Advanced Mechatronic Systems Group

ETH zürich

Lecture 4 – Part I

Circular Economy Compatible Power Electronics

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Topics

- **Global Context and Challenges**
  - Net-Zero CO_2 by 2xxx
  - Renewables & Storage
  - Hard-to-Abate Sectors
  - Raw Material Constraints
  - The Net Energy Cliff

- **Power Electronics 4.0: Do More with Less**

- **Power Electronics 5.0: Zero Waste**
  - The Elephant in the Room
  - Multi-Objective Optimization incl. LCA
  - Circularity

- **Conclusion & Outlook**

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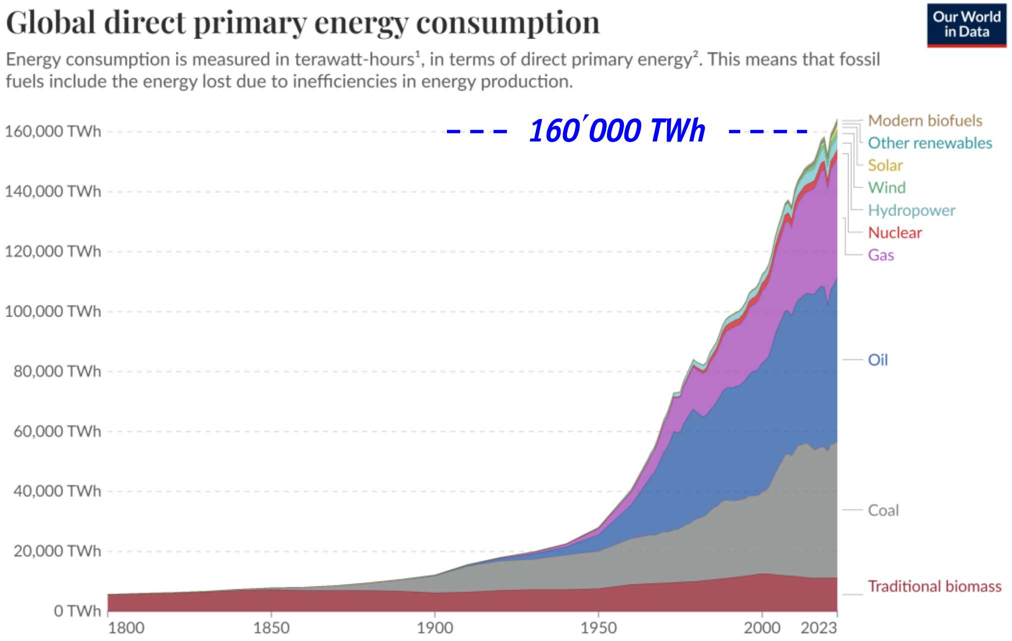
Else und Friedrich Hugel Fonds

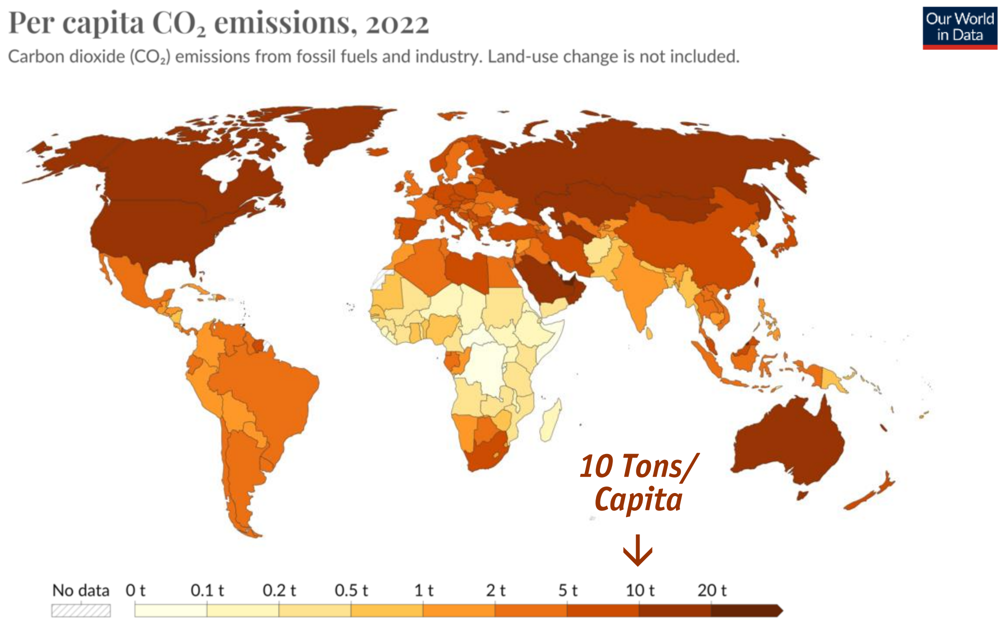
The Challenge

Still Increasing Use of Fossil Fuels
Increasing CO_2 Emissions / Global Warming
Net-Zero by 2XXX / $$$$

