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Zhuhai 2023

Energy Efficiency is NOT Enough (!)

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ETH zürich

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Environmental Impacts as New Dimensions in Multi-Objective Optimization of Power Electronic Systems

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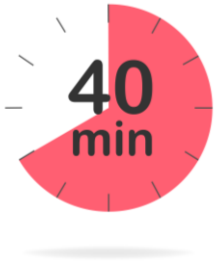
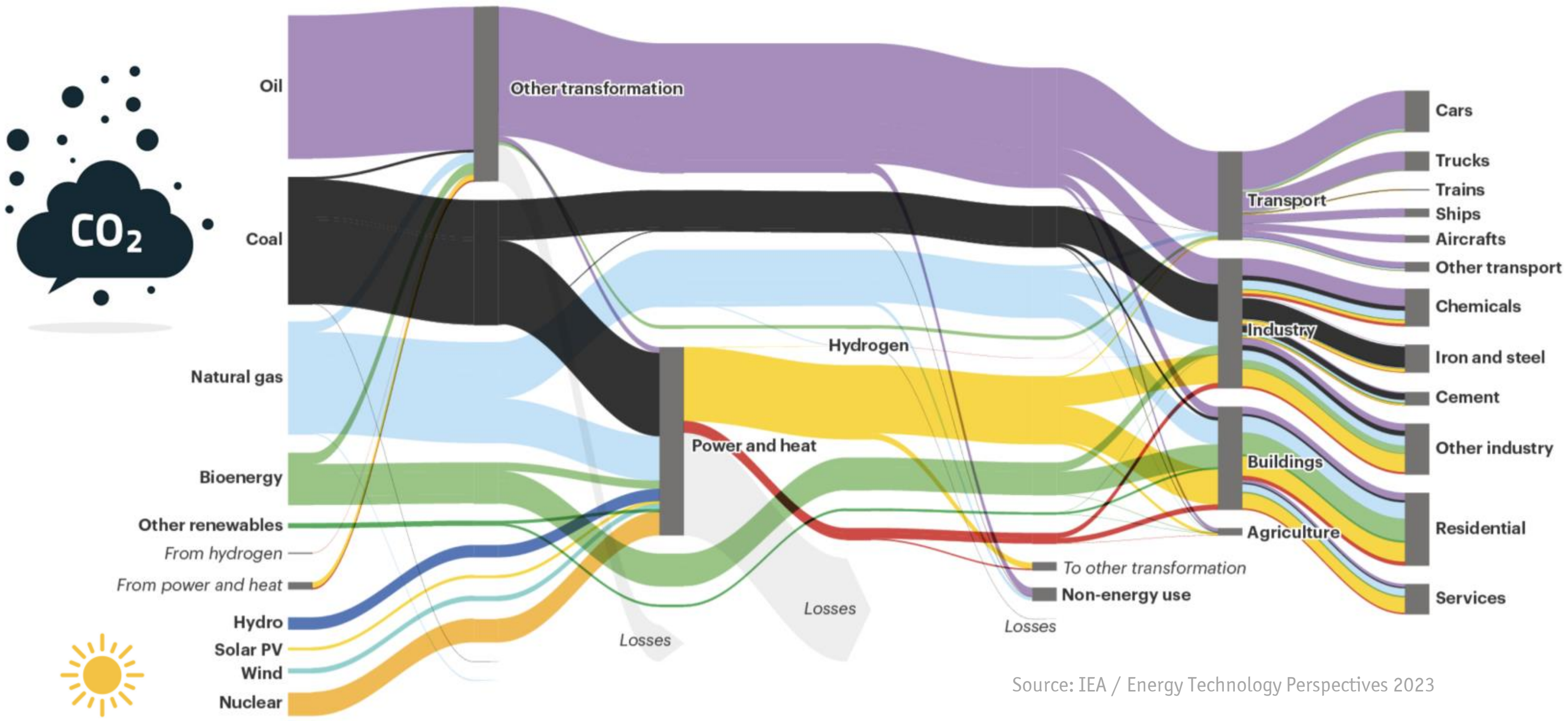


Outline

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

The Challenge

- *Global Energy Flows — 2021*



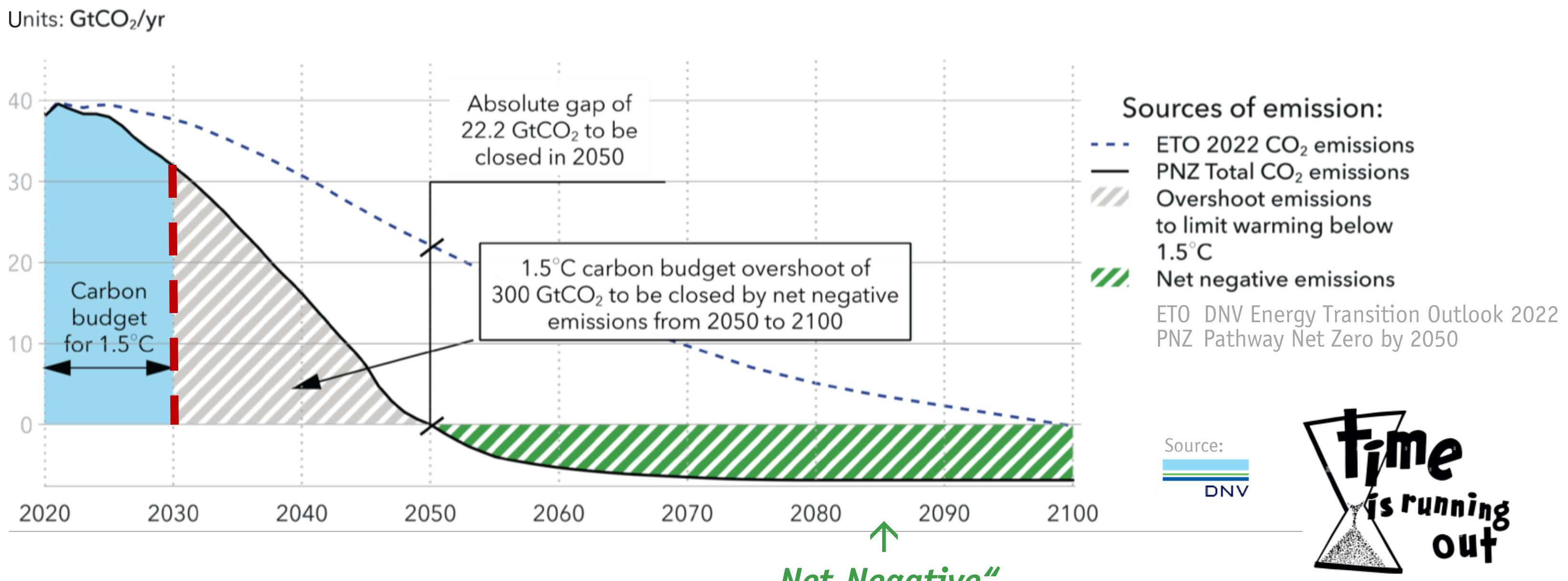
Source: IEA / Energy Technology Perspectives 2023

- *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*

40 $GtCO_2$ →

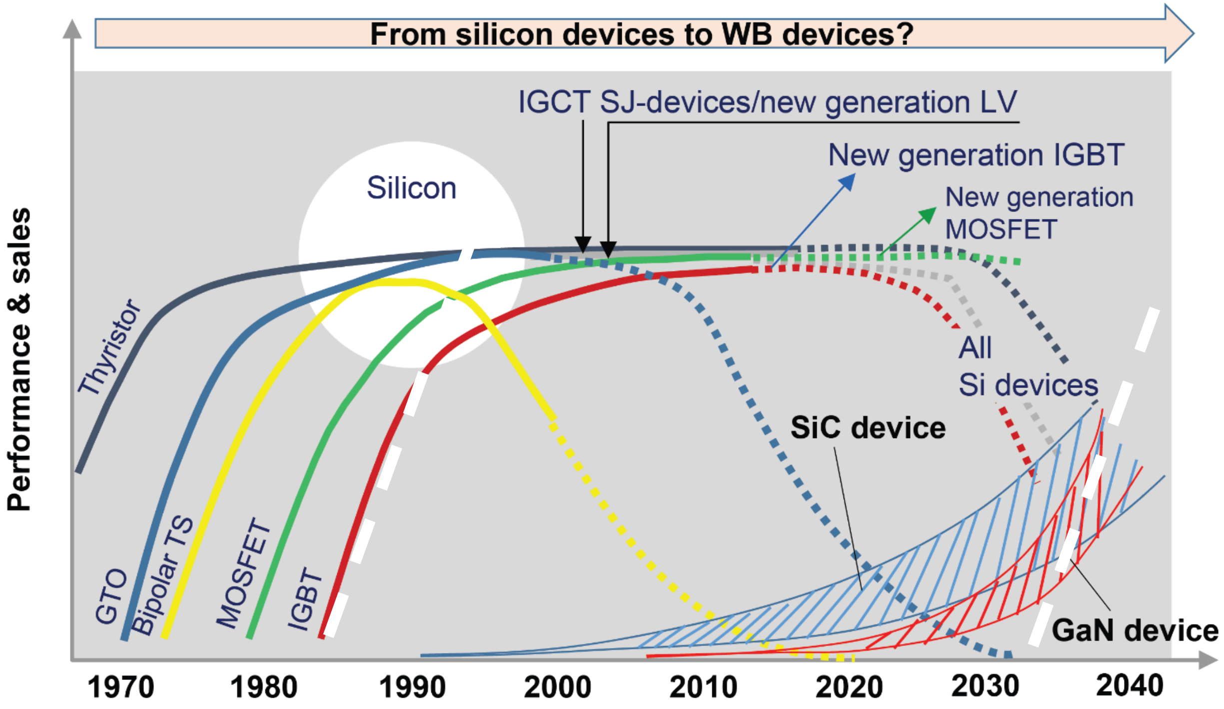


„Net-Negative"
Remove Overshoot
of 300 $GtCO_2$

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

Remark New Disruptive Technologies (?)

