ETH zürich

Workshop on Sustainable Energy Supply by 2050

Circular Economy Compatible Power Electronics

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Sept. 2, 2024

ETH zürich

ECPE

Workshop on Sustainable Energy Supply by 2050

"Zero-EOL-Waste" Power Electronics

Johann W. Kolar | Jonas Huber | Luc Imperiali

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Sept. 2, 2024

Outline

- *Decarbonization*
- *Critical Raw Materials*
- *Low Carbon Footprint Design*
- *Closing the Loop*
- *ECPE* Roadmap*

Acknowledgment

A. Anurag
R. Wang
P. Barbosa

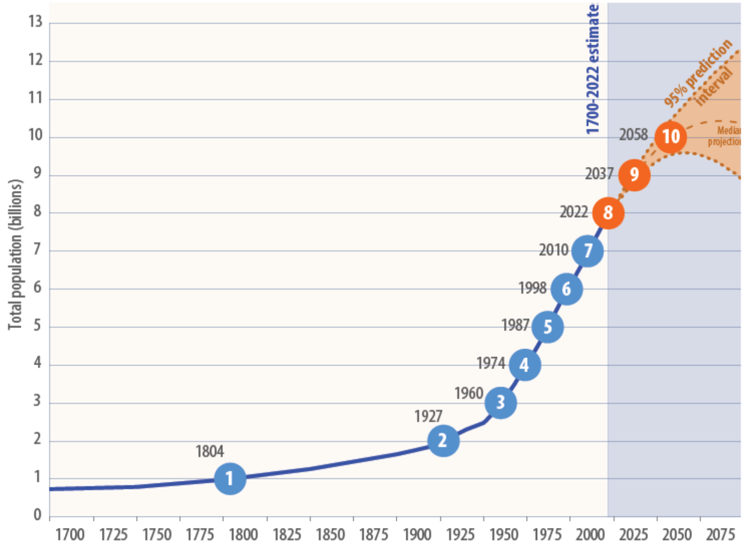
Decarbonization

Renewable Energy
Critical Raw Materials

The Challenge 1/2

- *Growth of World Population & Growth of Energy Use per Capita*
- *1980 — 4.4 Billion | ≈ 10 TW.yr → 2022 — ≈ 8 Billion | 20.4 TW.yr*

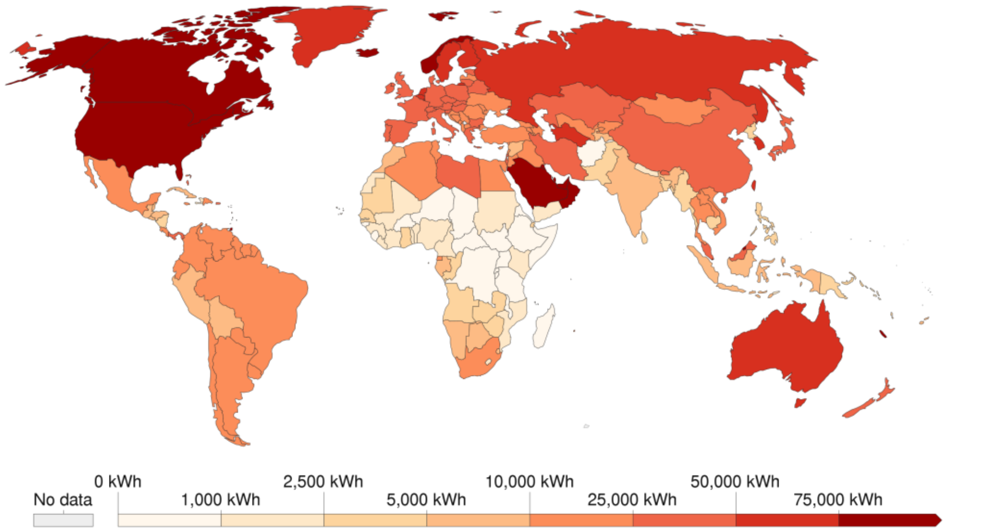
Global population size: estimates for 1700-2022 and projections for 2022-2100



Source: United Nations, DESA, Population Division (2022). World Population Prospects 2022.

Energy use per person, 2021

Energy use not only includes electricity, but also other areas of consumption including transport, heating and cooking.

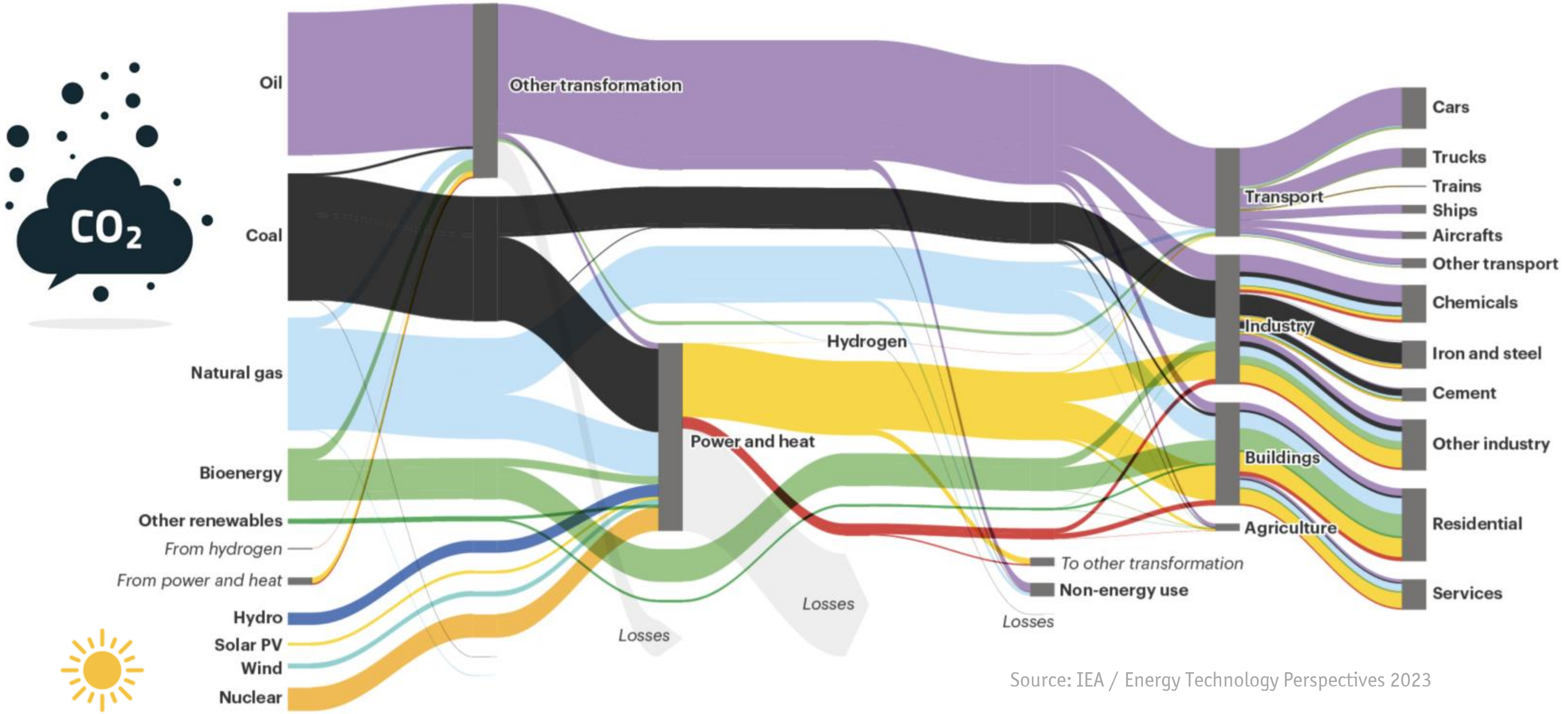


Source: Our World in Data based on BP & Shift Data Portal
Note: Energy refers to primary energy – the energy input before the transformation to forms of energy for end-use (such as electricity or petrol for transport).

- *2022 Global Energy Consumption per Capita — 22´400 kWh avg. | 2.6 kW avg. (2.3 kW avg. in 1980)*

The Challenge 2/2

- *Coal & Oil Powered the 1st Industrial Revolution (1750) / Enabled Mechanization*



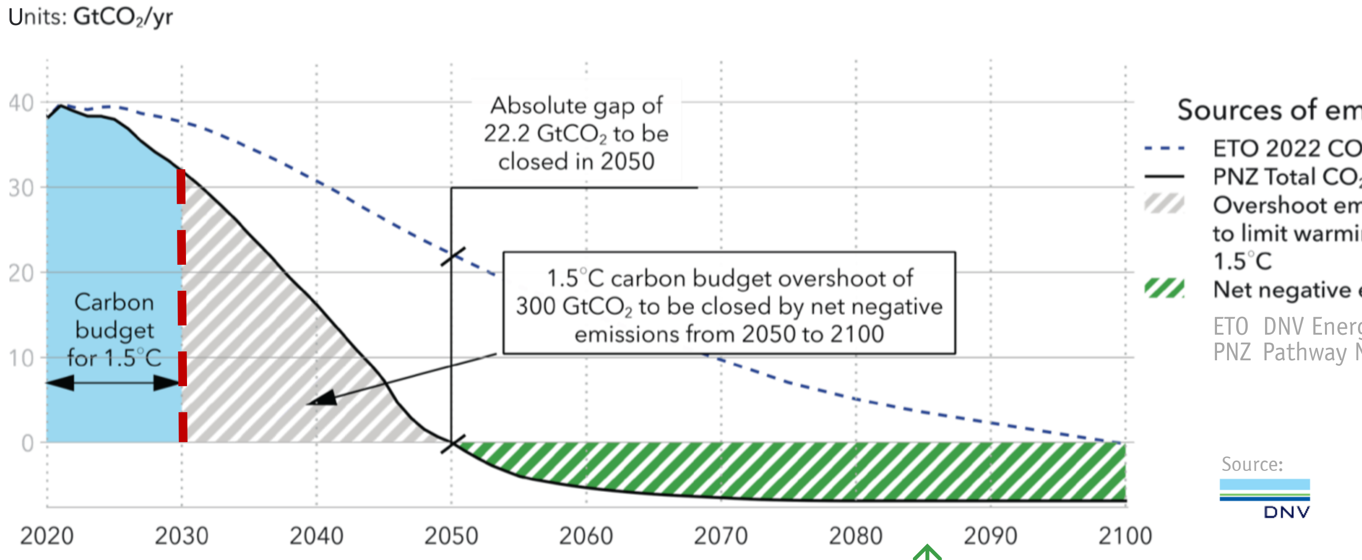
Source: IEA / Energy Technology Perspectives 2023

- *Global Energy Flows — 2021*
- *World Economy Heavily Depends on 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 $GtCO_2$ →



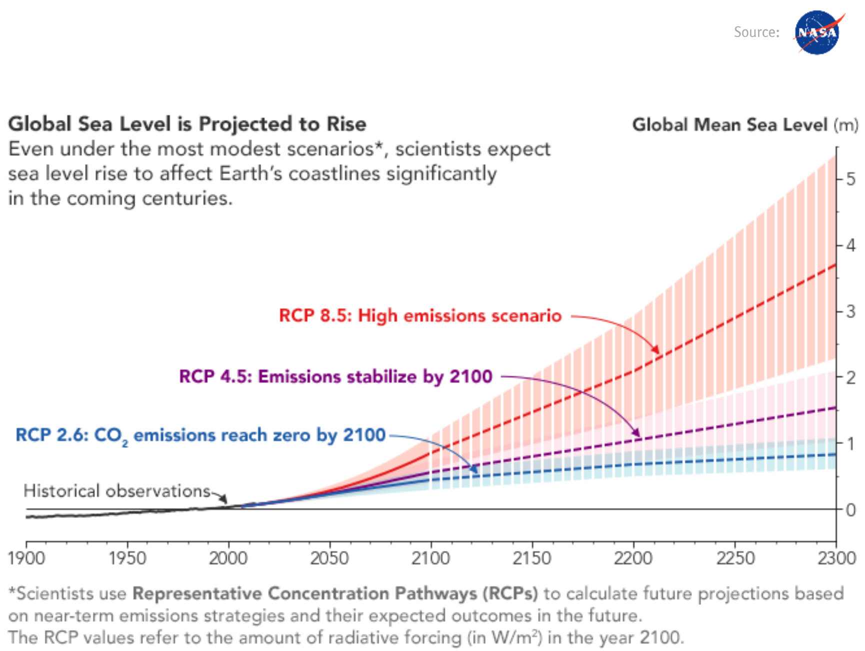
Source: DNV

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

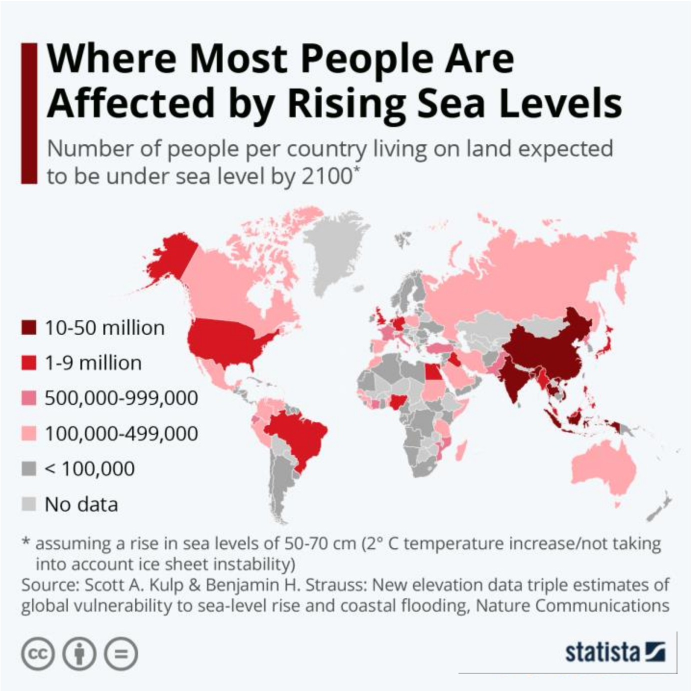
- *Human History — Transition from Lower to Higher Energy Density Fuels — Wood → Coal → Oil & Gas*
- *Challenge of Stepping Back from Oil & Gas to Low Energy Density Renewables*