Industrial Revolution 1 – 4

- *Technological / Economic Advances Linked to Exponential Increase of Fossil Fuel Consumption*
- *Continuous "Energy Addition" — Adoption of Larger Share of Higher Energy Density Fuels — Wood → Coal → Oil & Gas*



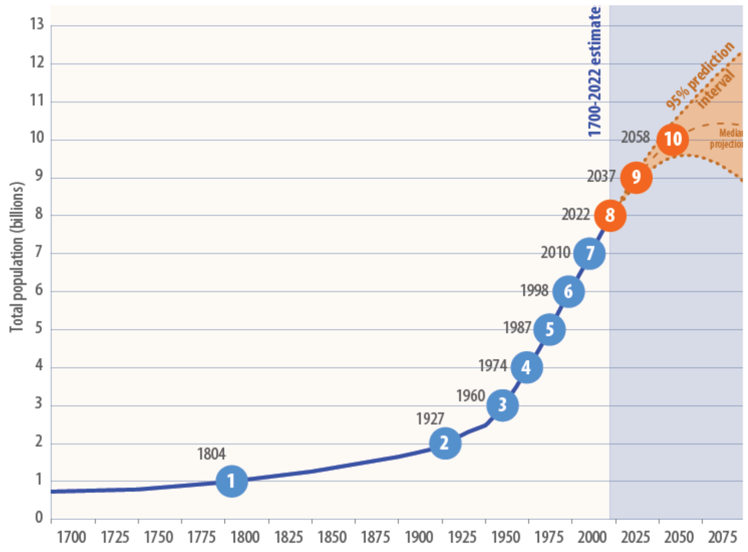


- *2024 % of Global CO_2 Emissions / % Global Population — China 32%/18% | USA 13%/4% | India 8%/18%*
- *Poorest Countries Contributed Least to Historic CO_2 Emissions/Climate Change BUT Are Most Vulnerable to Impacts*

Growth of Population & Energy Demand

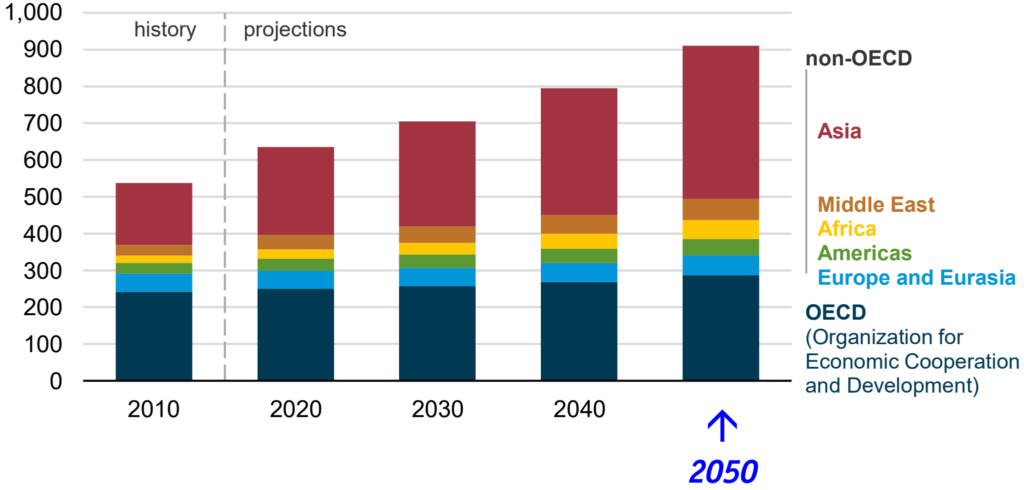
- *Growth of World Population / Increasing Energy Use in Developing Non-OECD Countries*
- *1980 — 4.4 Billion | ≈ 10 TW.yr → 2022 — ≈ 8 Billion | 20.4 TW.yr → ≈ 2.6 kW Continuous/Capita*