- *2050 → No Fundamentally New Concepts Product-Ready in 20+ Years Time Frame (!)*

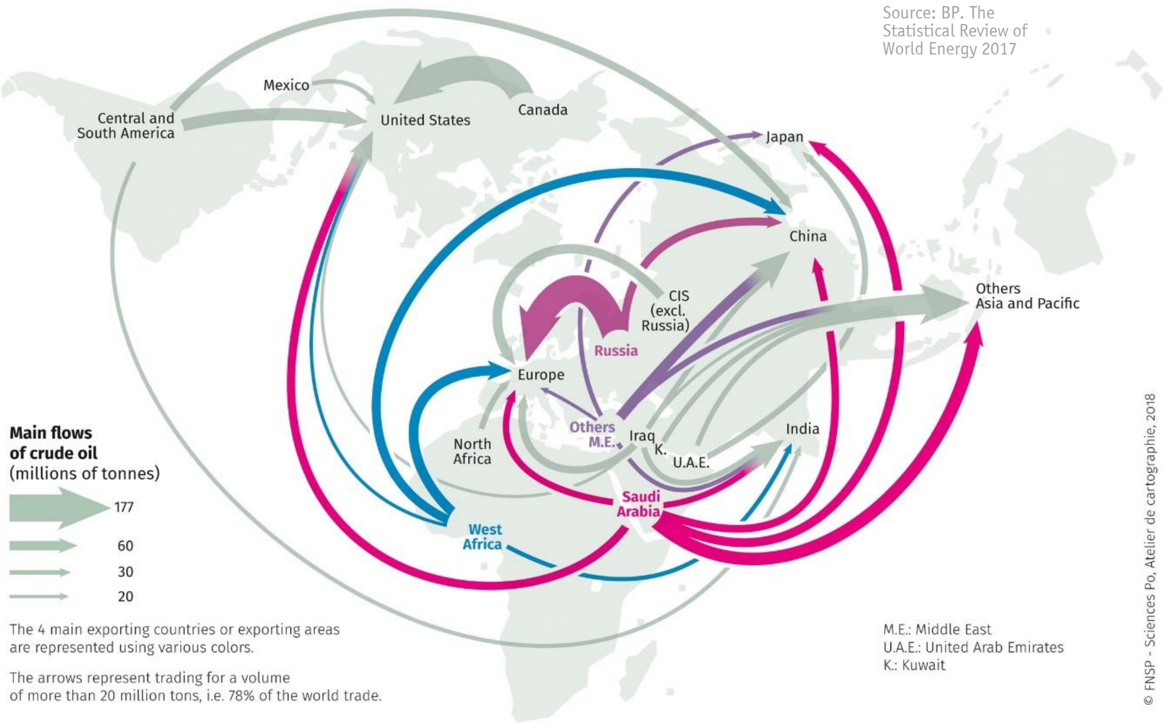


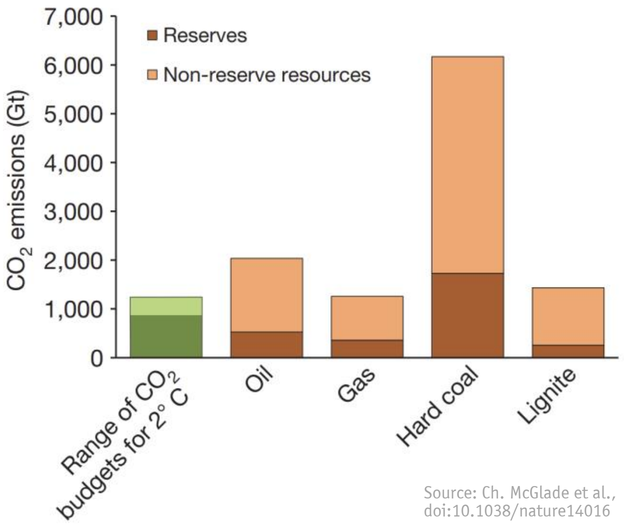
Source: ABB/ECPE
L. Lorenz et al.
Elsevier (2018)

- *Example — 10…20 Years Introduction Phase of New Power Semiconductor Technologies*

Energy Independence / Security of Supply

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





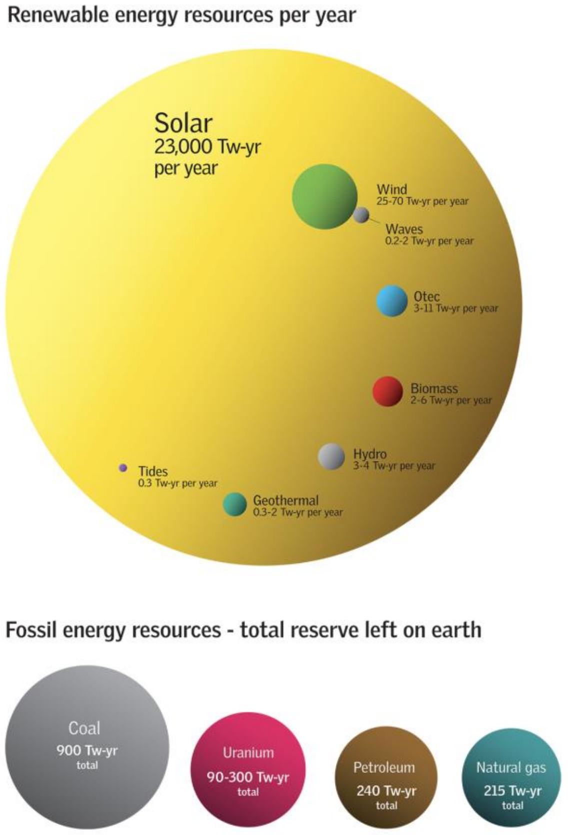
Source: Ch. McGlade et al., doi:10.1038/nature14016

- *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)

100% Conv. Efficiency
Excl. Oceans

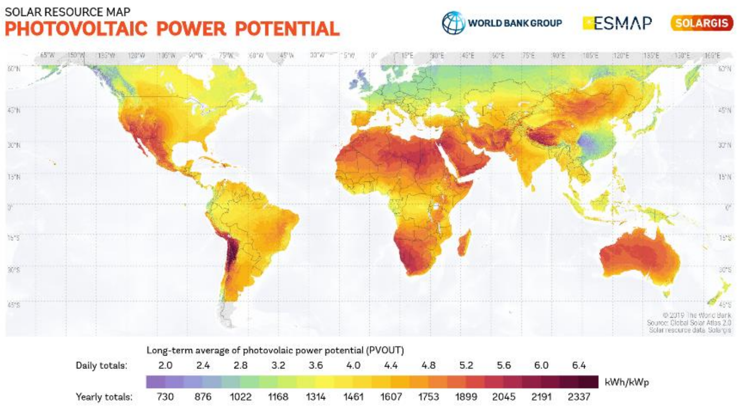


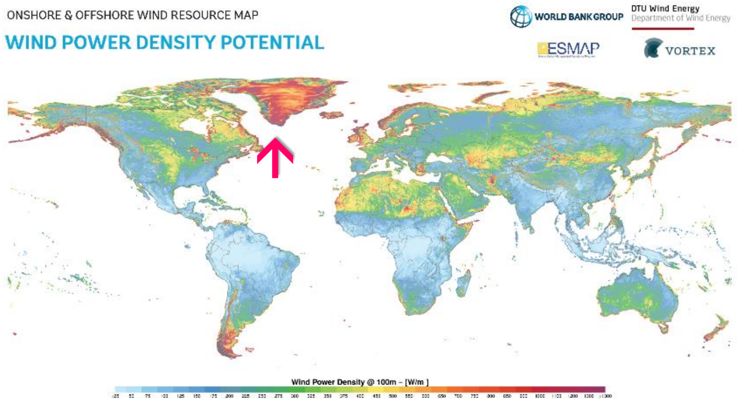
Note: Graphical Representation Assumes Spheres Not Circles

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)

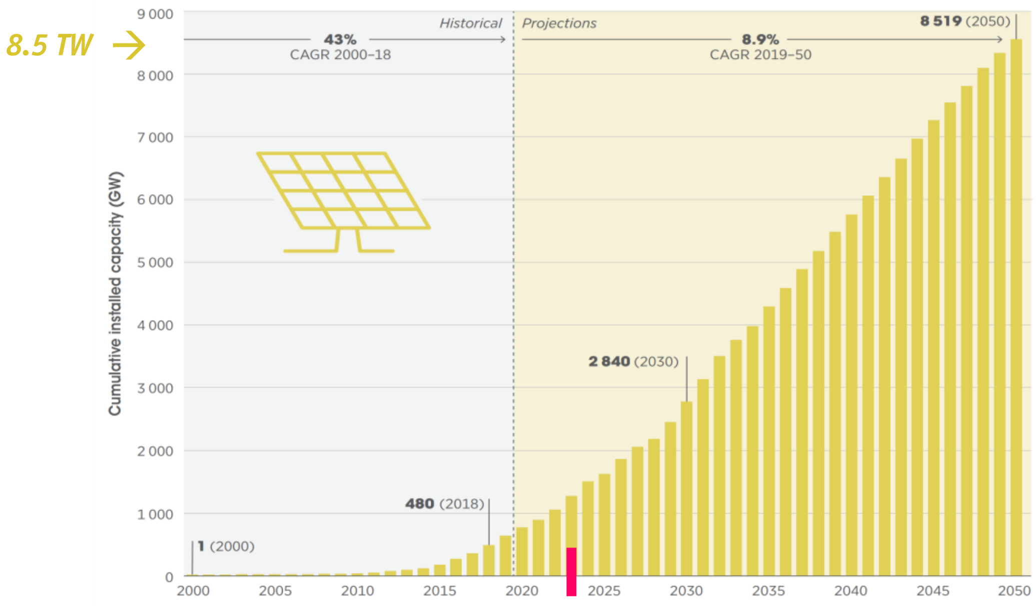
■ *Global Distribution of Solar & Wind Resources*



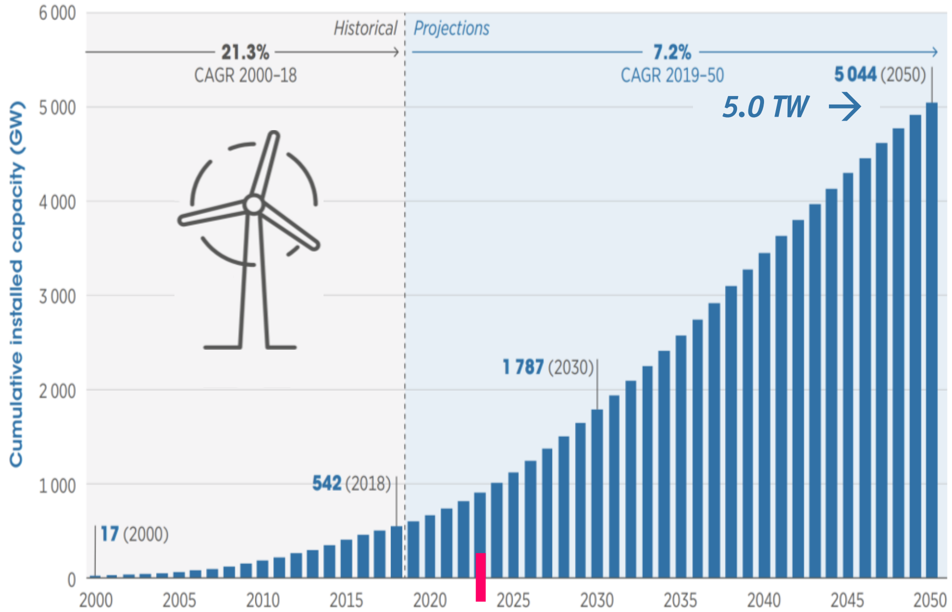


The Approach

- *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).