Global Sea Levels by 2100 1/2

- *Rising Sea Levels Due to Global Warming*
- *IPCC Predictions for Low/High Emissions Scenario*



@ 2°C Temp. Increase

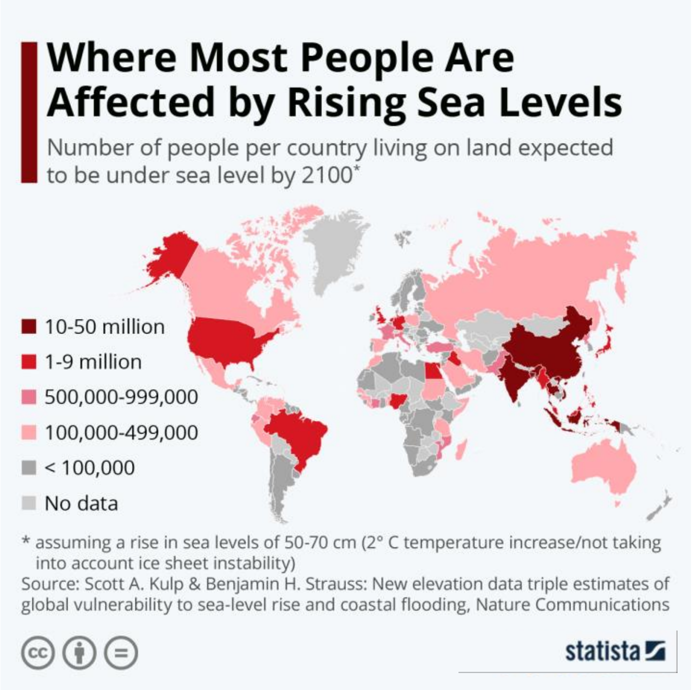


- *200 Million People will Globally Live Below the Sea Level Line by 2100*
- *Add. 160 Million Affected by Higher Annual Flooding Due to Rising Ocean Levels*

Global Sea Levels by 2100 2/2

- *Rising Sea Levels Due to Global Warming*

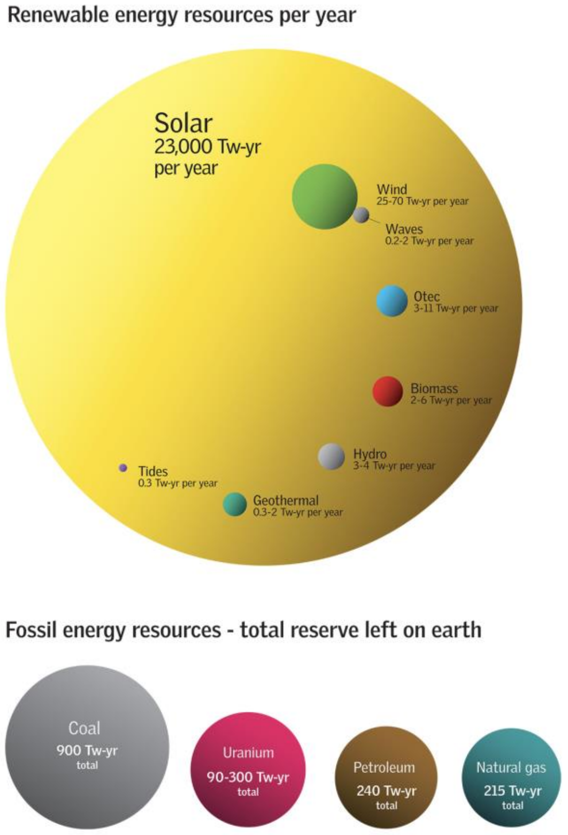
@ 2°C Temp. Increase



- *North Sea Enclosure Dyke — Mammoth Dams Envisioned to Protect 25 Million Europeans — €250bn ... €500bn*

The Opportunity

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



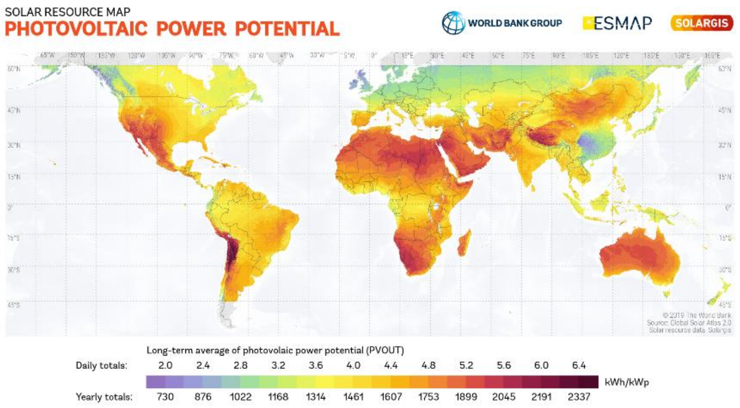
100% Conv. Efficiency
Excl. Oceans

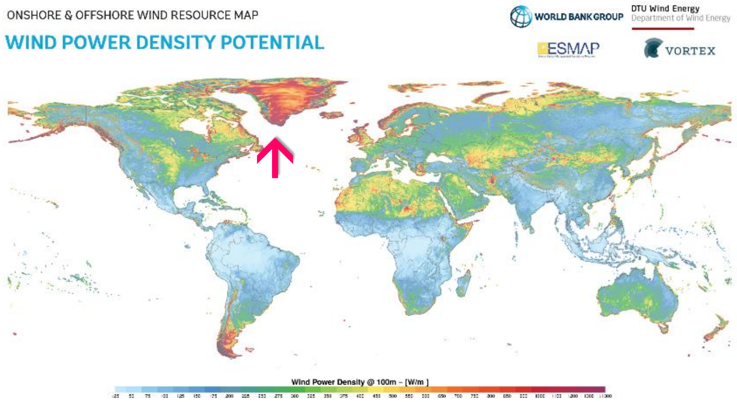
Note: Graphical Representation Assumes Spheres Not Circles

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)

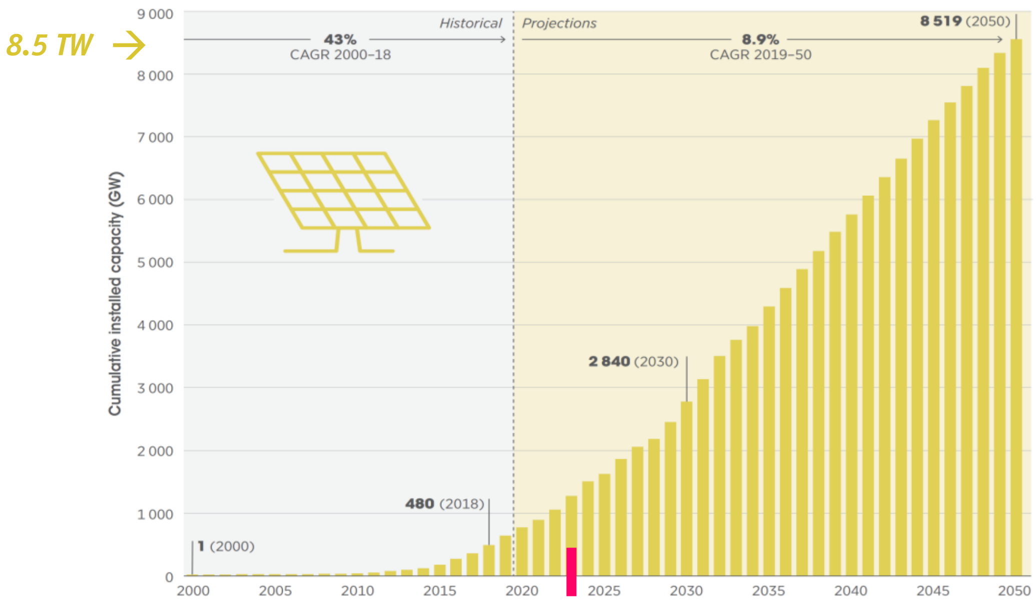
■ ***Global Distribution of Solar & Wind Resources***



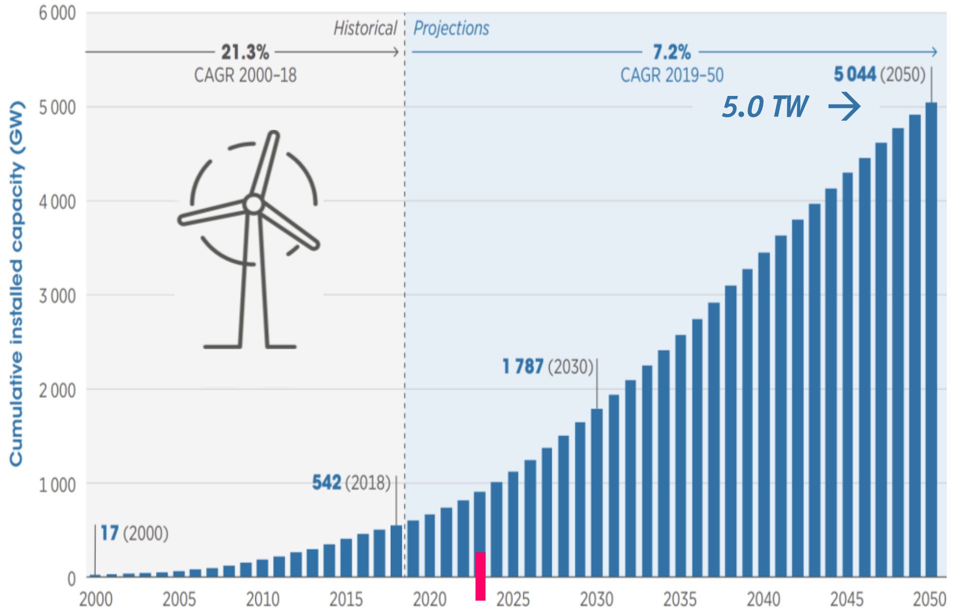


PV & Wind Power Installations

- *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).



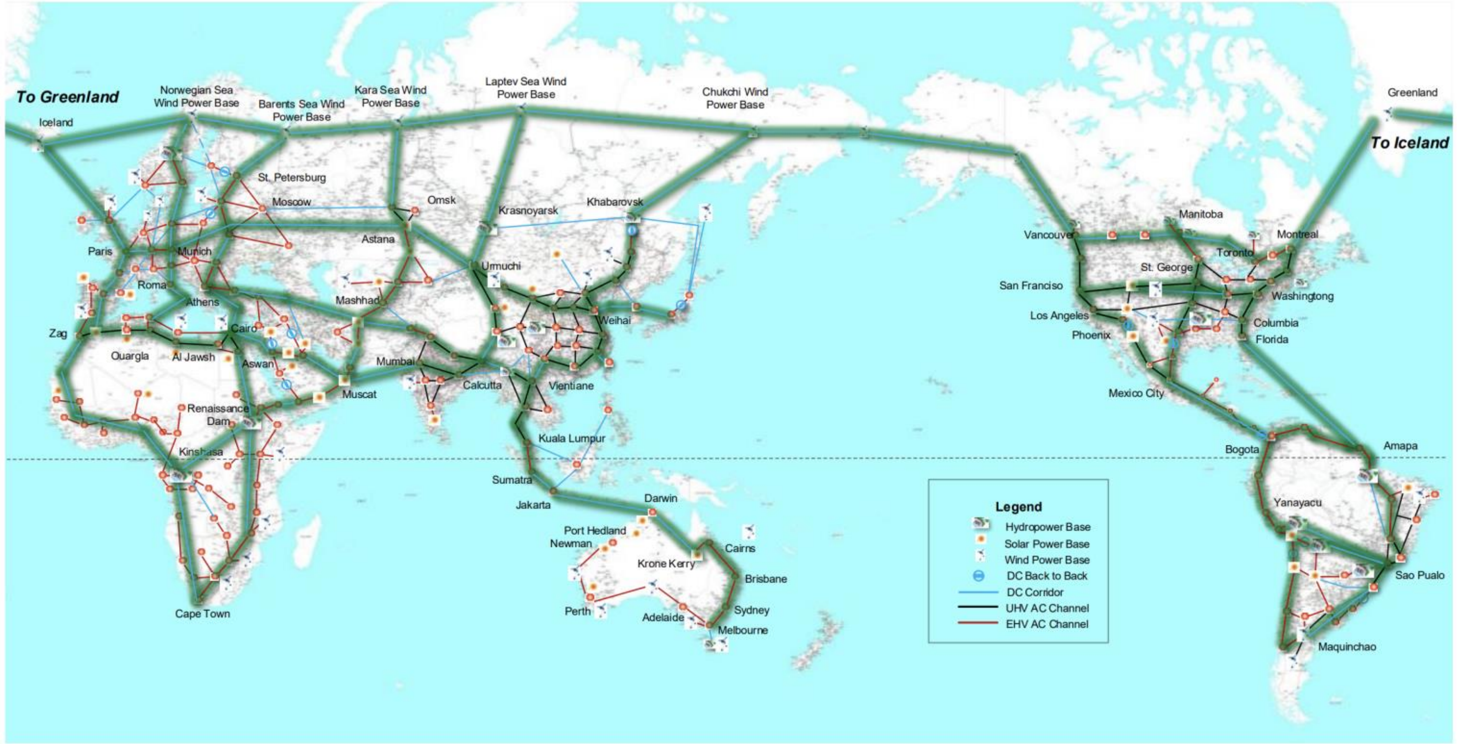
Source: Historical values based on IRENA's renewable capacity statistics (IRENA, 2019d) and future projections based on IRENA analysis (IRENA, 2019a).

