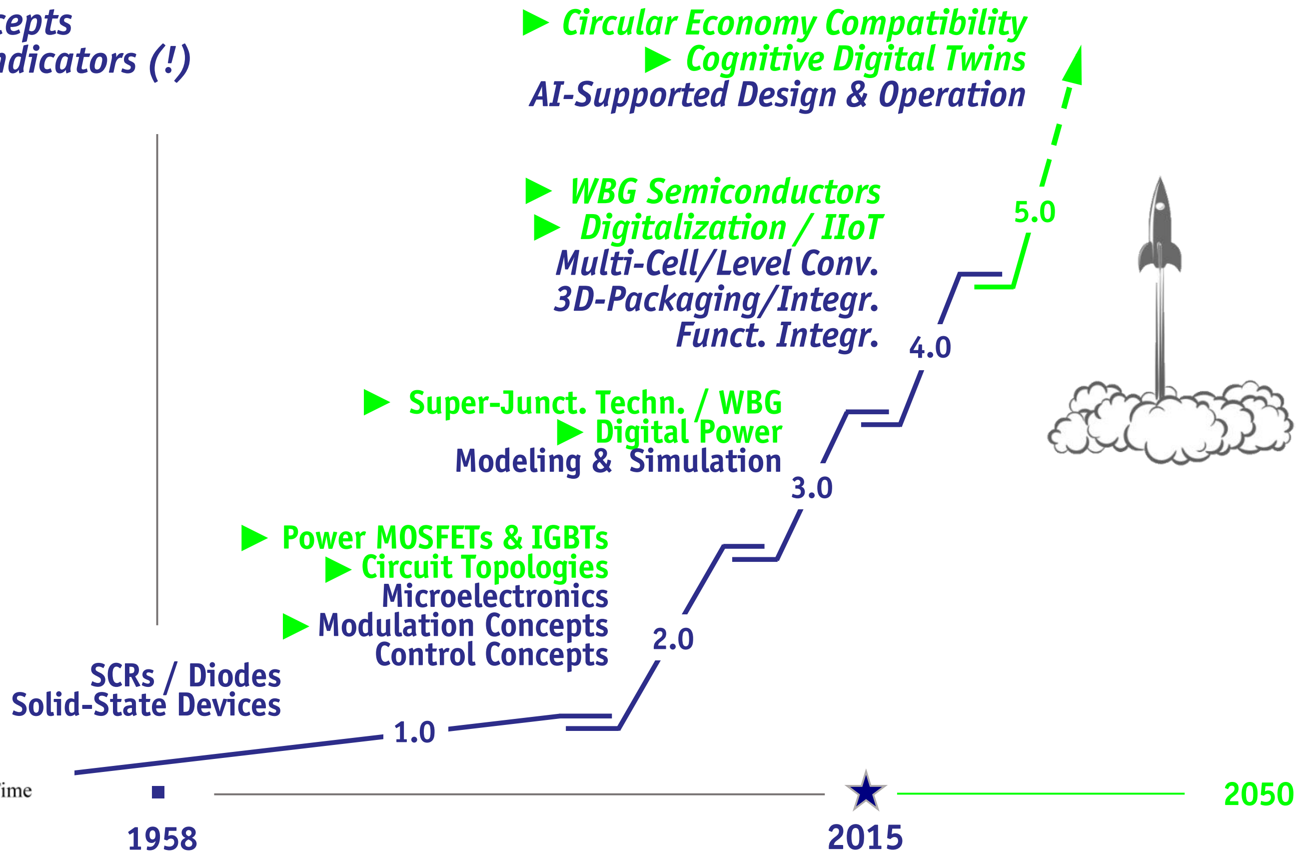
- *Manual A-Posteriori LCA of Complete Converters*

- *Automated Design | On-Line Monitoring | 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 !