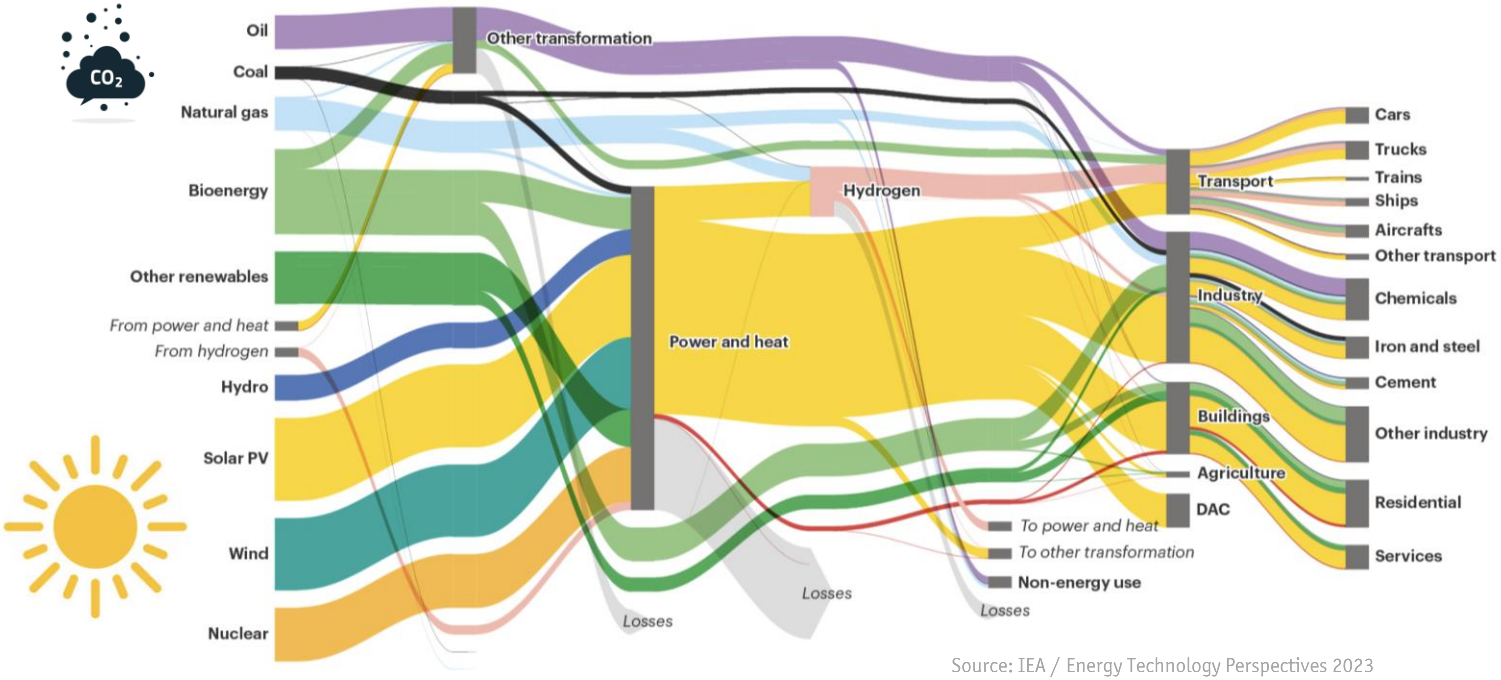


Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

- *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*



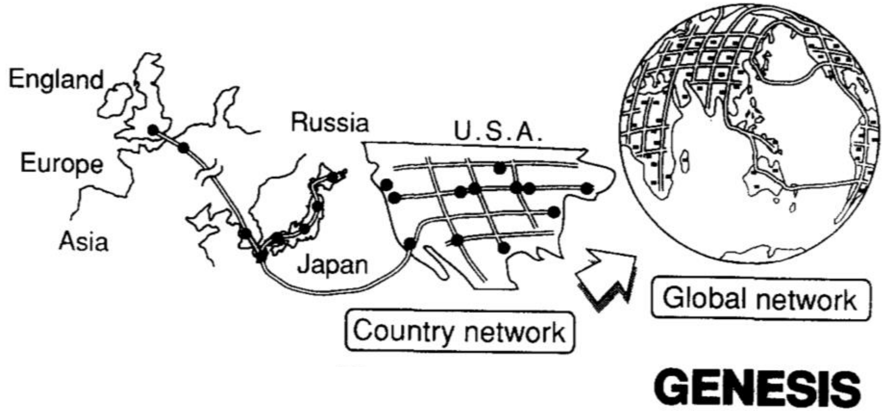
Source: IEA / Energy Technology Perspectives 2023

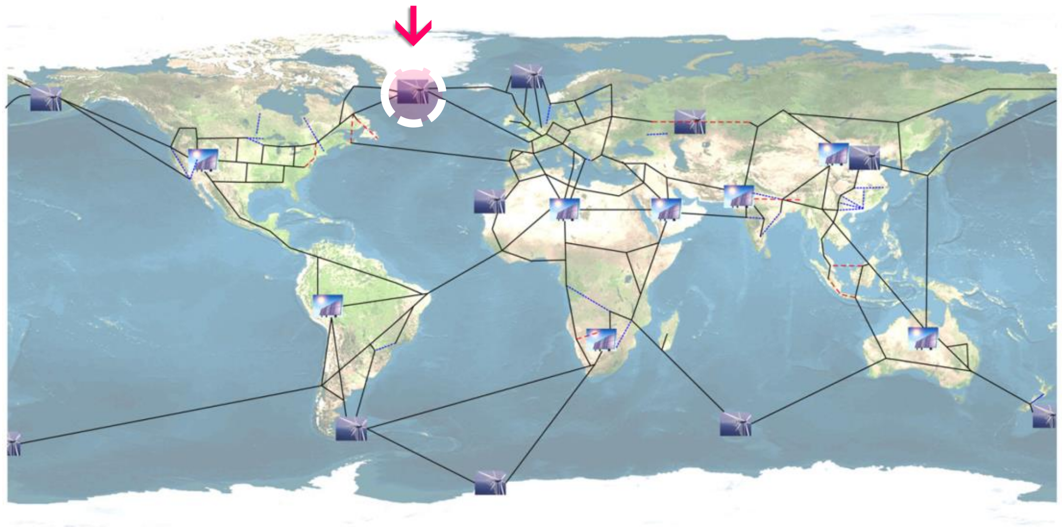
- *Dominant Share of Electric Energy — Power Electronics as Key Technology (!)*

GENESIS Project

- *GENESIS — Global Energy Network Equipped w/ Solar Cells & International Superconductor Grid*
- *"Top-Down" Approach*

Source: Y. Kuwano / SANYO (1994)





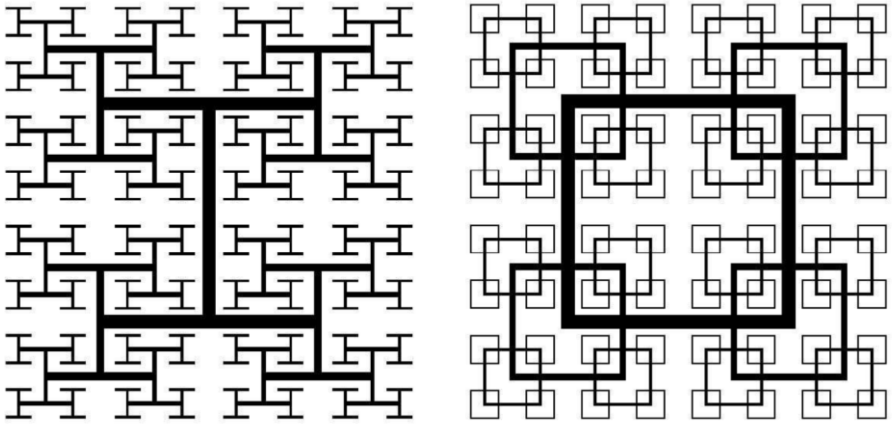
Source: G. Andersson / ETH Zurich (2013)

- *PV & Global Superconducting Grid (1994)*
- *Globally Interconnected HVDC-Network (2013)*

Fractal Electric Grid

- *Facilitates Integration of "Bottom-Up" Approaches*
- *20´000´000´000´000 $ (=GDP of USA) Global Electric Grid Investments Until 2050 / Decentralization & Digitization*
- *System of Independently Operable Coordinated Systems | Local Gen. & Storage | Distrib. Monitoring & Control etc.*

Source: D. Hurst et al. / Imperial College

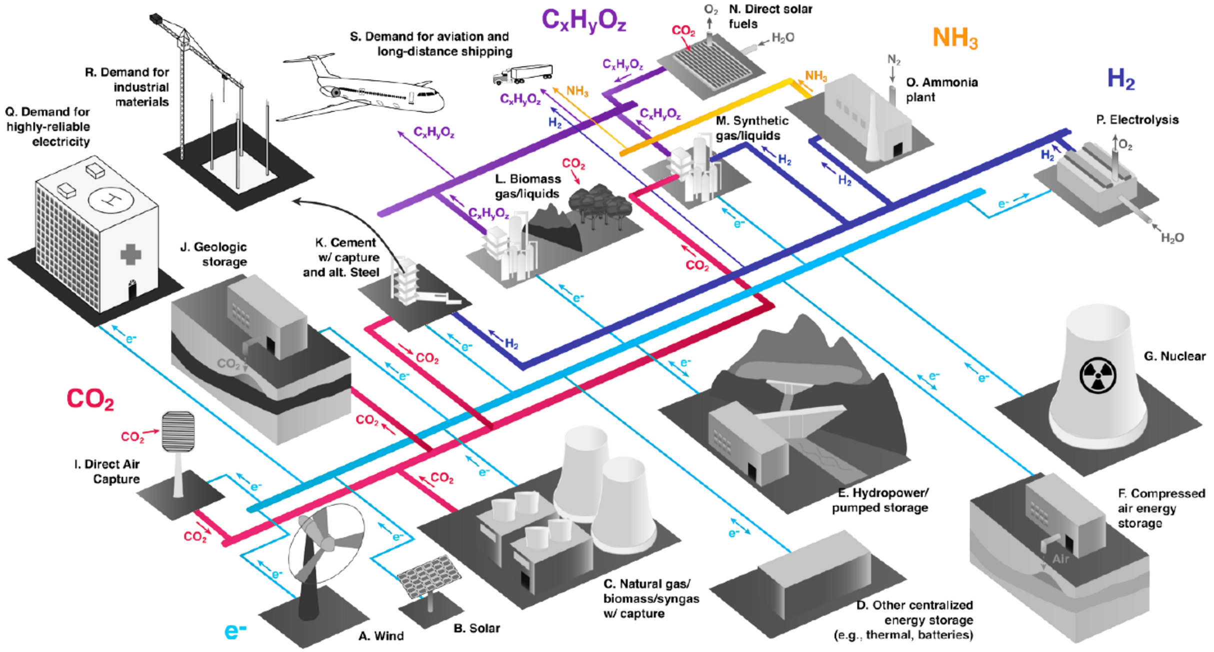


solarworx

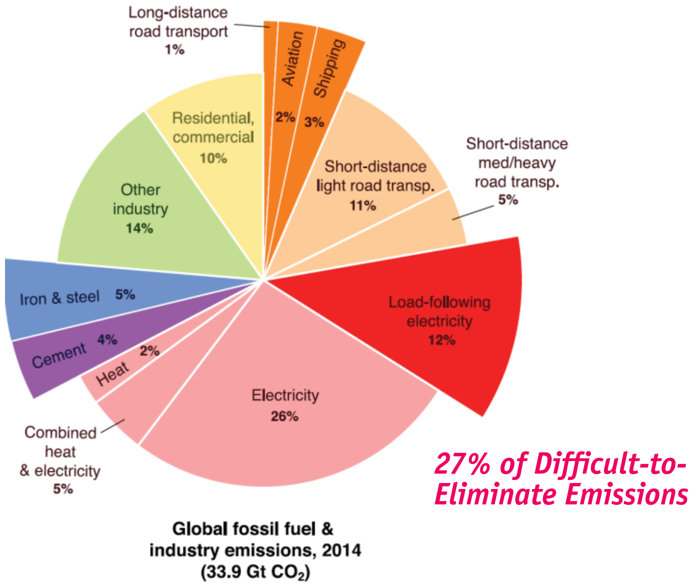
- *Load Management / Demand Response / Peak Shaving etc.*
- *Decentralized Smart 60VDC Pico-Grid in Zambia*

Net-Zero Multi-Carrier Energy Systems

- *CO_2-Free Electricity / Electrification — Viable Pathway for Reducing Emissions !&! Costs (Long Term)*
- *E-Fuels & P2X for Long-Haul Transport / Aviation / etc. & Short Term / Seasonal Storage*



Science
S.J. Davis et al.
(2018)