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

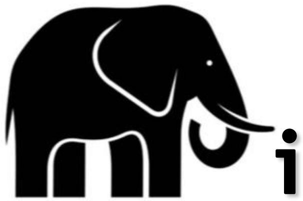
Aiming for a Global Solution (?)

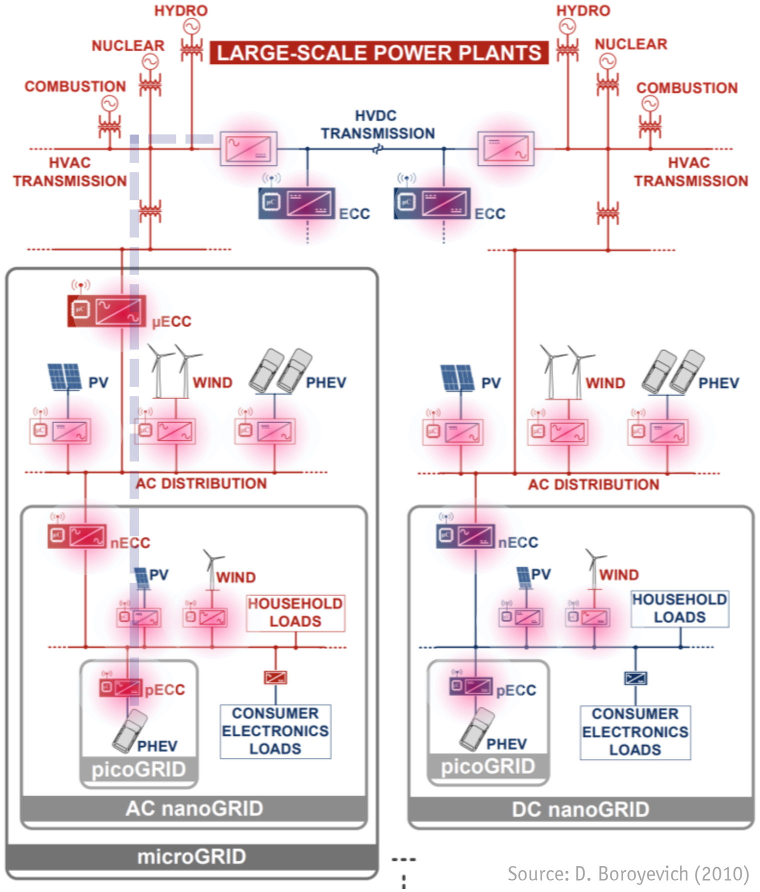
- *"Super/Mega/Overlay Grid"-Concepts Proposed since 1950s — GENESIS (1994), DESERTEC (2003), etc.*
- *U-HVDC Trans-Continental or Multi-National Supply & Trade of Clean Electricity*

Source: GEIDCO 2018



- *Example of the "Global Energy Interconnection Backbone Grid" (GEIDCO) Proposed by China in 2015*

The  in the Room



Source: D. Boroyevich (2010)

- *Global Population by 2050 — 10bn 2.5 kW/Capita*
- *25´000 GW Installed Ren. Generation in 2050*

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

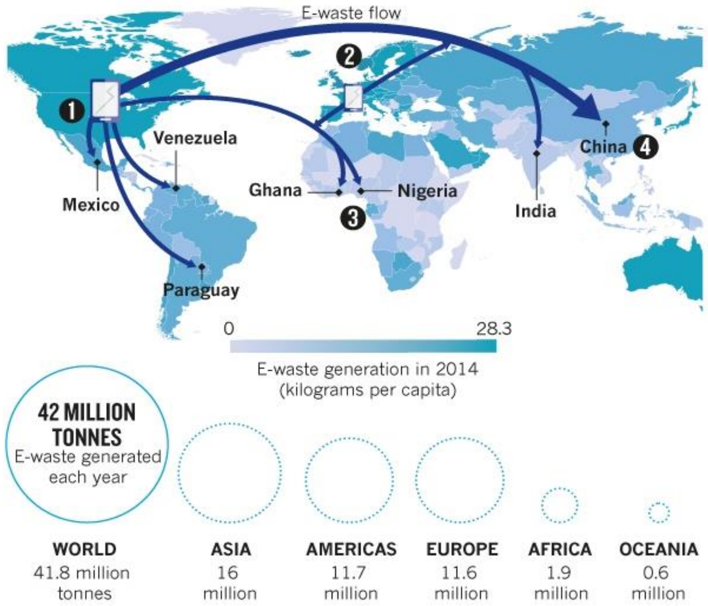

Source: www.e-waste-recyclers.co.in

- *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

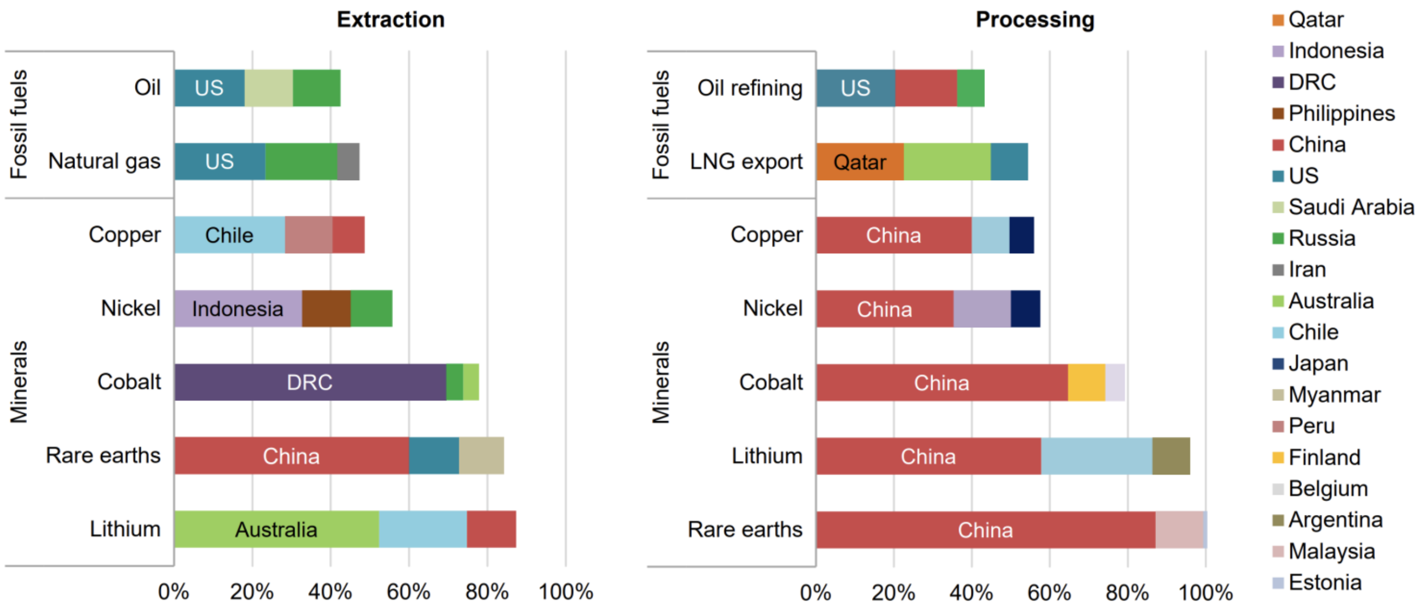


Source: nature

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

Critical Minerals

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



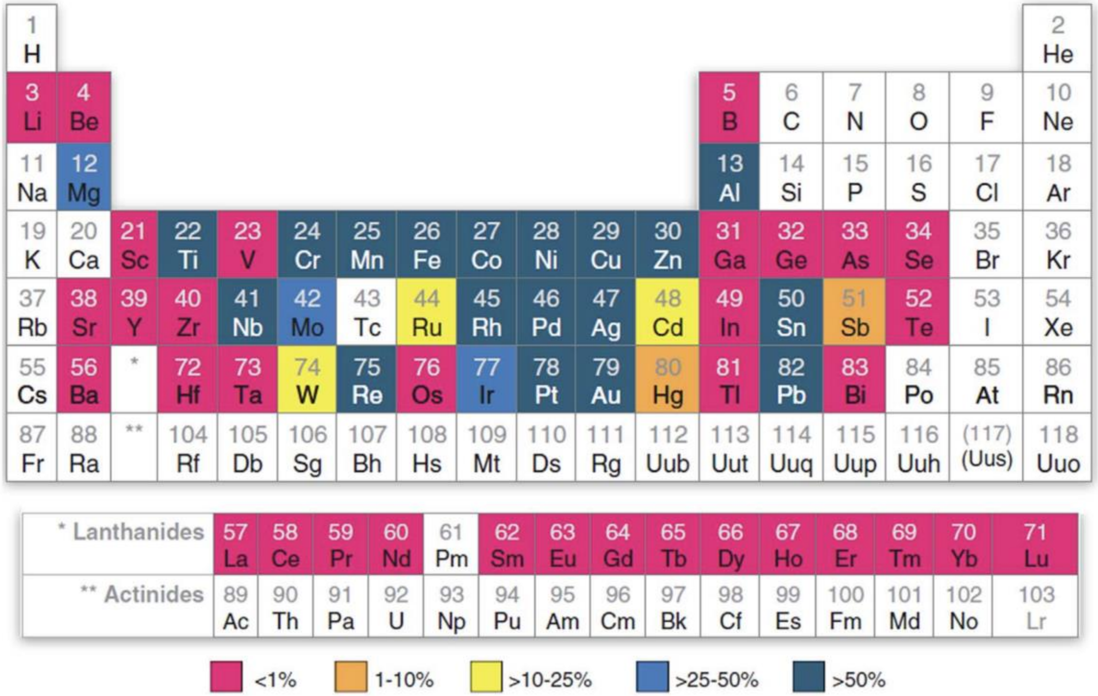
Shares of top three producing countries, 2019

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

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

End-of-Life Recycling Rates of Metals

- *Global Estimates of EOL-RRs of 60 Metals & Metalloids (2008)*



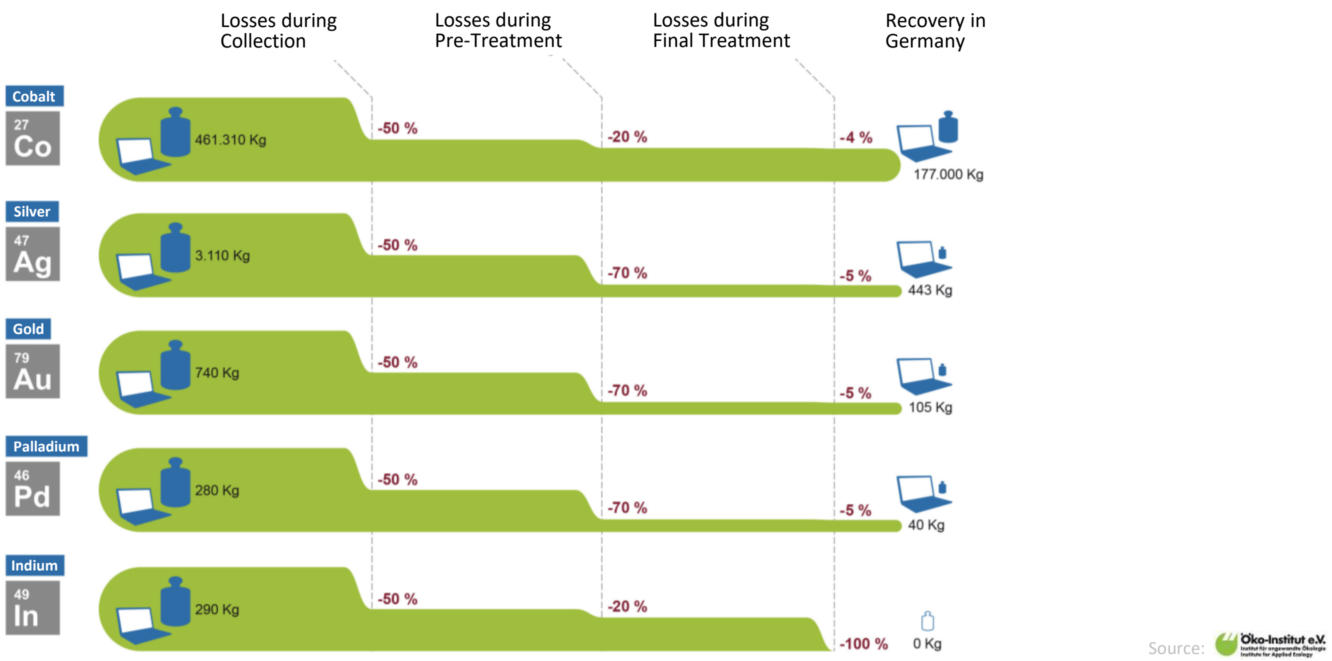
Source:
J. Song et al., 2018 /
T.E. Graedel et al., 2011