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



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

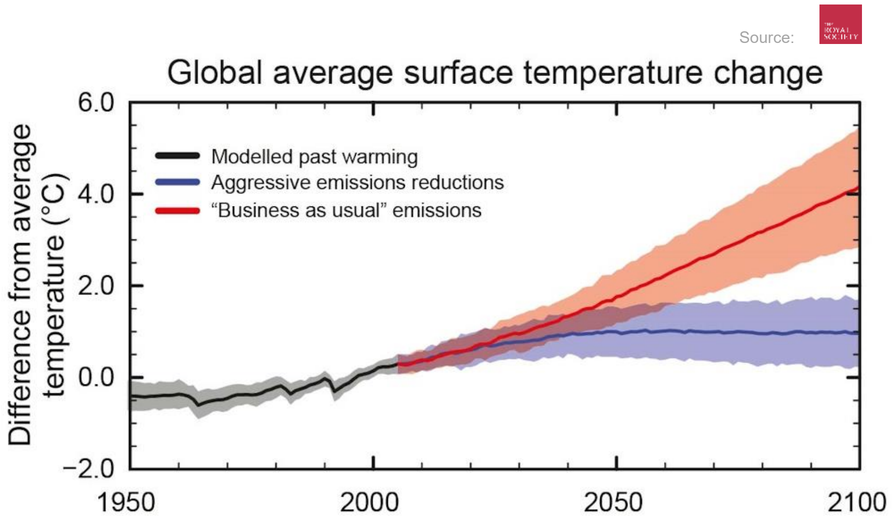
Global primary energy consumption by region (2010-2050)
quadrillion British thermal units

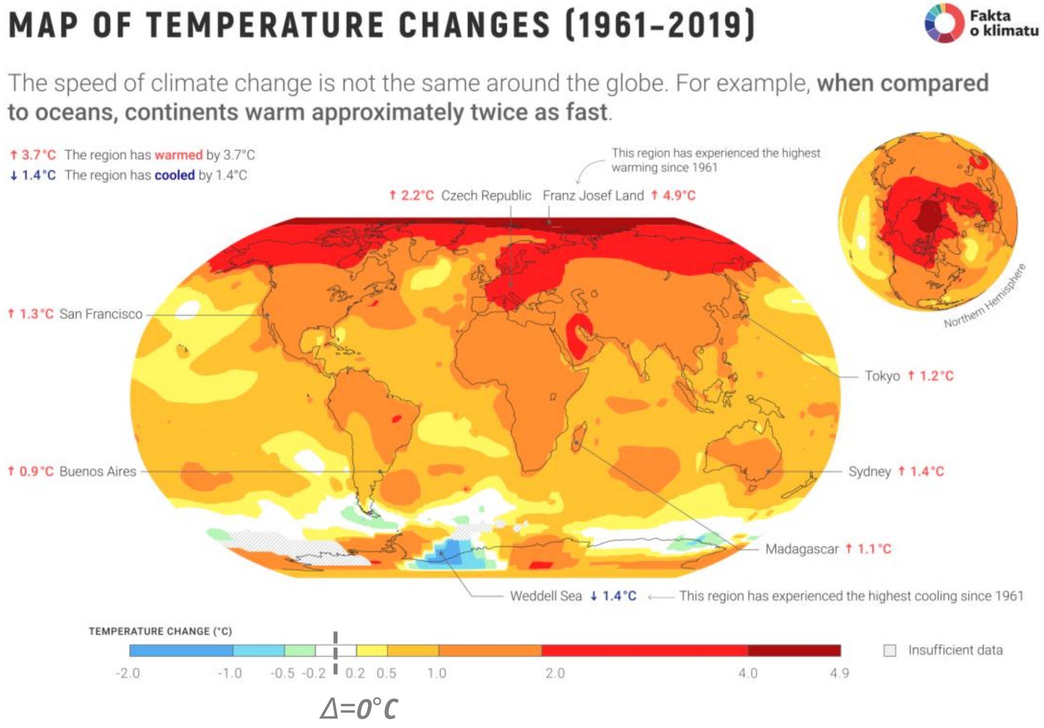


- *Direct Relation of Energy Use & GDP/Capita — There are No Low-Energy Intensity Rich Countries (!)*
- *Lower Energy Intensity (Energy per Unit of GDP) Pot. Resulting from Offshoring Energy-Intense Manufacturing*

Global Warming

- *Combustion of Fossil Fuels – Increasing Atmospheric CO_2 Concentration / +50% Since Industrial Revolution*
- *Gradual Increase of Tropospheric Temperature of ≈ +1°C since 1960*