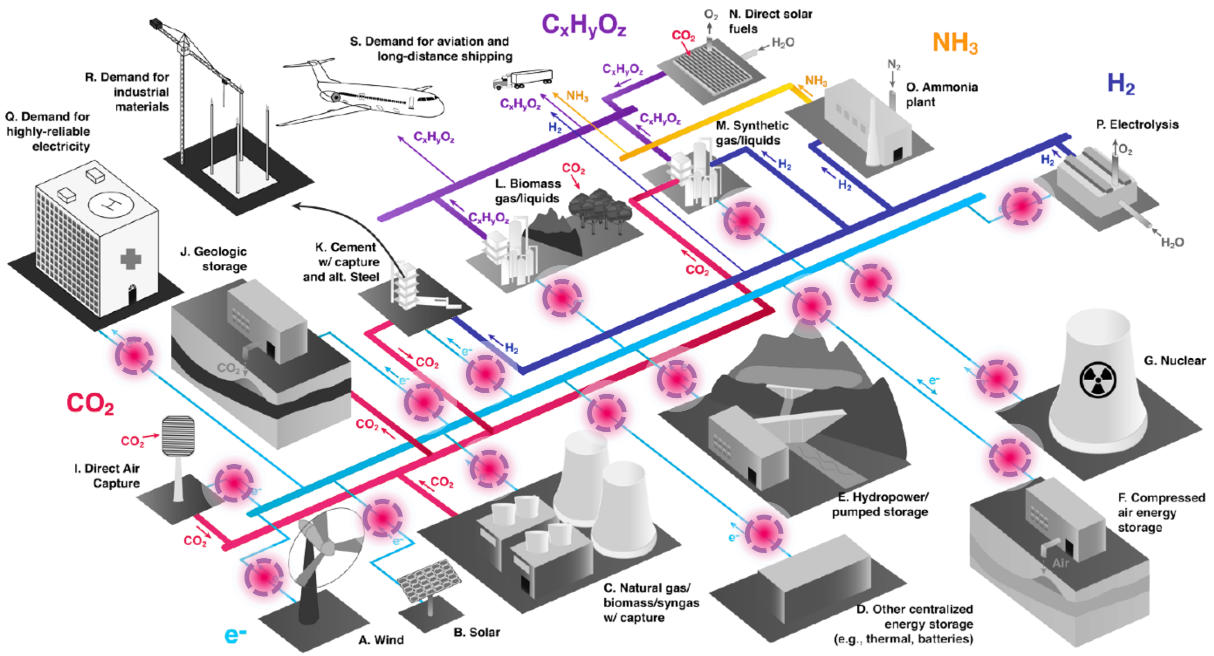


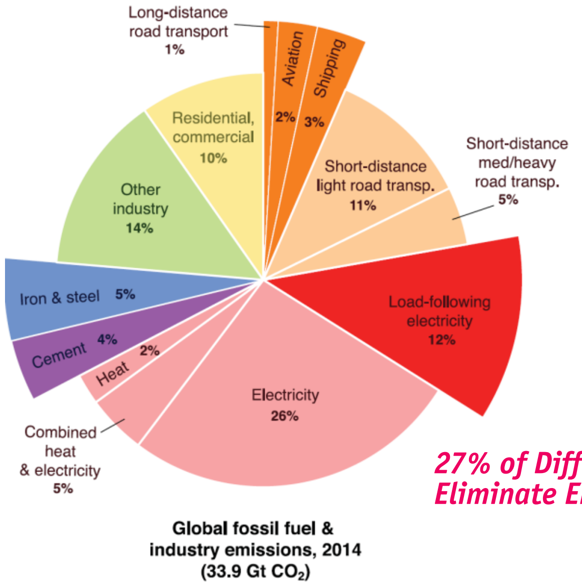
27% of Difficult-to-Eliminate Emissions

- *Integrated Net-Zero Multi-Carrier Energy System — E-Energy | Heat & Cold (N.N.) | etc. | Storage | CO_2C&S*
- *Missing Multi-Discipl. Research on Cross-Sector Converters / Technologies / Geogr. Diversity / Economics etc.*

Net-Zero Multi-Carrier Energy Systems

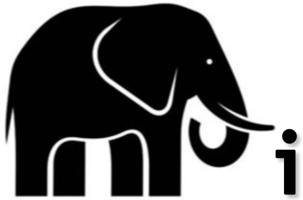
- *Power Electronics — A Key Enabler !*

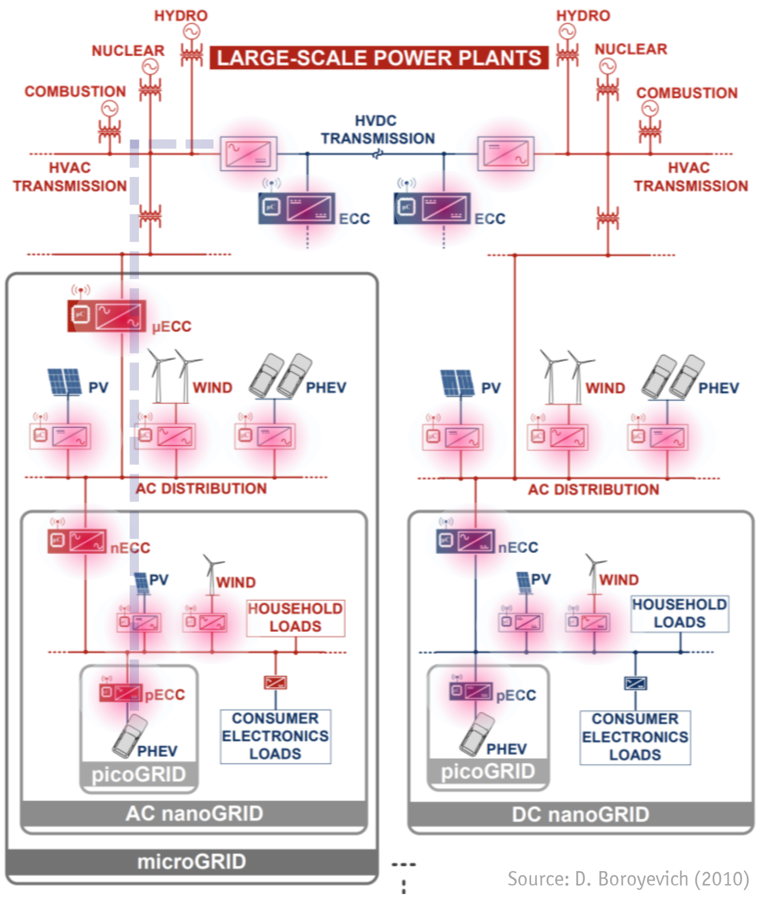




27% of Difficult-to-Eliminate Emissions

- *Ren. Gen. & Cross-Sector Conv. — Heat-Pumps / Electrolyzers / FCs / etc. → All Power Electronics Dependent !*

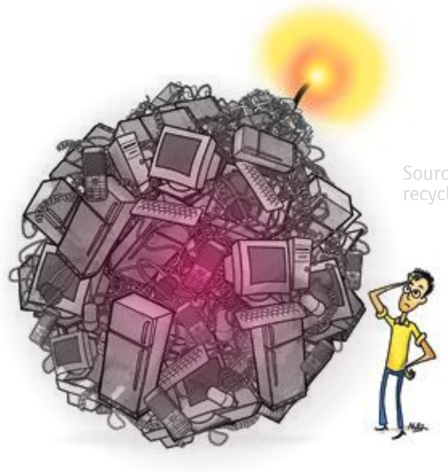
The  in the Room



Source: D. Boroyevich (2010)

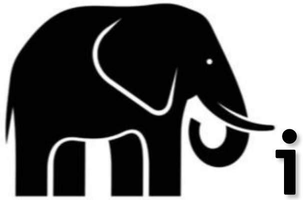
- 25´000 GW Installed Ren. Generation in 2050
- 15´000 GWh Batt. Storage

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



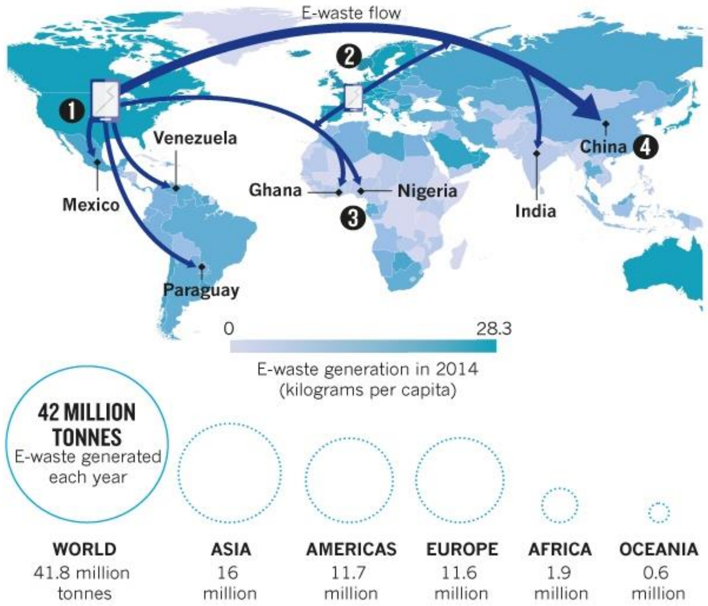
Source: www.e-waste-recyclers.co.in

- 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

- *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

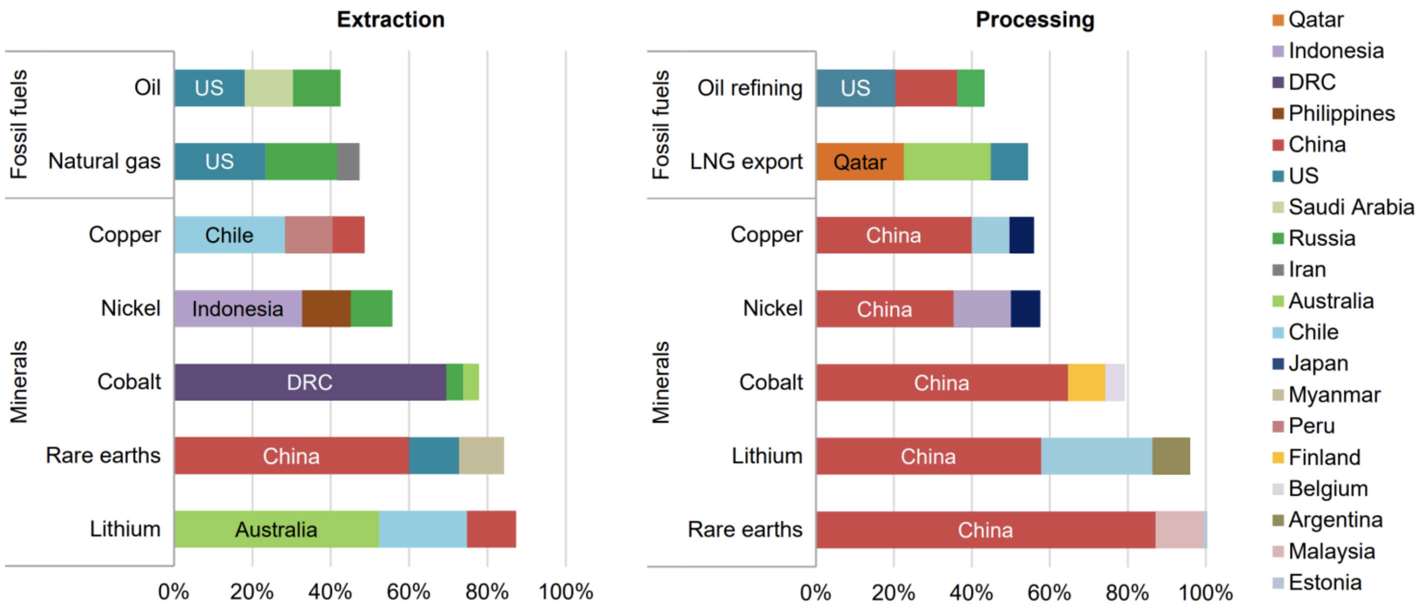


Source: nature

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

Critical Minerals

- *Production of Selected Minerals Critical for the Clean Energy Transition*



Shares of top three producing countries, 2019

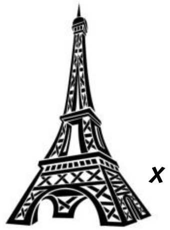
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