- *Partly Very Low EOL-RRs*
- *Rel. Low Efficiency in Collection & Processing of Most Discarded Products & Low $$$ of Primary Material*

ETH zürich

Raw Material Losses in Notebook Recycling

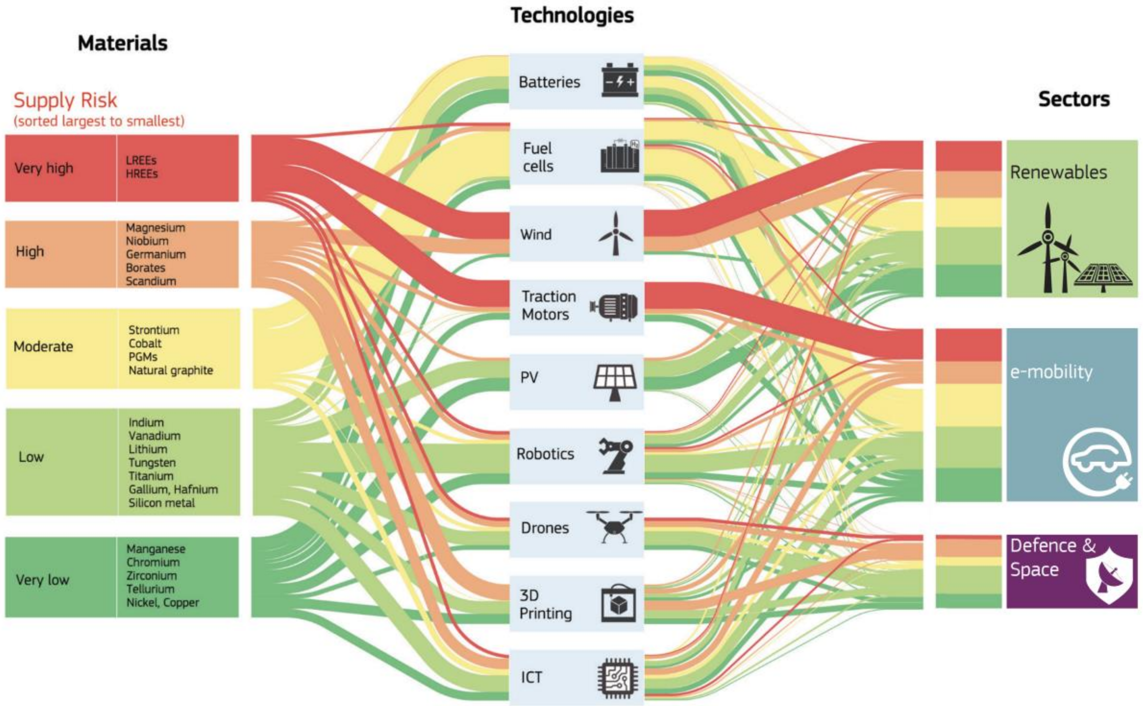
- *Weight Data Based on Notebooks Sold in Germany in 2010*



- *Missing Recovery of Low Concentration Precious Metals*
- *Recycling Hampered by Product Design, Recycling Technology, Social Behavior, Etc. — „Trapped Resources“*

EU Critical Raw Materials Act

- *Europe's / Global Green Transition → Substantial Increase in Demand for Critical Raw Materials*
- *Geospatial Concentration of Supply Chains / Significant Geopolitical Risks*



Source: European Commission

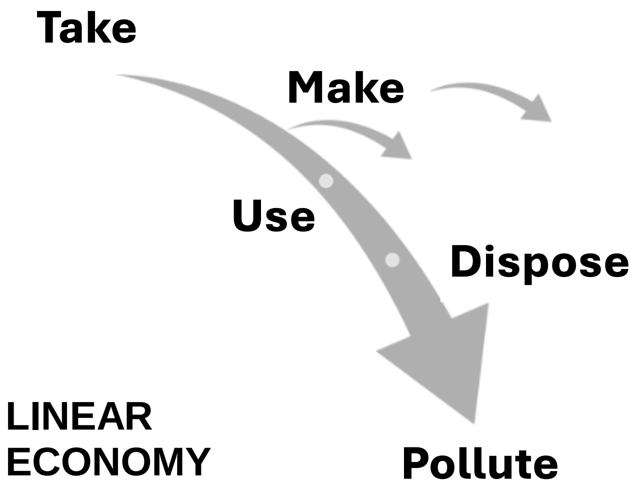
- *Access to Secure & Sustainable CRMs Supply Crucial for Achieving the 2030 Climate & Digital Objectives*
- *EU Critical Raw Material (CRM) Act 2024 → Sustainability & Circularity of CRMs on the EU Market*

Action #1
"Do More With Less"

Basic Scaling Laws
Enabling Technologies

The Paradigm Shift

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



Source: CC 3.0 Catherine Weetman 2016

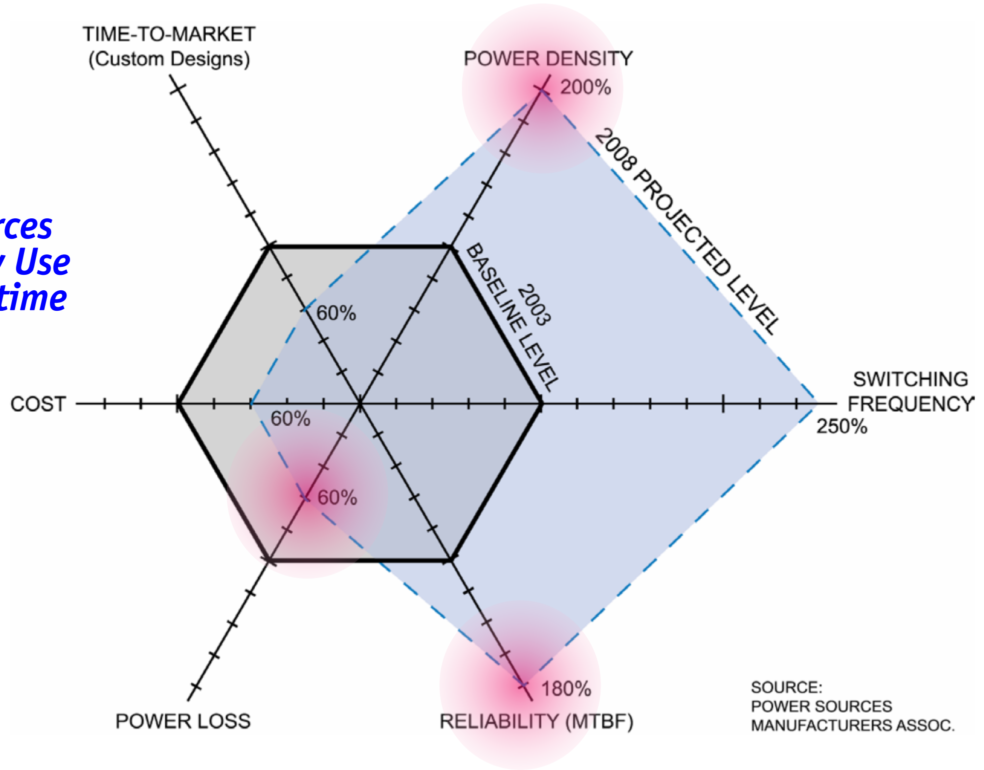
Source: UTS — Institute for Sustainable Futures

- *"Linear" Economy / Take-Make-Dispose → "6 Rs" Towards Perpetual Flow of Resources / "Circular" Economy*
- *Recycling Aluminum 95% More Energy Efficient, Plastic 85%, Paper 50%, Glass 40% — "Downgrading" Problem*

"Avoid and Reduce"

- *Today´s Power Electronics Innovation Basically Contributes to Lower Environmental Impact*

- *Power Density → Red. of Resources*
- *Efficiency → Red. of Energy Use*
- *Robustness → Increased Lifetime*

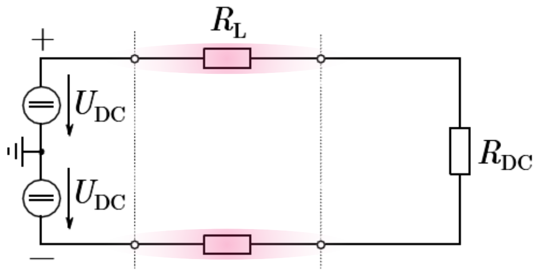


- *New Set of KPIs Mandatory to Meet Future Environmental Protection Objectives*

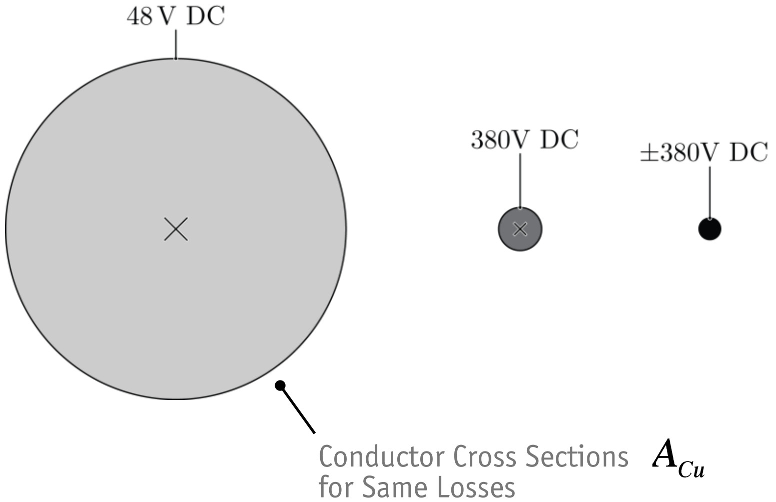
Scaling of DC Power System Losses

- *Increase of R_L with Transmission Distance l*
- *Red. of R_L only Through Larger Conductor Cross Section A_{Cu}*

→ *Transmission Losses* $P_{V,DC} = 2 \cdot \left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L \sim \frac{1}{U_{DC}^2}$



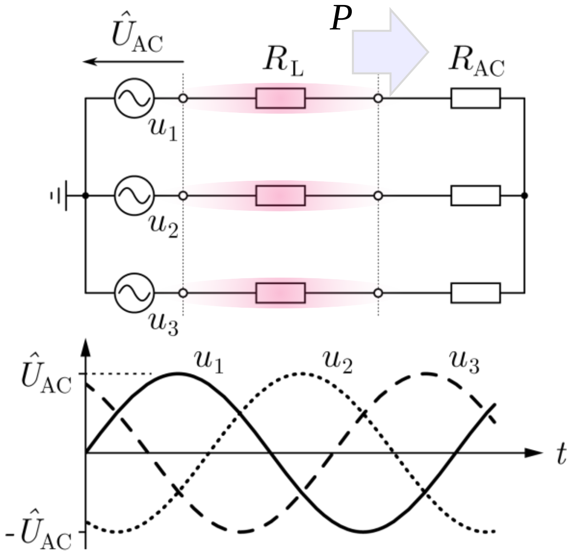
$$R_L = \frac{l}{\kappa A_{Cu}}$$

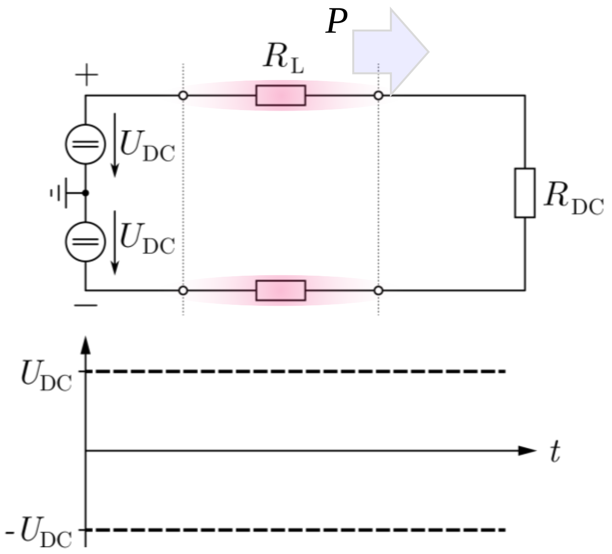


- *Quadratic (!) Dependency of Losses on Voltage Level*
- *Allows Massive Reduction of Conductor Cross Section with Increasing Operating Voltage*

3-Φ AC vs. DC Power Transmission

- *DC Voltage → Max. Utilization of Isolation Voltage → Lower Losses & Less Conductor Material (!)*

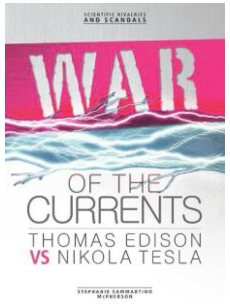




$$P_{V,AC} = 3\cdot\left(\frac{\frac{1}{3}P}{U_{AC}}\right)^2 \cdot R_L$$

$$P_{V,DC} = 2\cdot\left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L$$

$$\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2}\cdot\left(\frac{U_{AC}}{U_{DC}}\right)^2 \Big|_{U_{DC}=\hat{U}_{AC}=\sqrt{2}\,U_{AC}} = 0.75$$



- *Transformation of DC Voltage Level Requires Power Electr. Interfaces / "DC-Transformers" (!)*

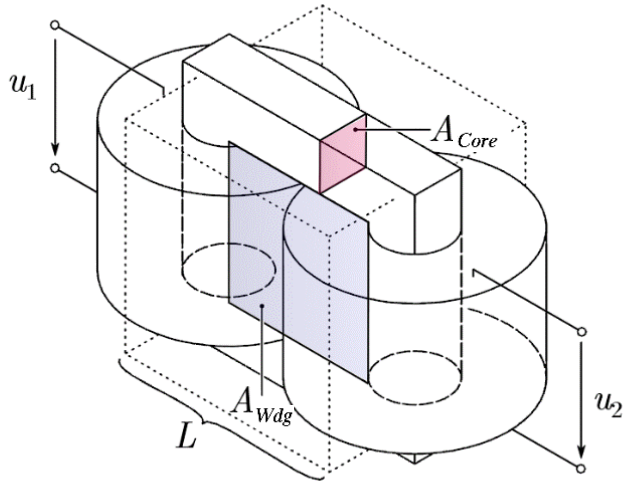
Classical Transformer — Scaling Law

- ***Magnetic Core Cross Section*** $A_{Core} = \frac{1}{\sqrt{2}\pi}\frac{U_1}{\hat{B}_{max}\, f}\frac{1}{N_1}$
- ***Winding Window*** $A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$
- ***Construction Volume***

$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{rms}\hat{B}_{max}\, f} \propto L^4$$

↑ ↑ ↑

P_t .... Rated Power
k_W .... Window Utilization Factor
B_{max} .. Flux Density Amplitude
J_{rms}... Winding Current Density
f ..... Frequency

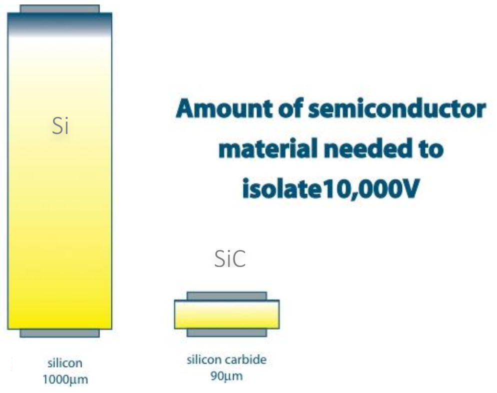


- ***Low Frequency*** → ***Large Weight / Volume***
- ***Trade-off*** → ***Volume vs. Efficiency***

Low $R^*_{DS(on)}$ High-Voltage Devices

- SiC MOSFETs / GaN HEMTs
- Low Conduction Losses
- High Efficiency

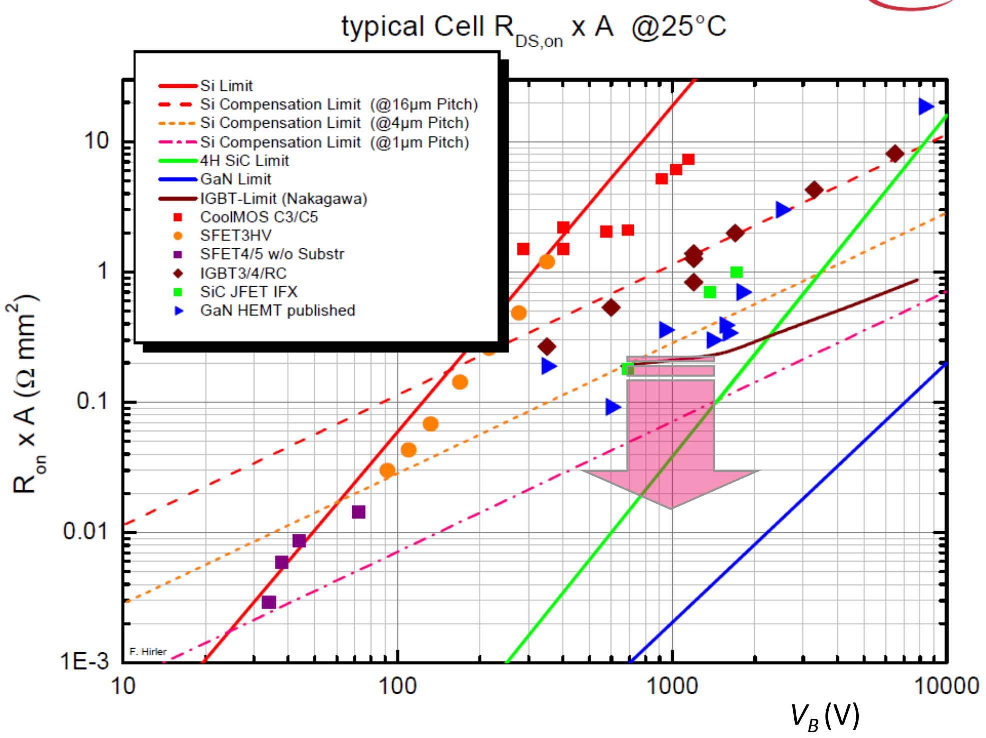
Source: www.evincetechnology.com



$$R^*_{on} = \frac{4V_B^2}{\varepsilon \mu_n E_C^3} \leftarrow$$

$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$

Source: Infineon



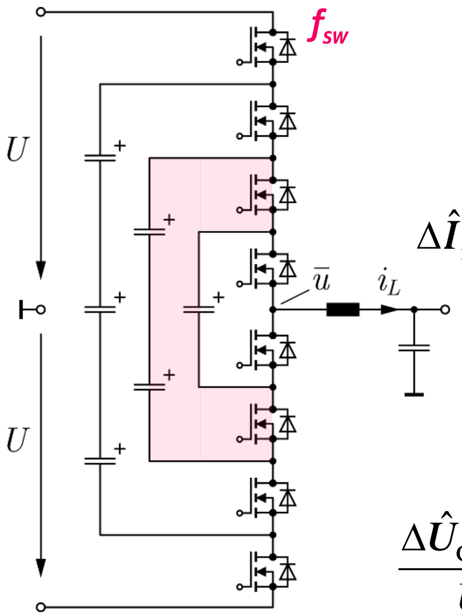
- High Voltage Unipolar (!) Devices → Excellent Sw. Performance / High Power Density

Scaling of Multi-Cell/Level Concepts

- *Reduced Ripple @ Same (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage*
- *Application of LV Technology to HV*

Source: R. Pilawa

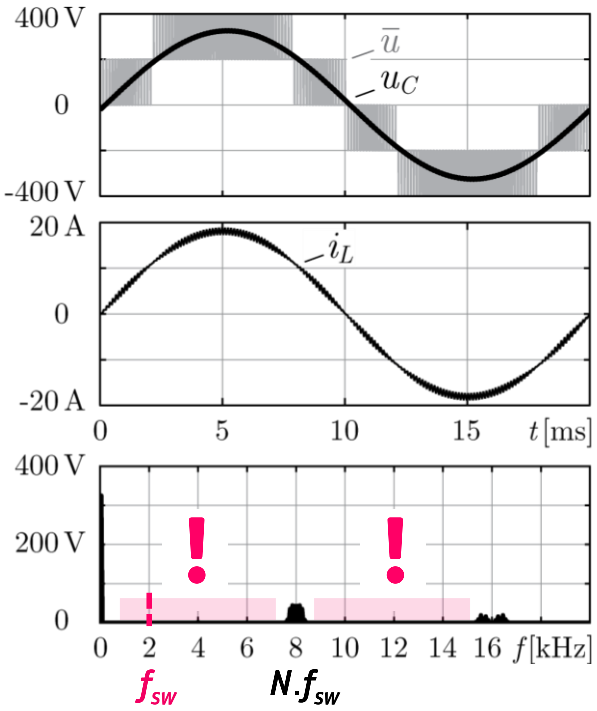
Integrated Dual-Sided Half-Bridge Flying Capacitor Converter Switching Cell



$$\Delta \hat{I}_{max,N} = \frac{1}{N^2} \Delta \hat{I}_{max,N=1}$$

$$\frac{U}{8 f_s L}$$

$$\frac{\Delta \hat{U}_{C,max,N}}{U} = \frac{\pi^2}{32} \left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$

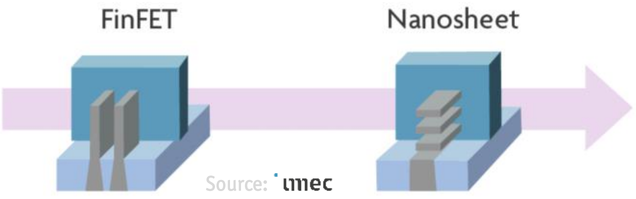


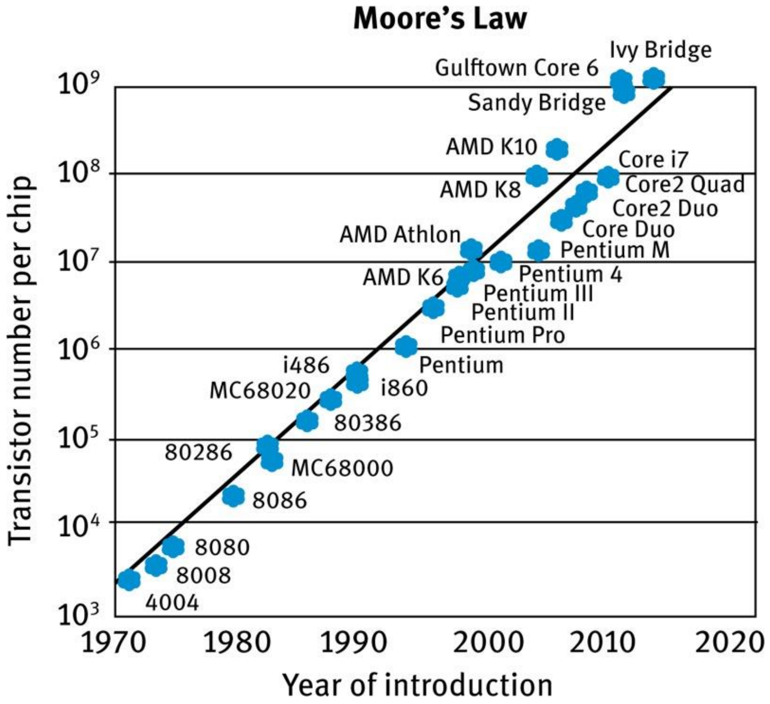
- *Scalability / Manufacturability / Standardization / Redundancy*

Digital Signal / Data Processing

- *Exponentially Improving uC / Storage Technology (!)*

— *Extreme Levels of Density (nm-Nodes) / Processing Speed*
— *Continuous Relative Cost Reduction*





Source: Ostendorf & König /DeGruyter

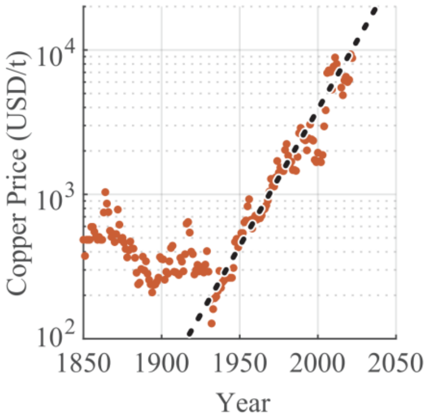
- *Fully Digital Control / Distributed Intelligence — "Complexity Management"*
- *AI-Based Design / Digital Twins / Industrial IoT (IIoT)*