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

The Paradigm Shift (1)

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

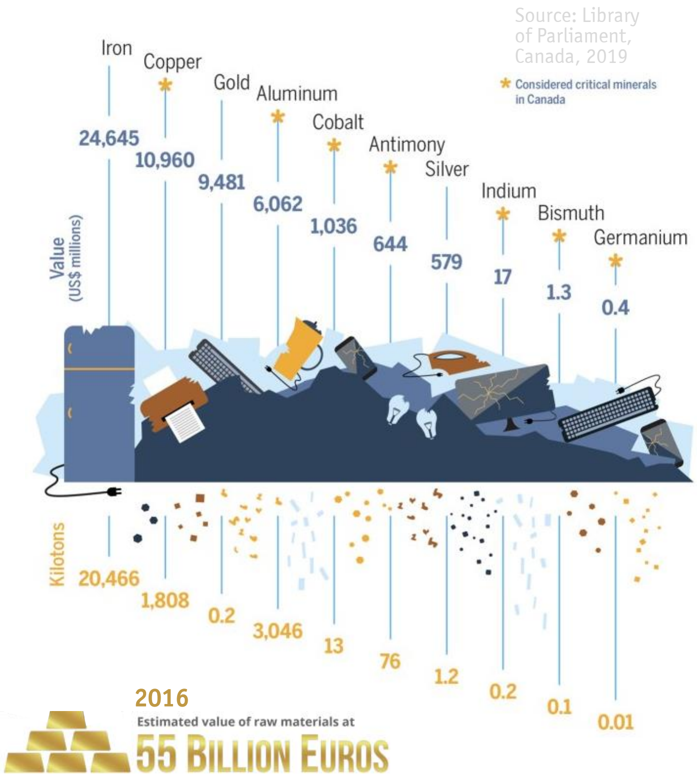
← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

unitar



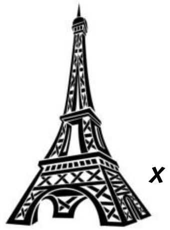
Global / 2019

- *"Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources*
- *Resources Returned into the Product Cycle at the End of Use*
- *E-Waste Represents 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*

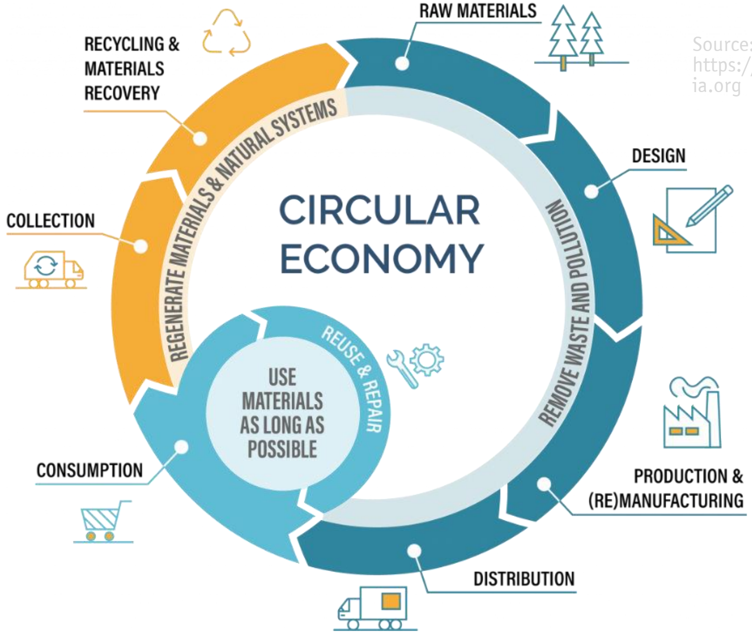
← 52 Mt (!)



x 5´200

Source: The Global E-waste Monitor 2020

unitar

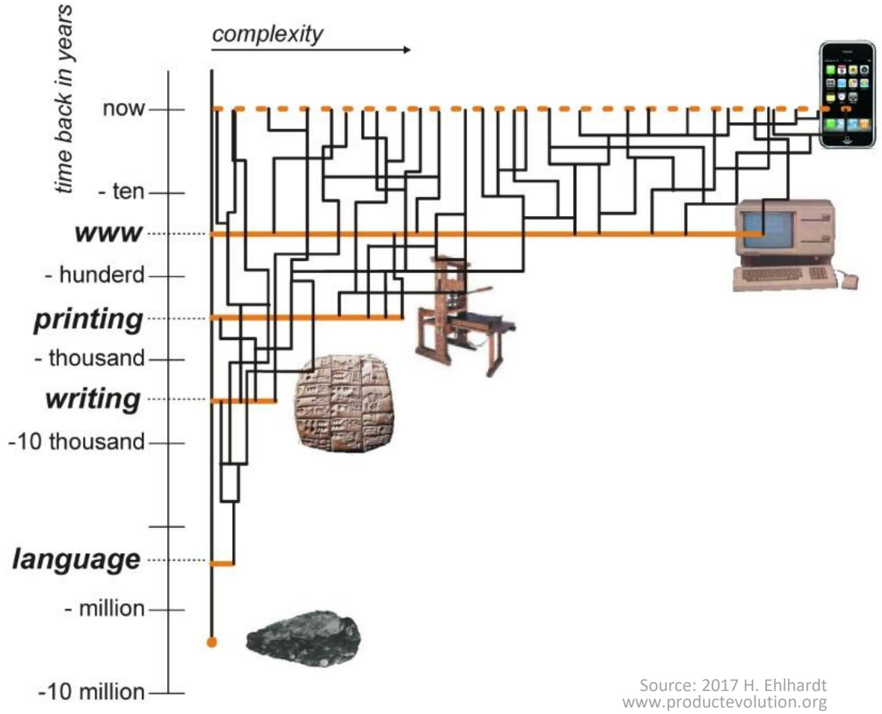


Source: https://circularphiladelphia.org

- *"Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources*
- *Resources Returned into the Product Cycle at the End of Use*

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*

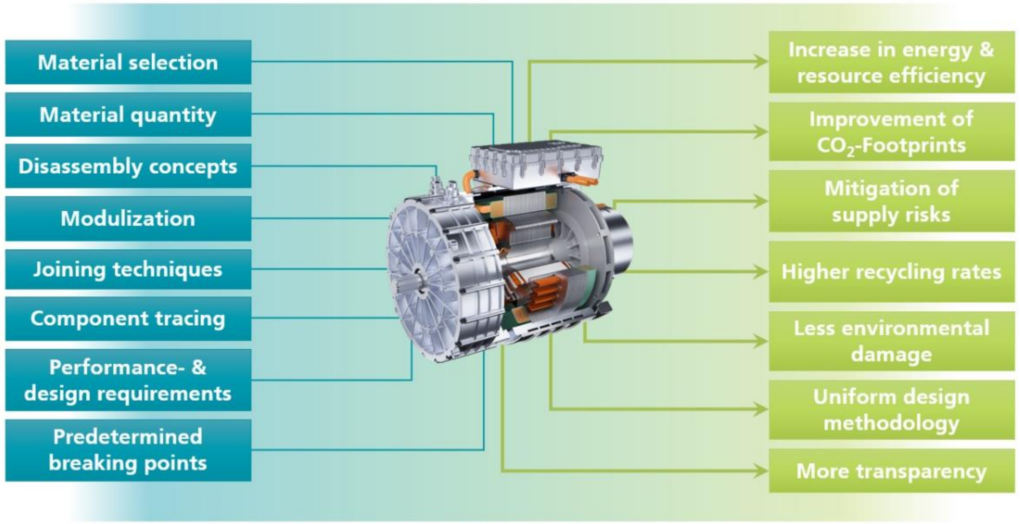
Design for Repairability & Circularity

- *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: www.ligman.com/

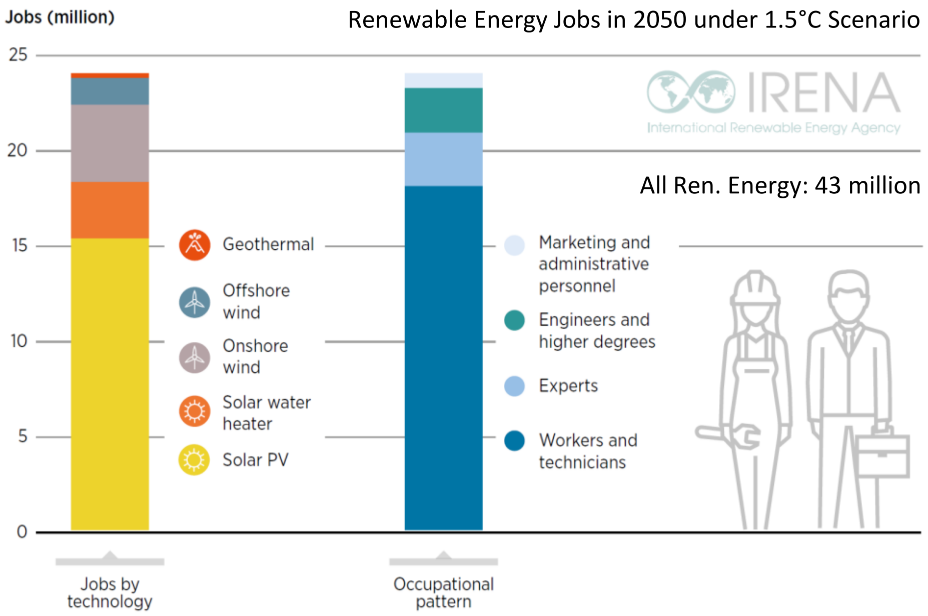
Source: https://de.ifixit.com/

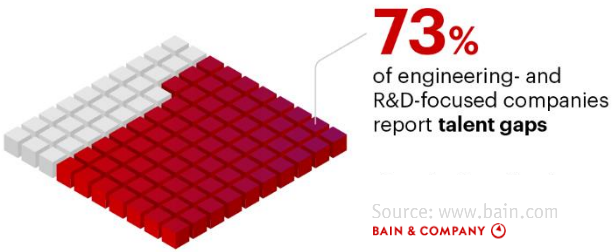


- *FAIRPHONE — Modular Design | Man. Replaceable Parts | 100% Recycl. of Sold Products | Fairtrade Materials*
- *80% of Sustainability / Environmental Impact of Products are Locked-In at the Design Phase*

Remark Scarcity of Specialized Talent

- *Increasingly Complex Technologies — Increasing Difficulty to Find Adequate Skills*





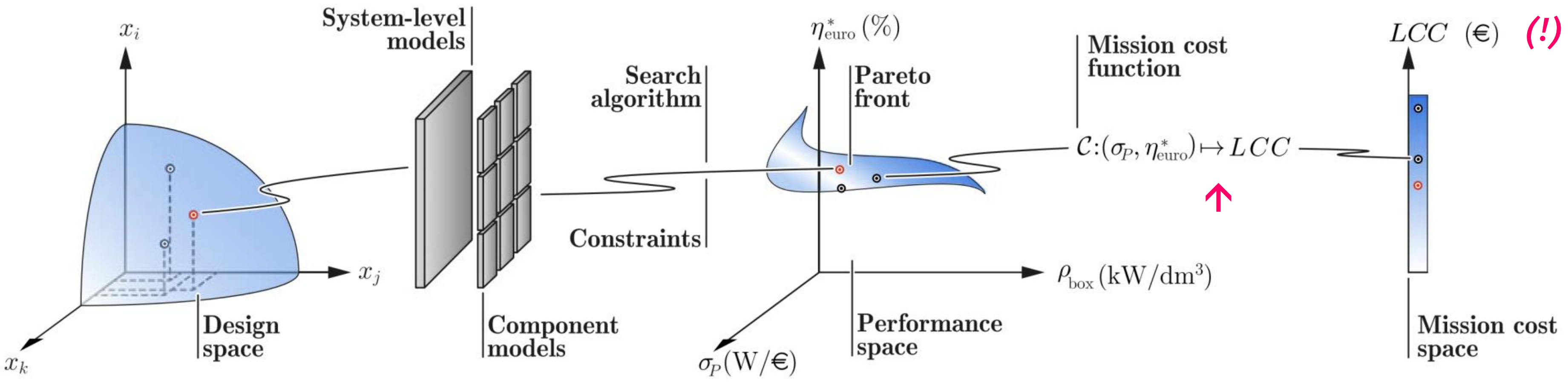
- *Demography (!) — Aging Society / Retirements / Mid-Career Engineers Transitioning to Non-Eng. Roles*
- *Reskill (Oil & Gas) & Upskill Programs & Use of AI Mandatory for Achieving the Renewables Goals*

New Holistic (!) Design Approach

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

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*

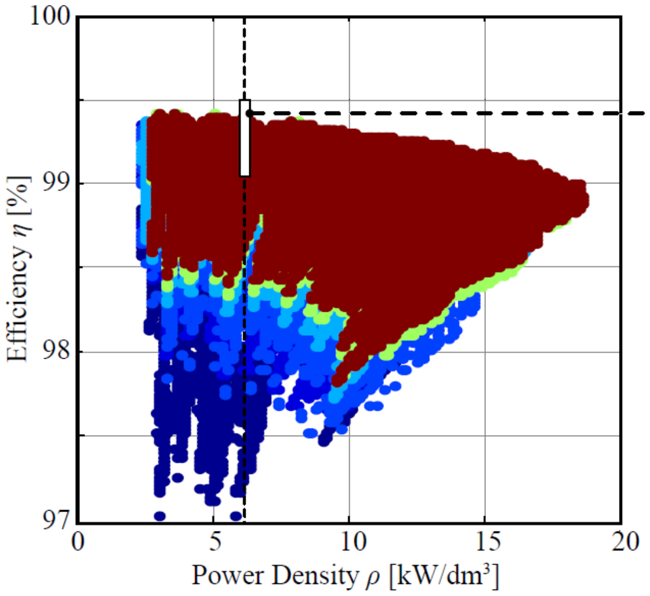


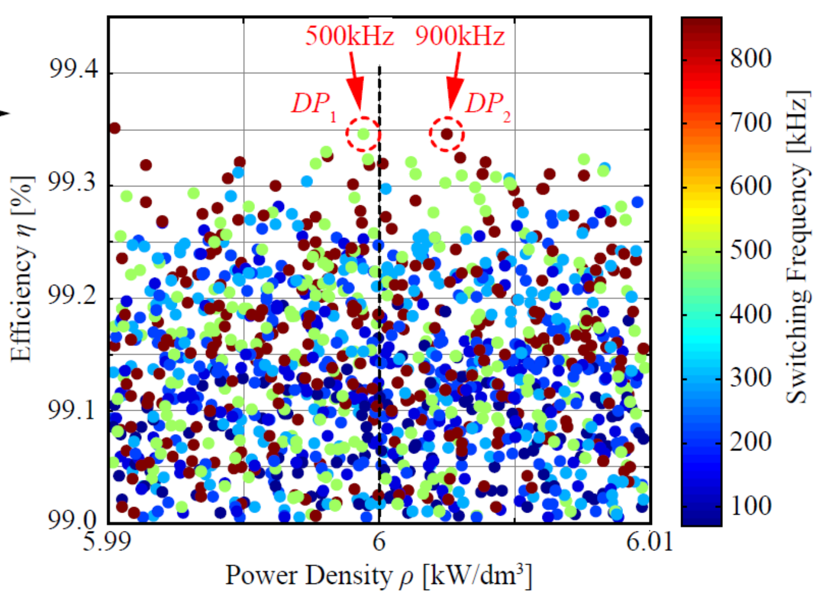
- *Mission Profile — Power Loss → Energy Loss / Life-Cycle Cost (!)*

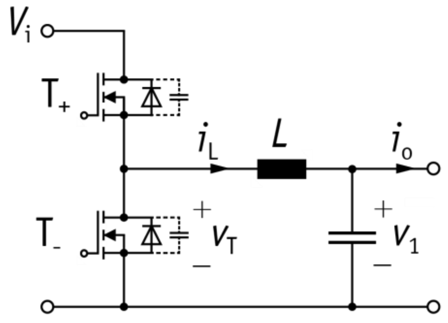
Design Space Diversity (1)

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

(!)







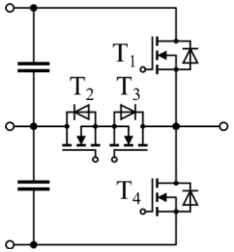
ρ = 6kW/dm^3
$\eta \approx$ 99.35%

L = 50uH
f_S = 500kHz or 900kHz

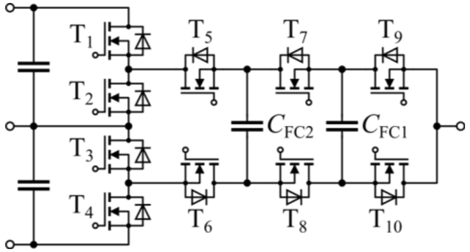
- *Example of GOOGLE Littlebox Challenge 1.0 Design Optimization w/ PWM Operation & Ideal Switches*
- *Mutual Compensation of HF and LF Loss Contributions, Winding and Core Losses, etc.*

Design Space Diversity (2)

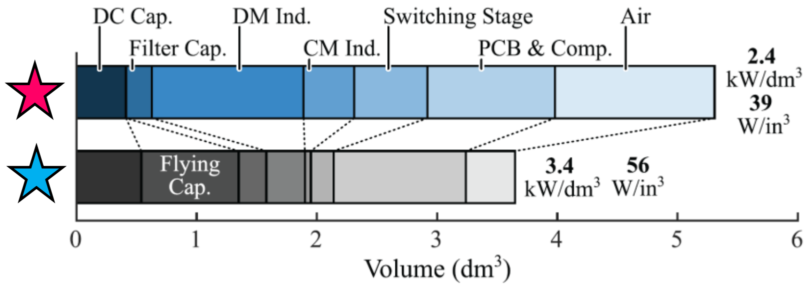
- *Two Concepts / Similar Specs — 12.5 kW, 650...720 V_{DC}, CISPR 11 Class A — Similar Performance (η_{CEC} = 99.1%)*
- *Differences in Environmental Impact (?)*

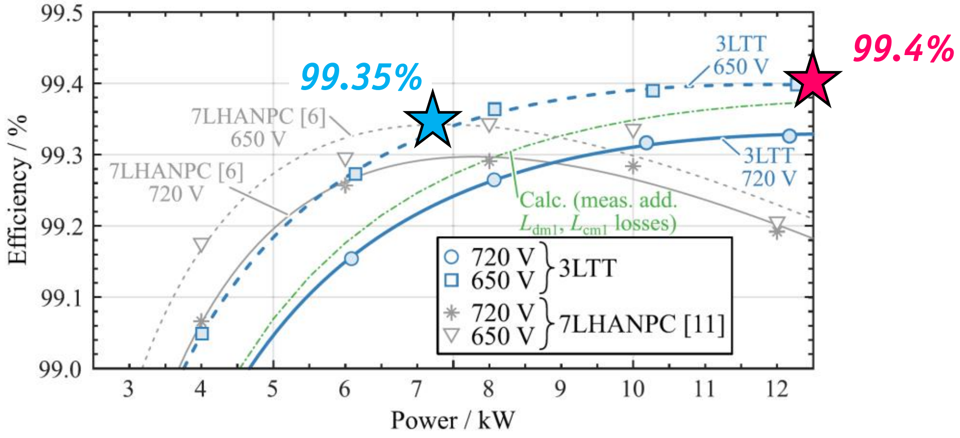


3-Level All-SiC T-Type PV Inverter
99.4% @ 2.4 kW/dm³



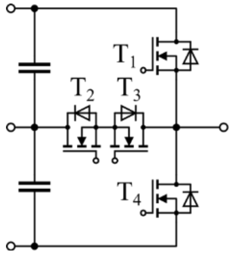
7-Level All-Si HANPC PV Inverter
99.35% @ 3.4 kW/dm³

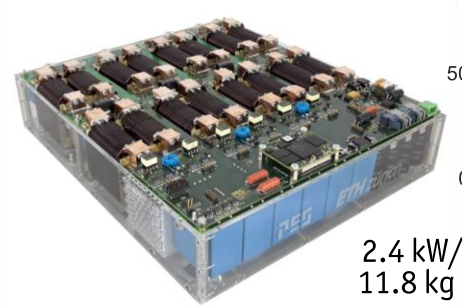


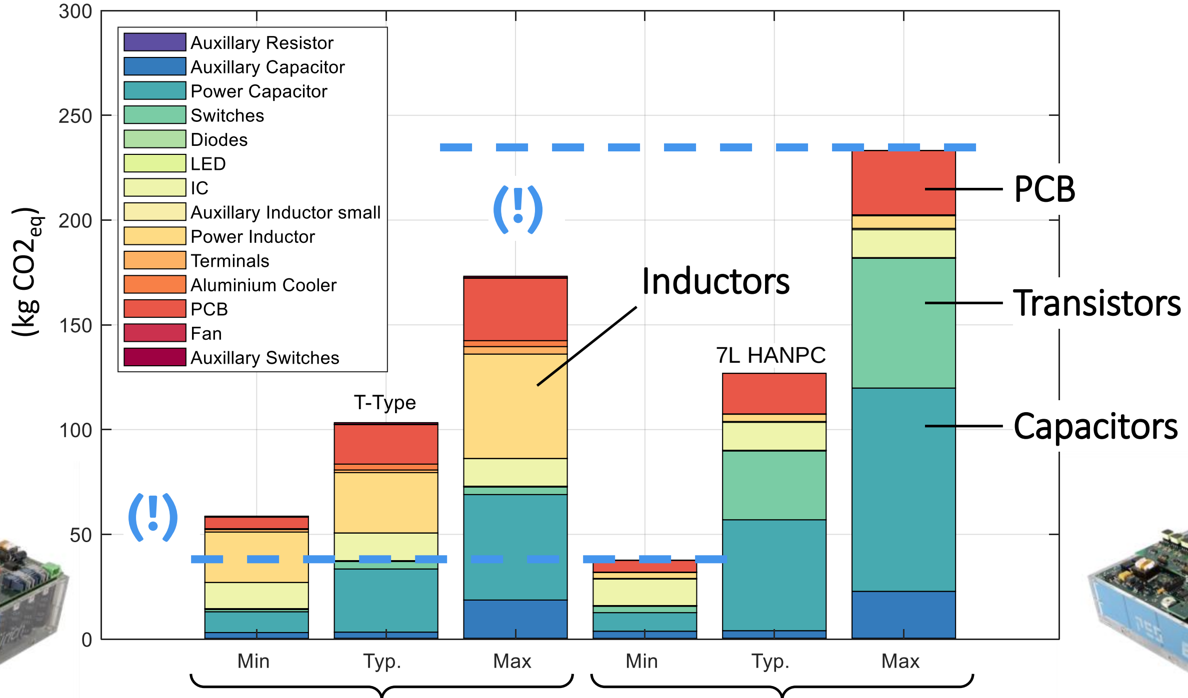


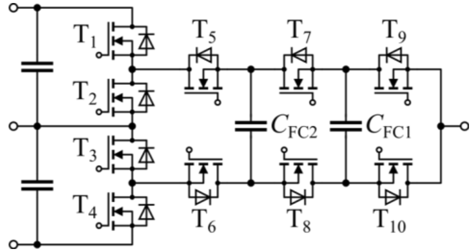
A-Posteriori LCA of 3L & 7L PV Inverters