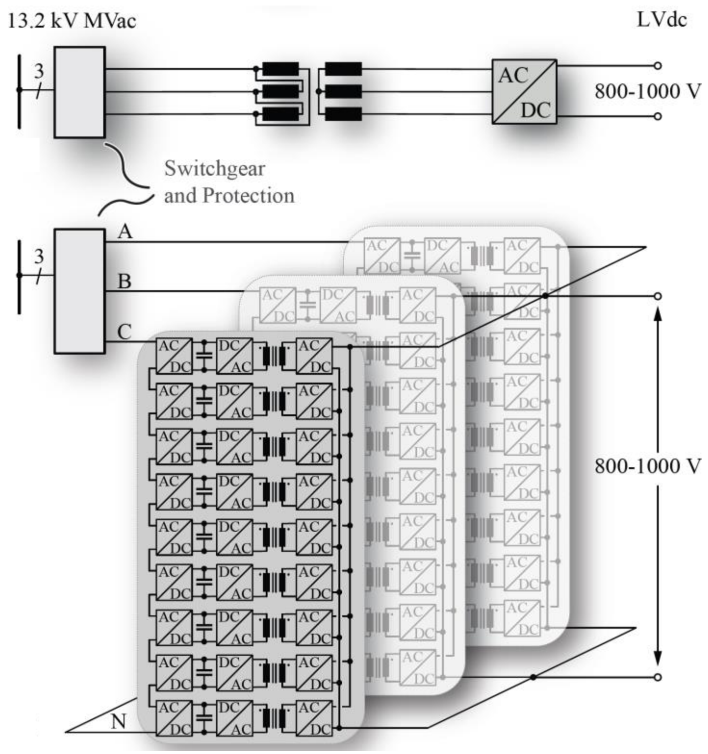
Examples of "Do More With Less"

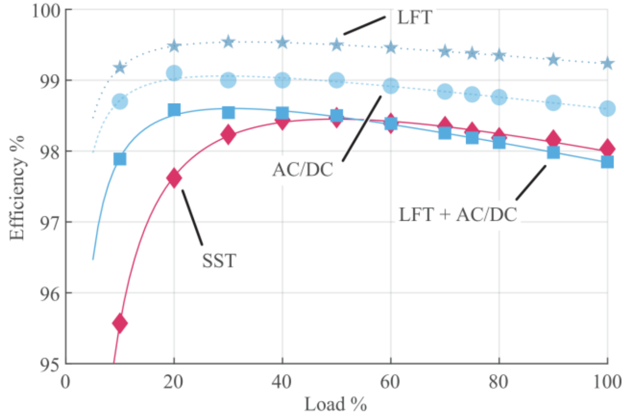
Solid-State Transformer
EV Power Electronics

Carbon Footprint of 3-Φ AC/DC SST 1/2

- *400kW Fully-Modular Solid-State-Transformer (SST) w/ HF-Isolation Stages*
- *Lower Raw Material Effort / Lower Impact of Increasing Raw Material Costs*





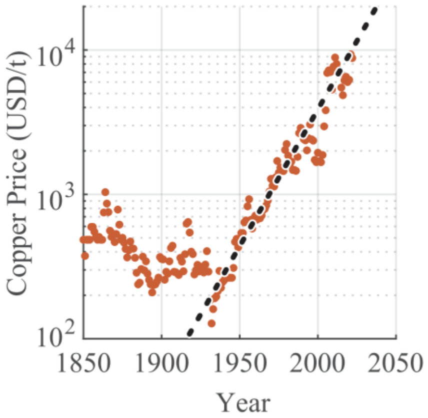


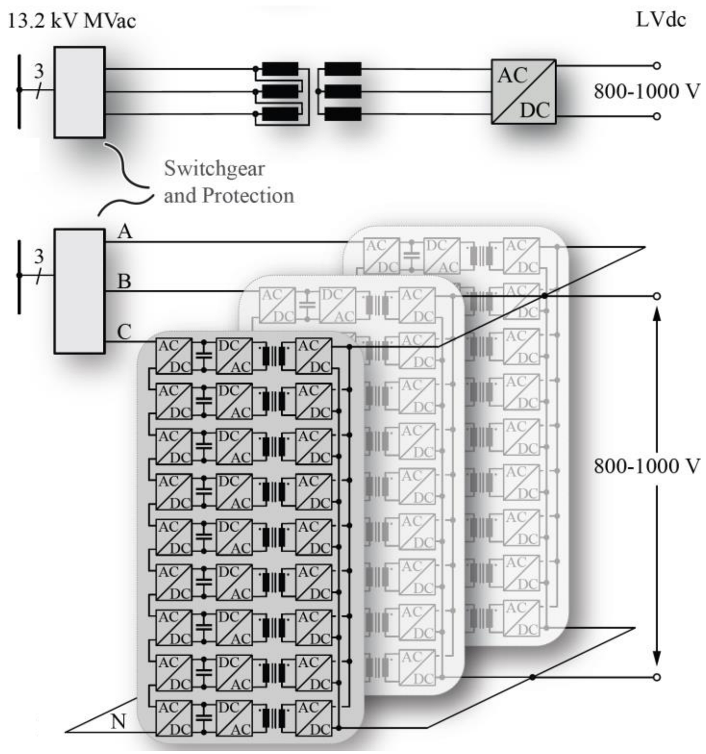
- *Evaluation Against Dry-Type LFT-Based MVAC-LVDC Interface w/ Equal Full-Load Efficiency*

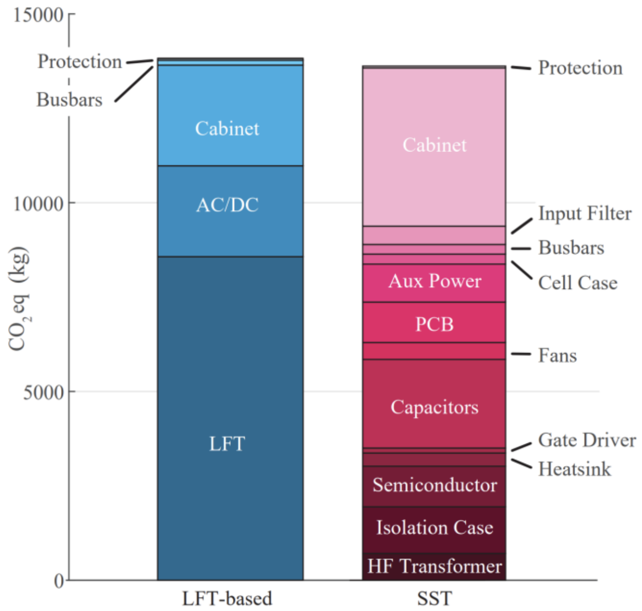
Source: DELTA

Carbon Footprint of 3-Φ AC/DC SST 2/2

- *400kW Fully-Modular Solid-State-Transformer (SST) w/ HF-Isolation Stages*
- *Lower Raw Material Effort / Lower Impact of Increasing Raw Material Costs*





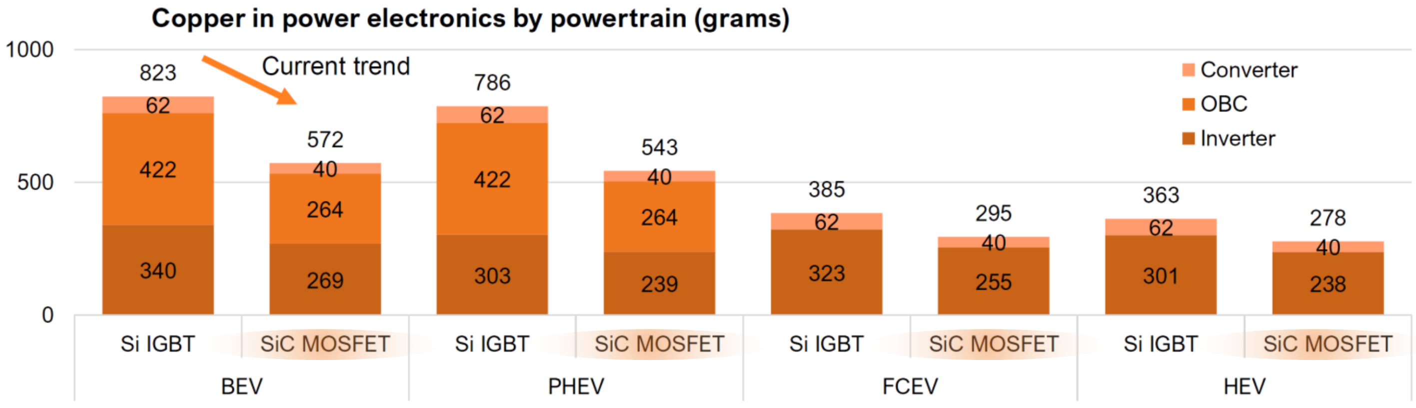


- *SST-$CO_{2,eq}$ Data Shown for Early Prototype — Potential for Massive Future Improvement (!)*

Source: DELTA

Copper Used in xEVs

- *Cu Used for Traction Motors, Energy Storage, Power Electronics, HV & LV Distribution, Etc.*
- *ICE (2023) — 29.5kg | BEV Robotaxi in 2034 — 73kg (7.8kg Motor & Power Electronics)*



Source: IDTechEx

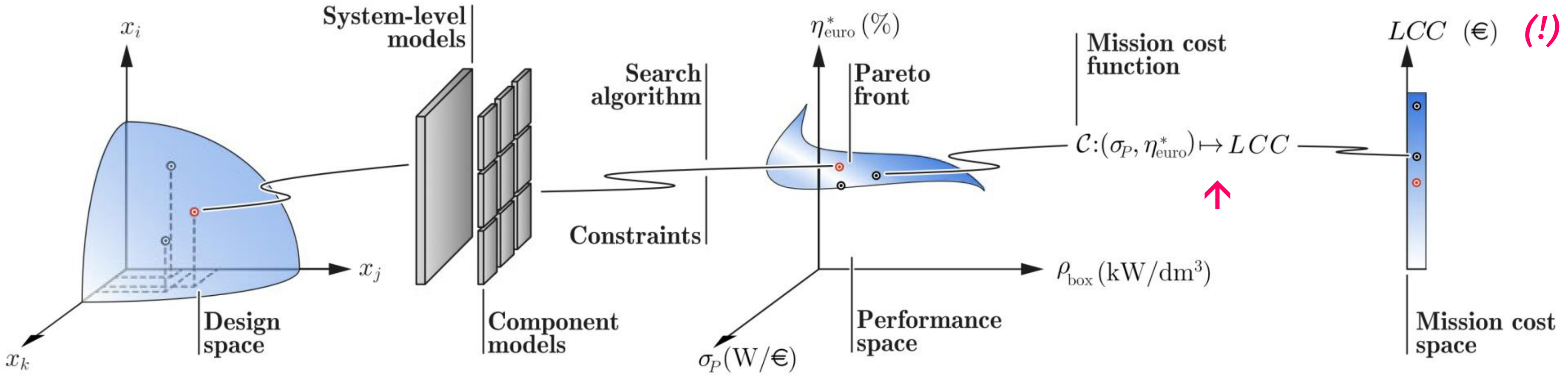
- *Transition Si IGBTs → SiC MOSFETs — 25...30% Decrease of Power Electronics Cu Intensity*

Action #2
Eco-Design of Power Electronics

New Key Performance Indicators
Operation Phase Assessment

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*

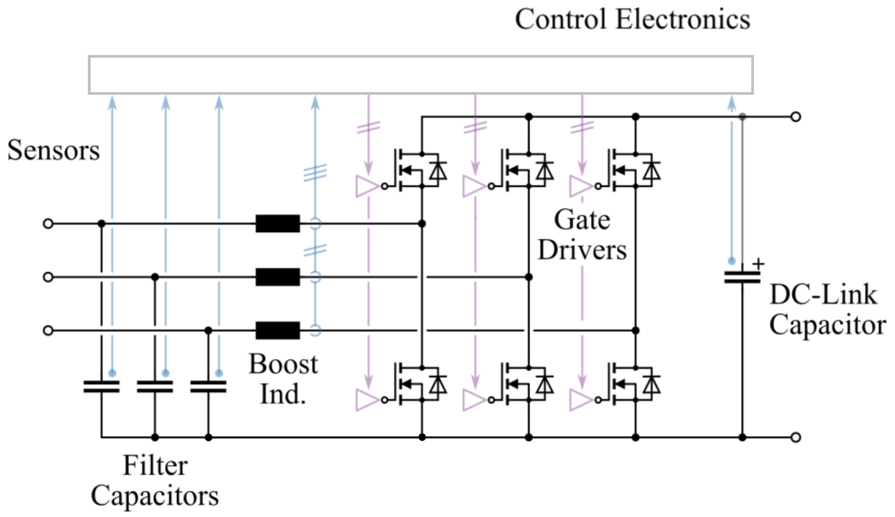


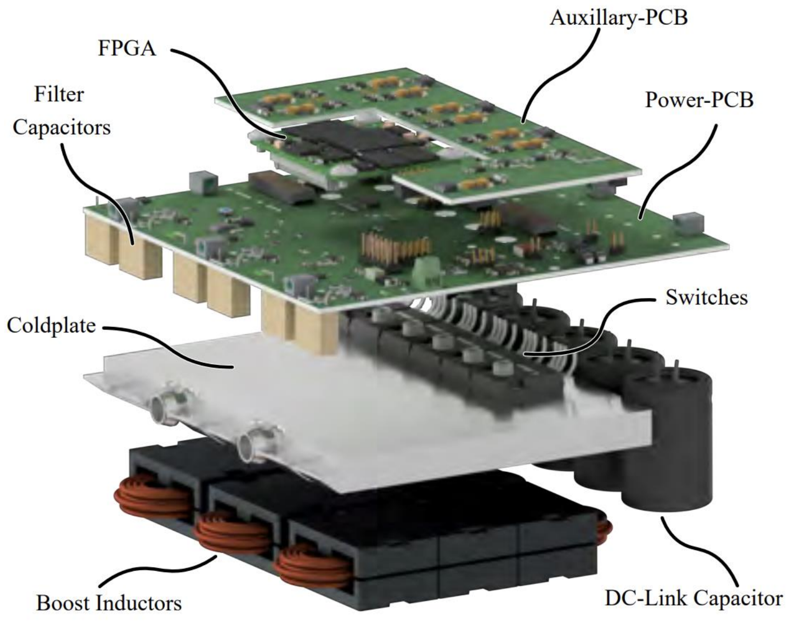
- *Mission Profile — Power Loss → Energy Loss / Life-Cycle Cost (!)*

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

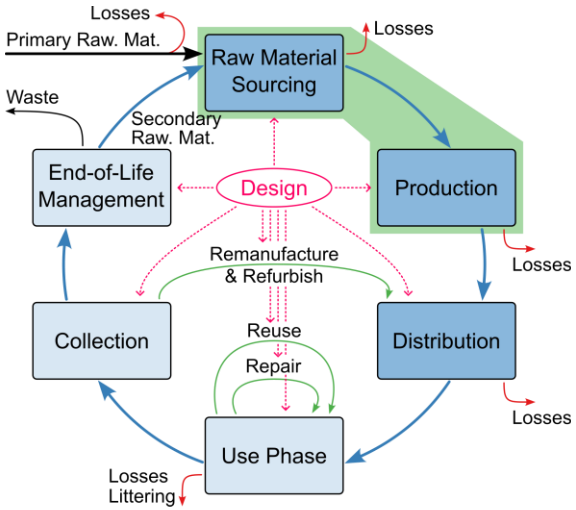


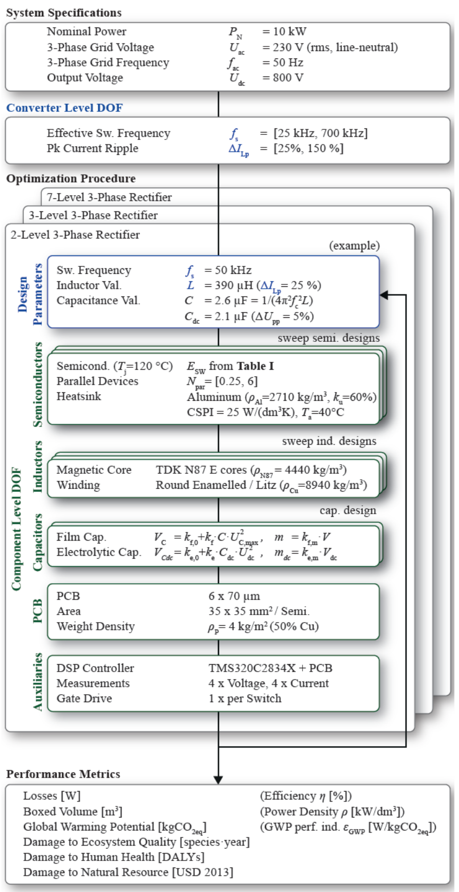


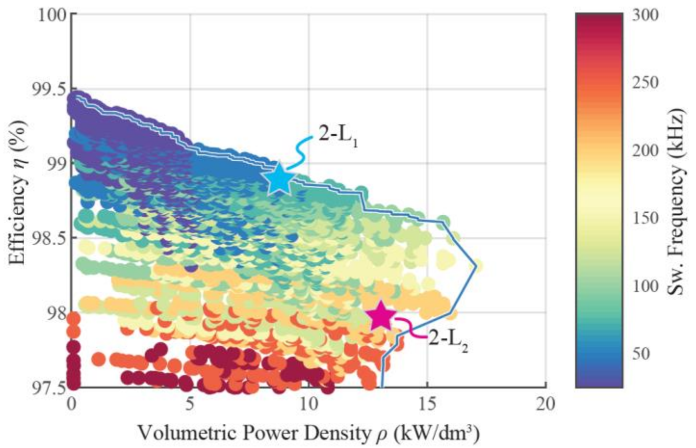
- *Main Components Considered (Losses, Volume, CO_{2eq})*
- *Power Trans., Heat Sink, Boost Ind., DC-Link Cap., Filter Cap., Gate Drivers, Sensors, Contr. Electr., PCBs*

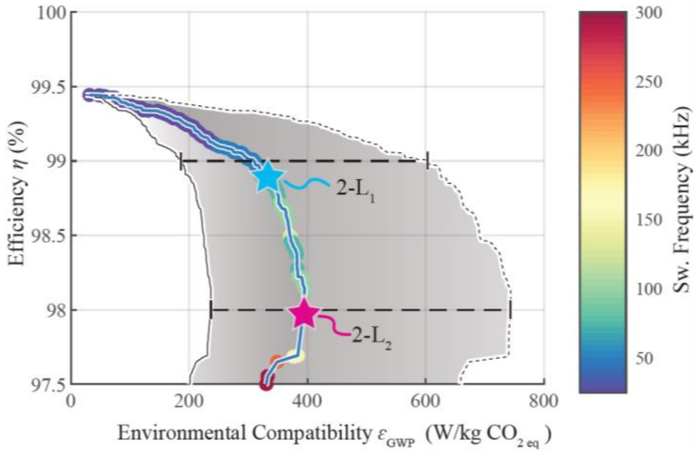
Multi-Objective Optimization incl. Env. Impacts

- *Efficiency vs. Env. Compatibility / Carbon Footprint [W/kg CO_{2eq}]*
- *Limited Data Availability / Quality — High Uncertainties*



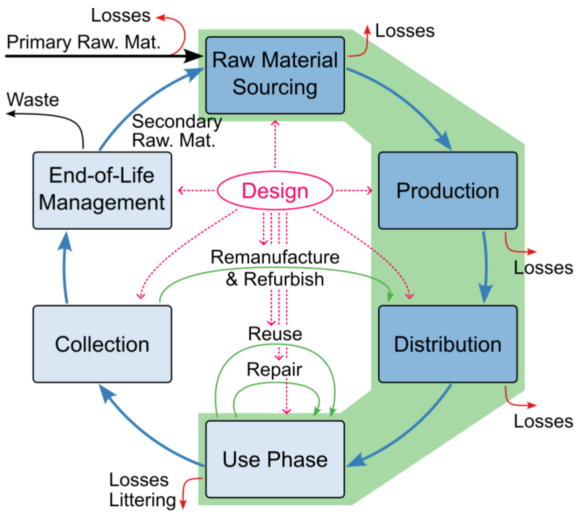


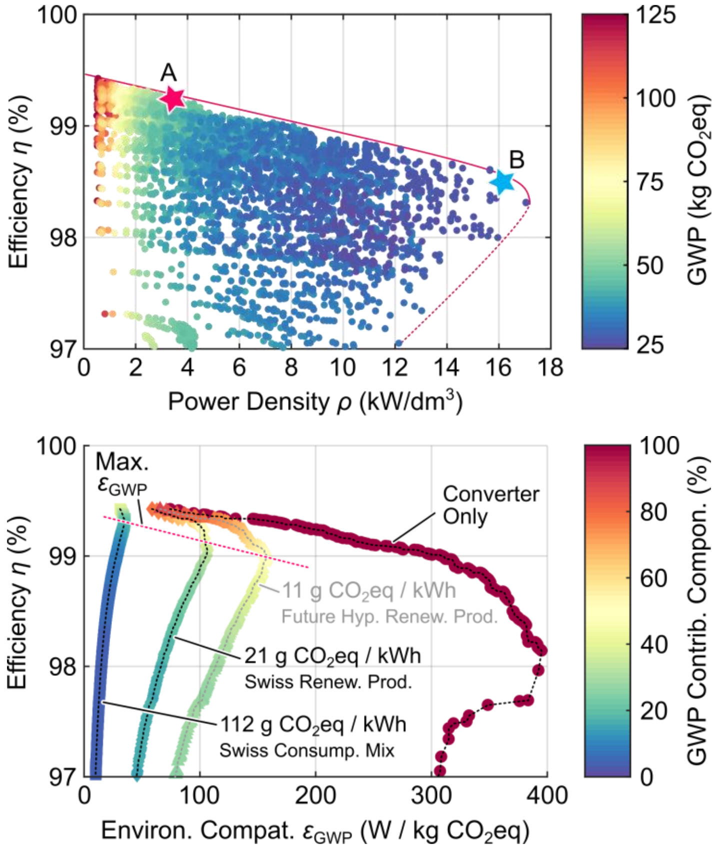


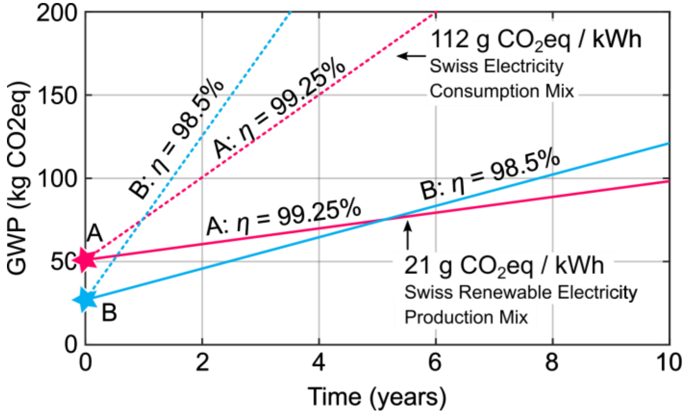


Multi-Objective Optimization incl. Use Phase

- *Design Considers Use Phase / Aims for Best Life-Cycle Performance*
- *Analogy to Total Cost of Ownership (TCO) Considerations*







- *Life-Cycle Carbon Footprint Strongly Depends on Electricity Mix & Mission Profile / Usage Intensity*

Power Electronic Systems Laboratory

Action #3
Circular Economy Compatibility

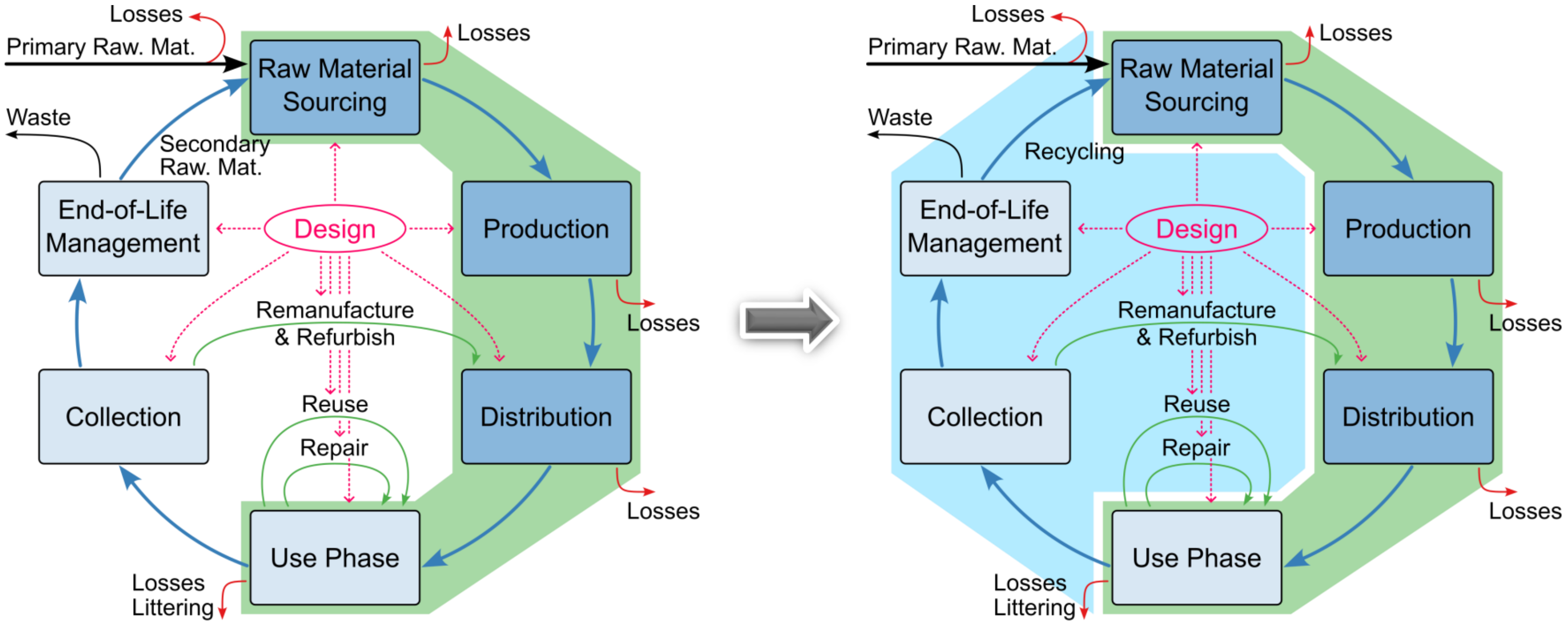
Integration (?)
Power Electronics 5.0

Source:
zone.recycledevon.org

ETH zürich

"Closing the Loop"