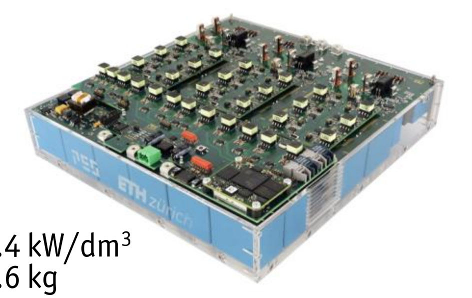
- *Two Concepts / Similar Specs — 12.5 kW, 650...720 V_{DC}, CISPR 11 Class A — Similar Performance (η_{CEC} = 99.1%)*











2.4 kW/dm³
11.8 kg

★ *3L T-Type*

★ *7L HANPC*

3.4 kW/dm³
4.6 kg

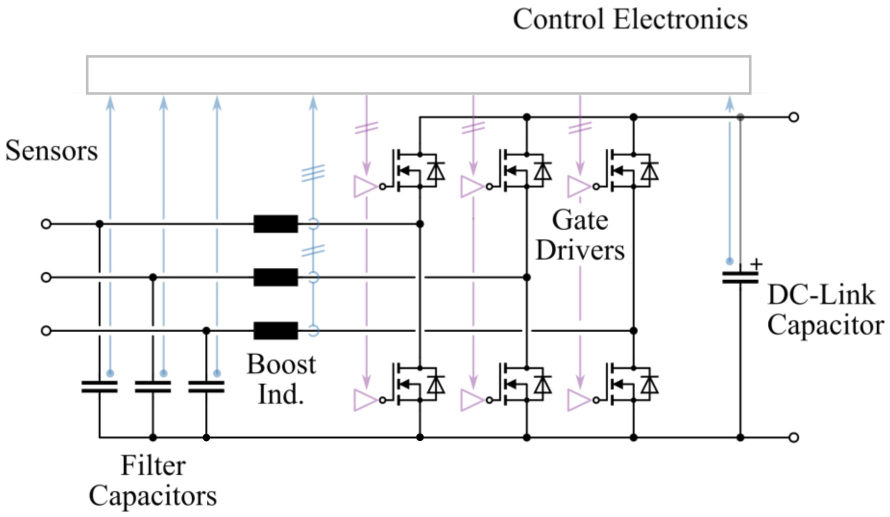
- *Generic Compon. Models / ecoinvent & Literature as Data Sources → Widely Varying CO_{2eq}-Results*

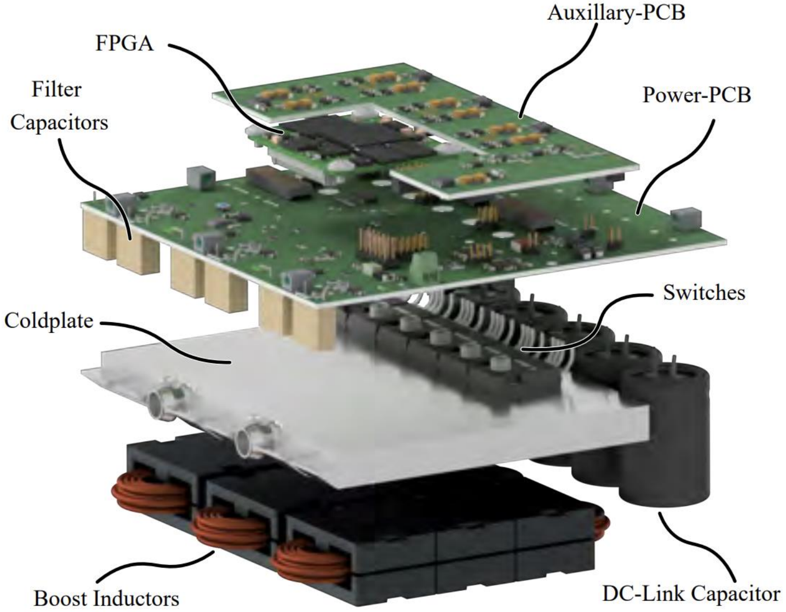
A-Priori Consideration of Environmental Impacts in the Design Process

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



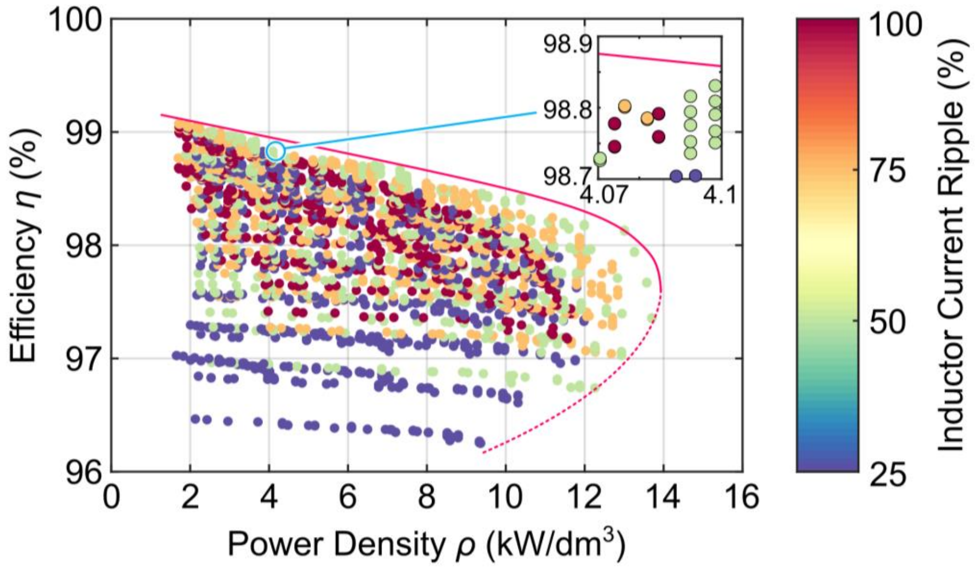


- *Main Components Considered (Losses, Volume, CO_{2eq})*
- *Power Trans., Heat Sink, Boost Ind., DC-Link Cap., Filter Cap., Gate Drivers, Sensors, Contr. Electr., PCBs*

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*

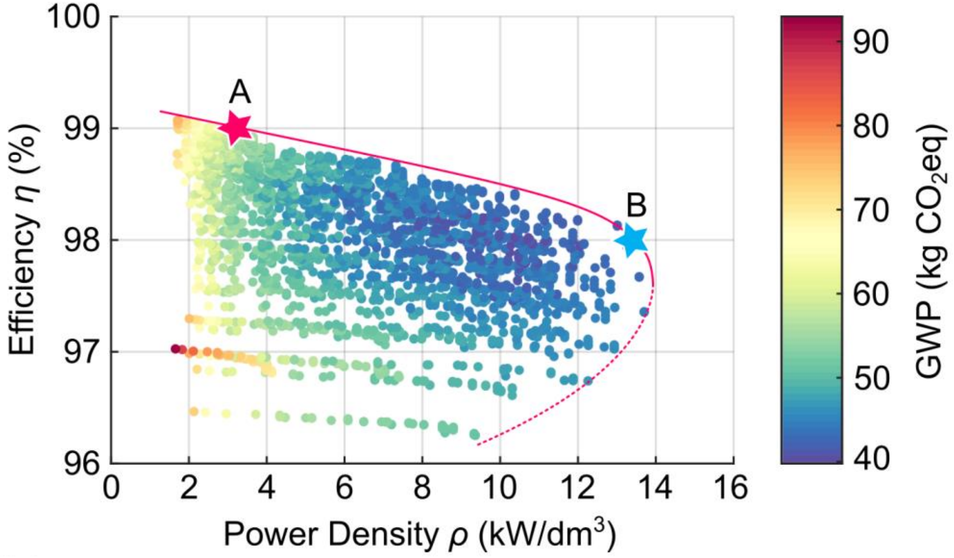
10 kW
400 V_{AC} Mains
800 V_{DC} Output
1200 V SiC

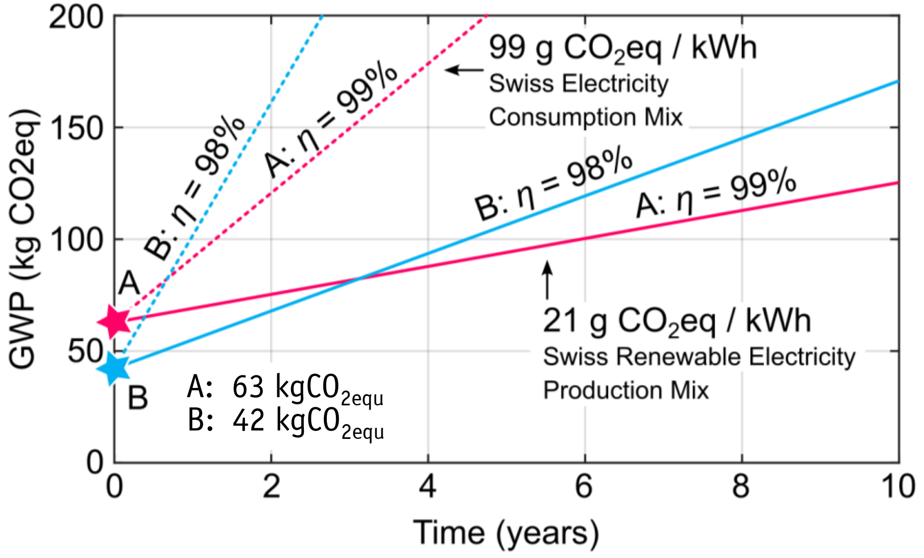


- *Degrees of Freedom*
  - *Switching Frequency [25...200 kHz]*
  - *Rel. Ind. Peak Current Ripple [0.25...1]*
  - *Variable Transistor Chip Area*
  - *Variable Ind. Size (N87; Solid/Litz Wire)*
- *Assumptions*
  - *Junction Temp. @ 120 °C*
  - *Ambient Temp. 40 °C*
  - *Necessary Heat Sink Vol. via 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*