- *"4R" Included Into the Design Process — Repair | Reuse | Refurbish | Recycle*
- *80% of Environmental Impact of Products Locked-In at the Design Stage*

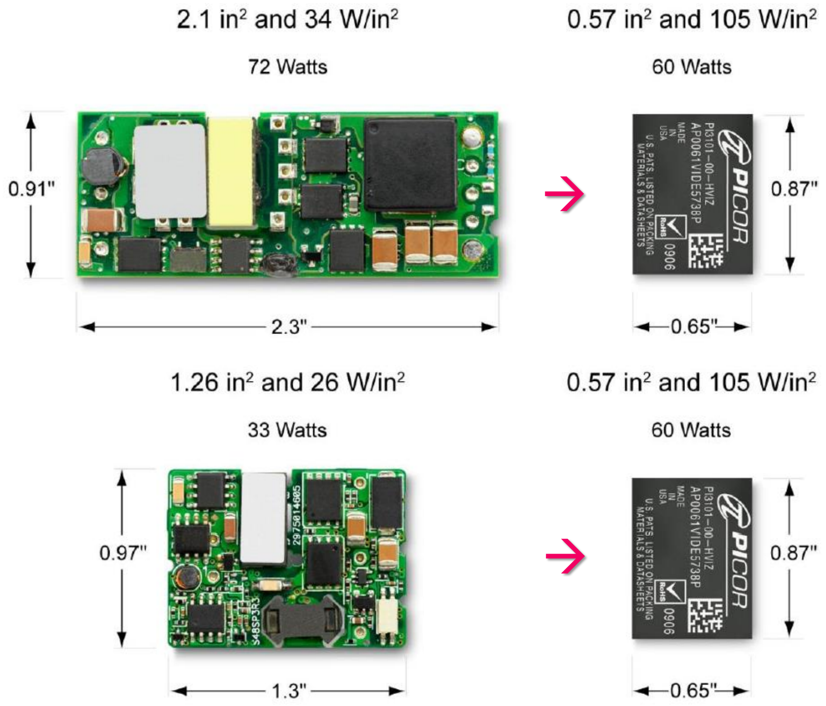


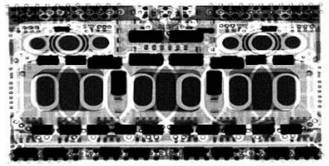
- *"Life-Cycle Cost Perspective" — Potentially Advantageous for Suppliers & Customers*
- *Quantification of Repairability / Reusability / etc. Still to be Clarified*

"Integration" — The Polar Opposite of CEC (?)

- *System in Package (SiP) Approach — Isol. & Non-Isol. DC/DC Converters, PFC Rectifiers, etc.*
- *Minim. of Parasitic Inductances / EMI Shielding / Integr. Thermal Management*

Source: VICOR

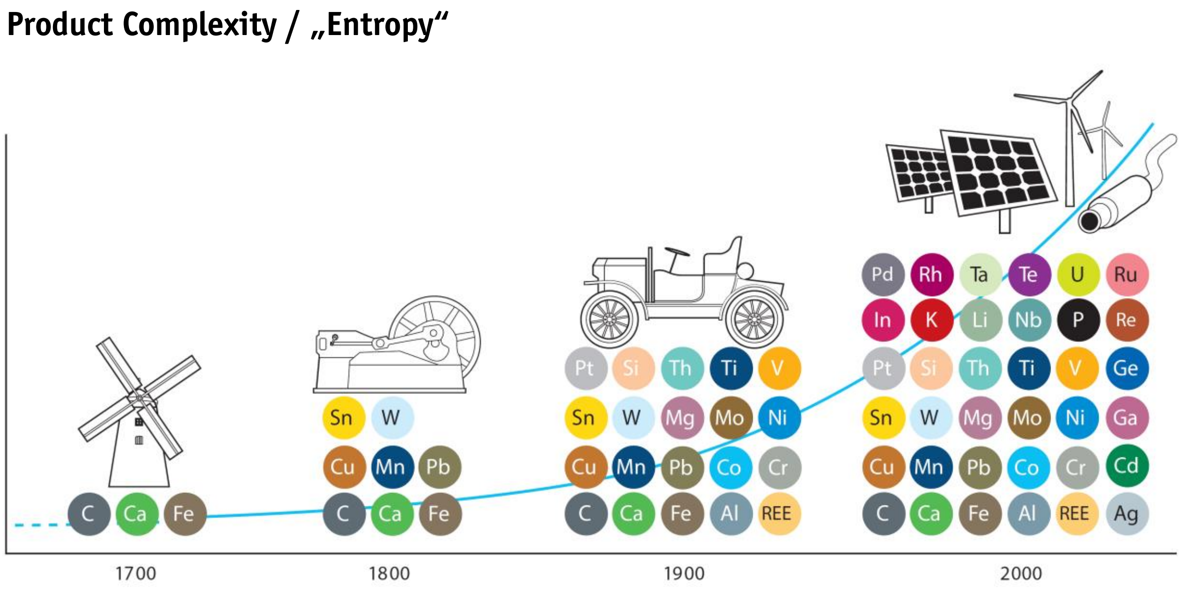




- *Extreme Power Density / Shrinks BOM*
- *Automated Manufacturing / High Reliability*
- *CEC - Circular Economy Compatibility (?)*

The Complexity Challenge

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

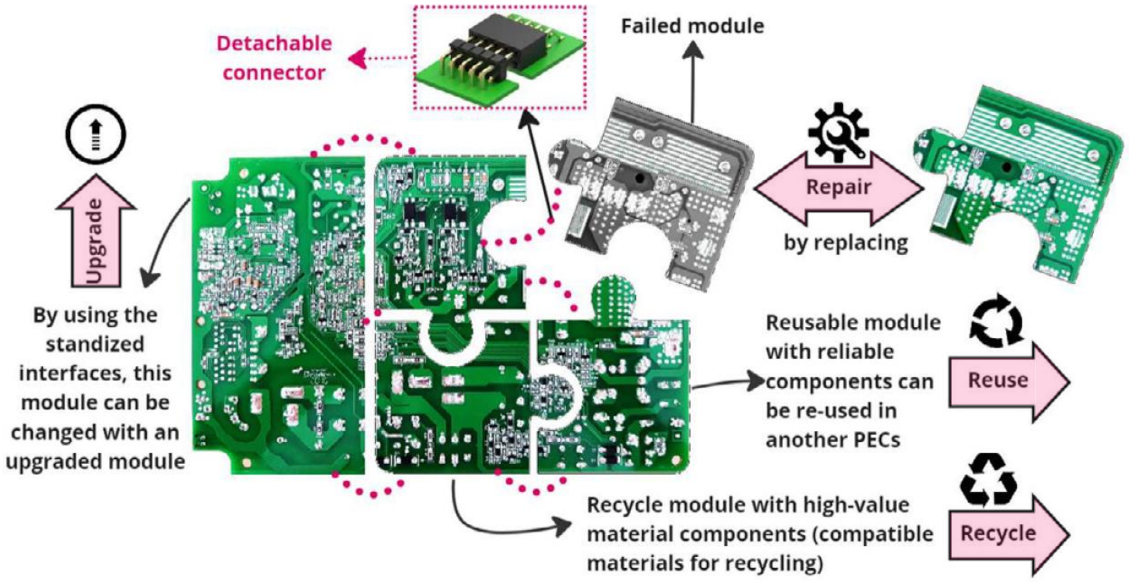


Source: Materials Critical to the Energy Industry An introduction

- *More than 60 Metallic Elements Involved in Pathways for Substitution of Conv. Energy Systems*
- *Ultra-Compact Systems / Functional Integration — Main Obstacles for EOL Material Separation (!)*

"Modularity" — Facilitating Upgrade | Reuse | Repair

- *Modular Design Considering Ease of Disassembly | Maintainability | Upgradability | Reusability | etc.*
- *Grouping of Components Determined by Reliability Level & Expected Lifetime / Level of Reusability or Recyclability*

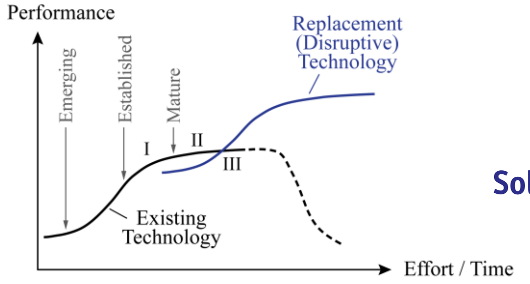


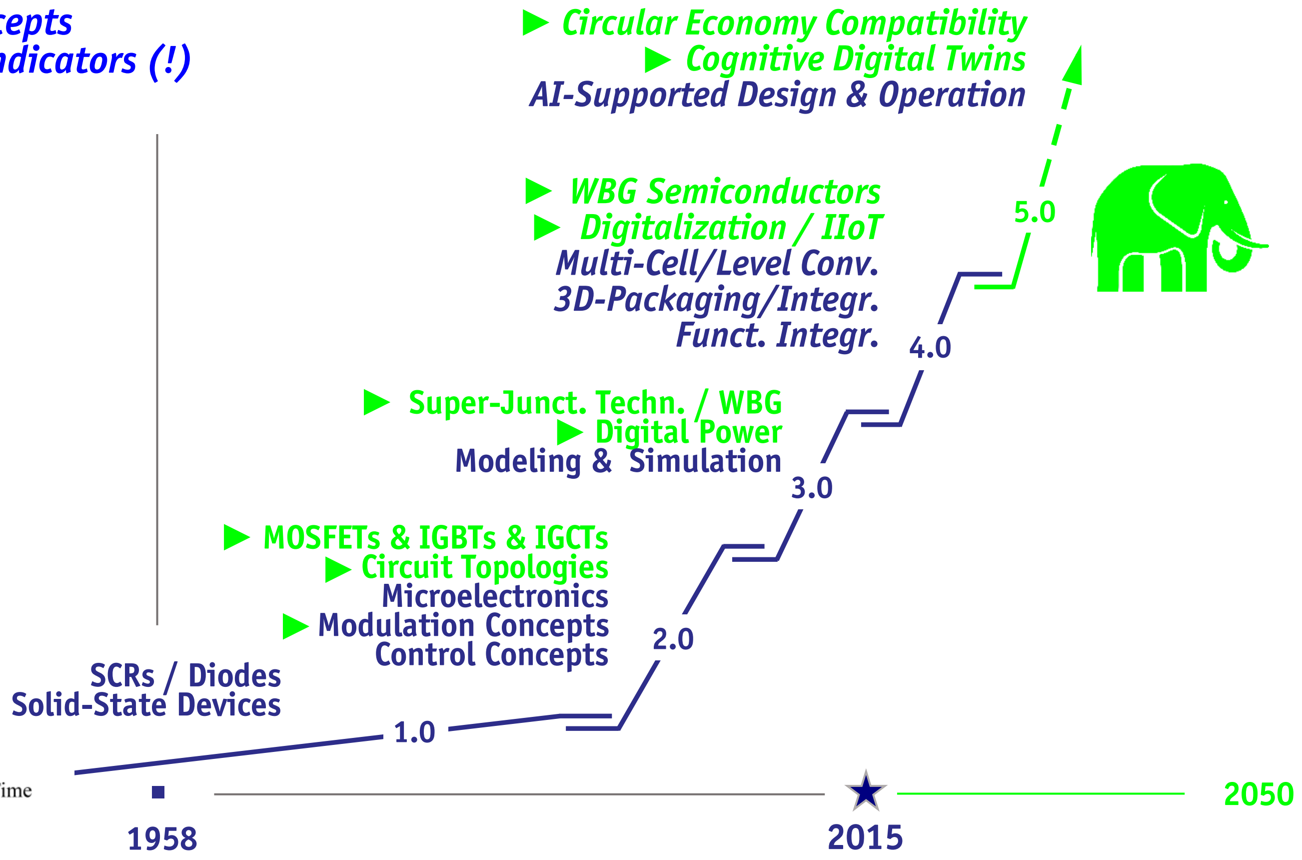
université de BORDEAUX
GRENOBLE INP

- *FAIRPHONE — Modular | Manually Replaceable Parts | 100% Recycl. of Sold Products | Fairtrade Materials*
- *Standardized Interfaces / Mechanically Separable Connections*
- *Leveraging Economies of Scale to Compensate Interface Costs*

Power Electronics 5.0

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





CEC-Power Electronics Roadmap

- *Environmental Awareness as Integral Part of Future Power Electronics R&D (!)*

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 ηρ-Pareto Optimization / Design
- Manual A-Posteriori LCA of Complete Converters

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

Thank you!

Zero-Waste!