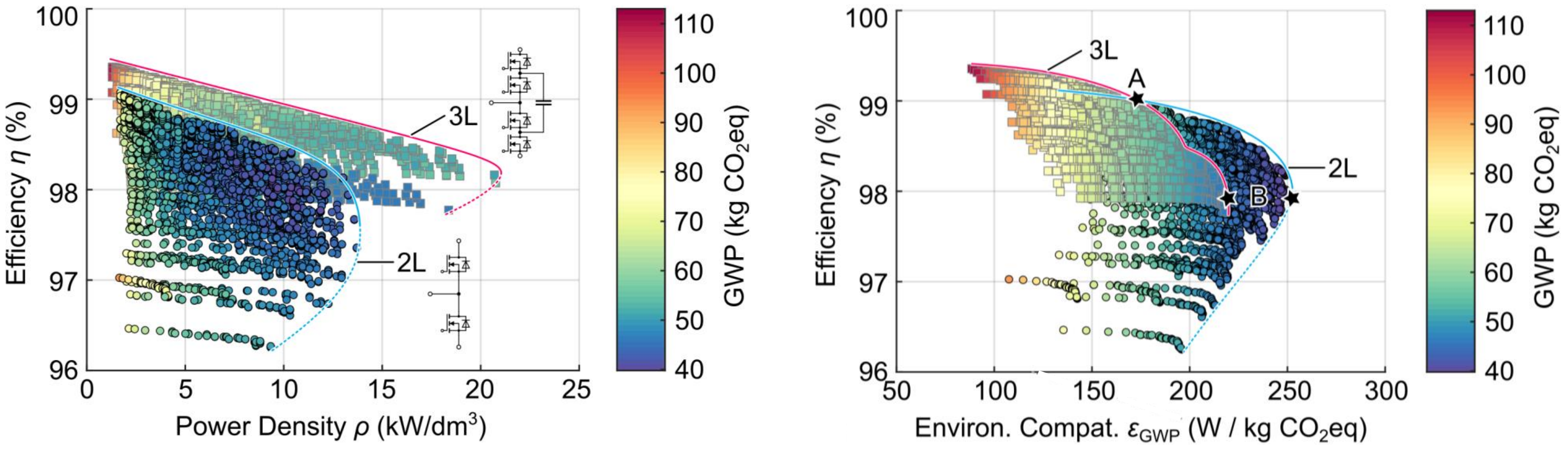




- *Energy Losses During Use Phase Contribute to Overall GWP*
- *More Eff. Designs w/ Higher Initial GWP Outperform Less Eff. Designs for Longer Operating Times*

2-Level vs. 3-Level PEBB Evaluation

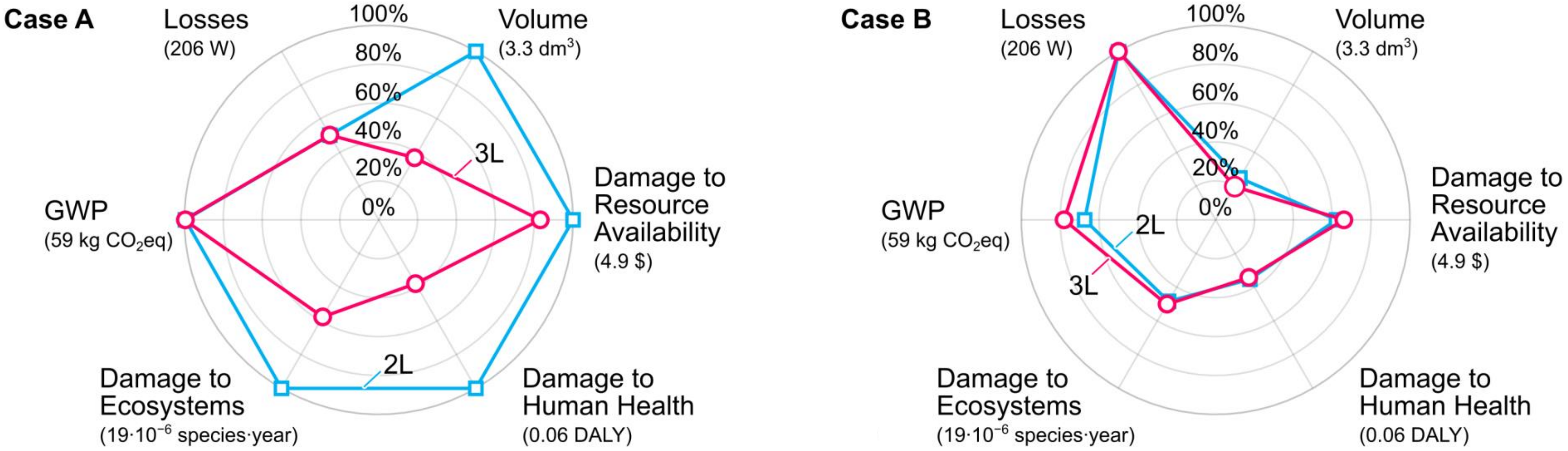
- *3-Level Flying-Capacitor Bridge-Legs w/ 650 V SiC MOSFETS / 2-Level Bridge-Legs w/ 1200 V SiC MOSFETs*
- *400 V_{AC} Mains | 800 V_{DC} | 10 kW | LC-Filter w/ Same Capacitor Voltage Ripple*



- *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*



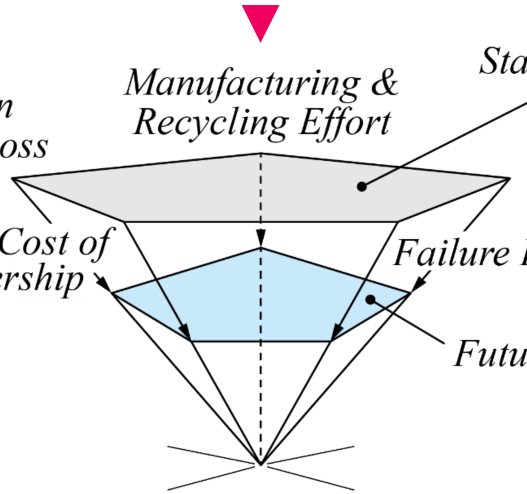
- *Case A 99% Eff. @ Equal GWP — Significantly Diff. Volumes & Diff. ReCiPe Performance*
- *Case B 98% Eff. @ Highest Rel. Environm. Compatibility — Similar Volumes & Environm. Impacts*

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*

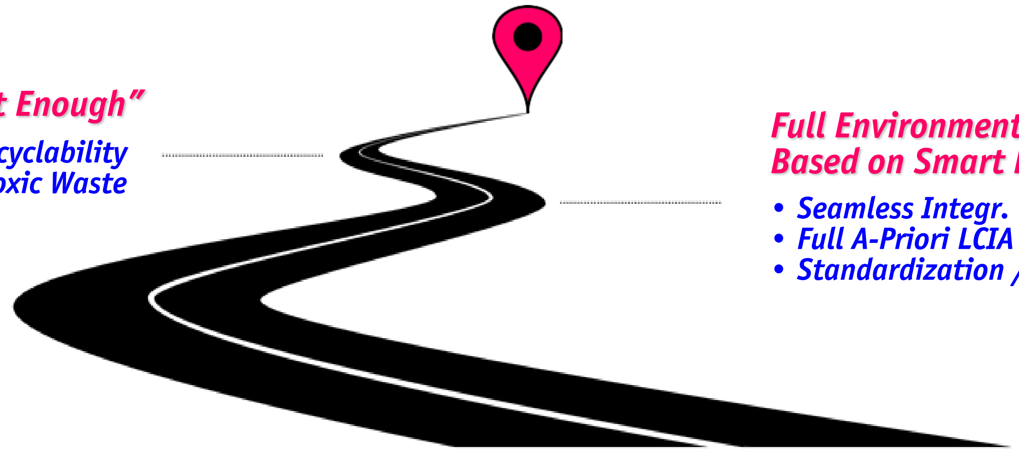
— Environmental Impact [kgCO_2eq/kW]
— Resource Efficiency [kg_{xx}/kW]
— Embodied Energy [kWh/kW]
— TCO [$/kW]
— Power Density [kW/m^2]
— Mission Efficiency [%]
— Failure Rate [h^{-1}]



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, 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*

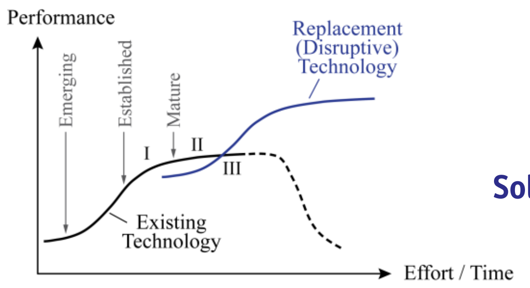
Generic Life-Cycle ImpactAnalysis (LCIA)
- *New KPIs in Multi-Obj. Opt.*
- *Data Sources / Quality / Abstraction / Generalization as Key Challenges*

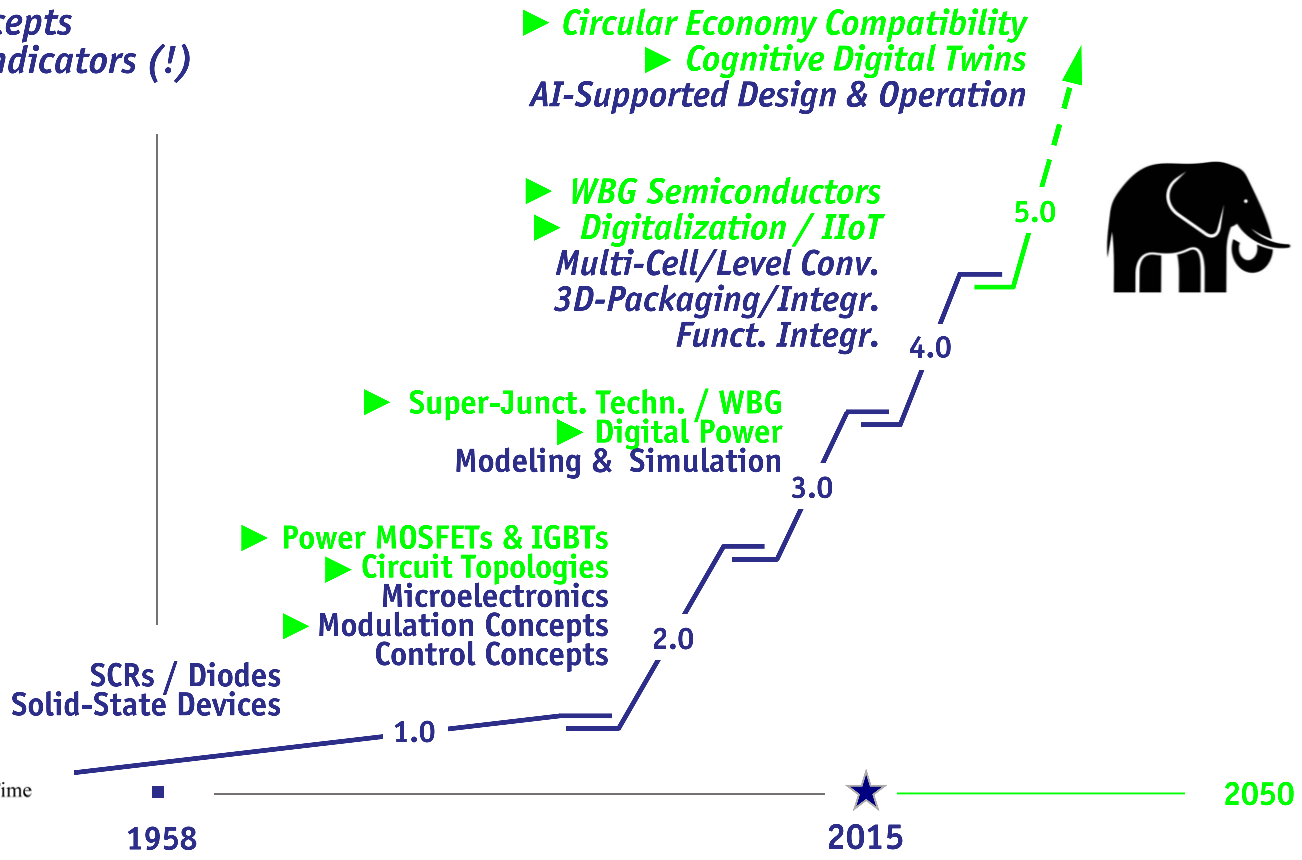
Classical $\eta\rho$-Pareto Optimization / Design
- *Manual A-Posteriori LCA of Complete Converters*

- *Automated Design | On-Line Monitoring | 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 !