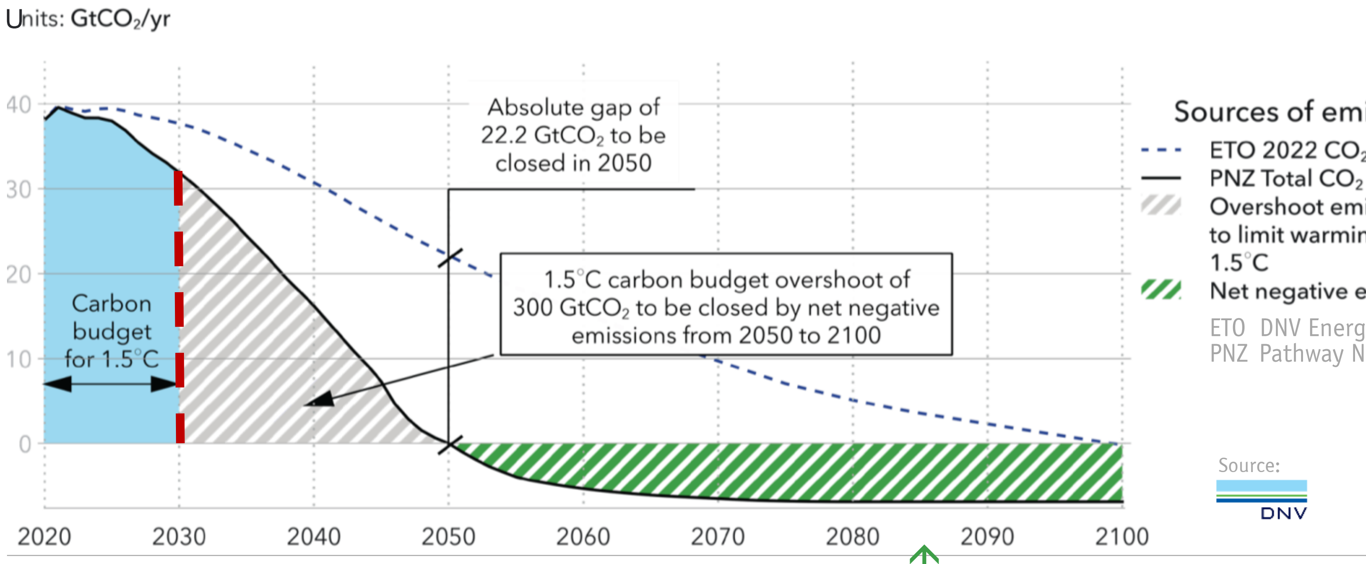


- *Different Warming Rates for Different Locations / Land is Warming Faster than Oceans (+0.8°C)*
- *Due to Climate System Feedback Loops Arctic Ocean Shows Highest Warming / +4°C since 1960 (!)*

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 $GtCO_2$ →



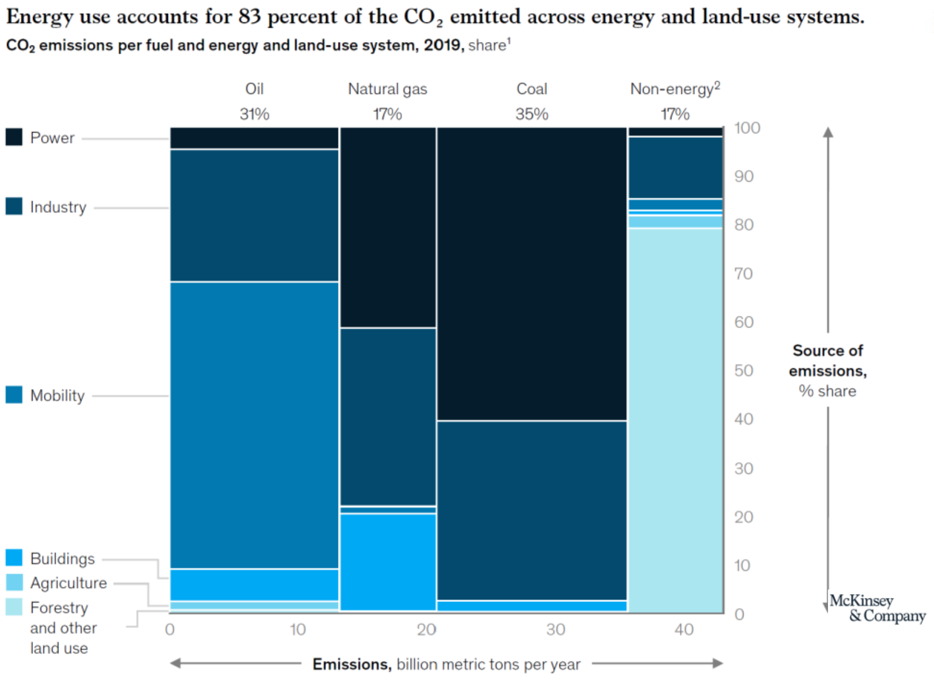
↑ „Net-Negative" Remove Overshoot of 300 $GtCO_2$

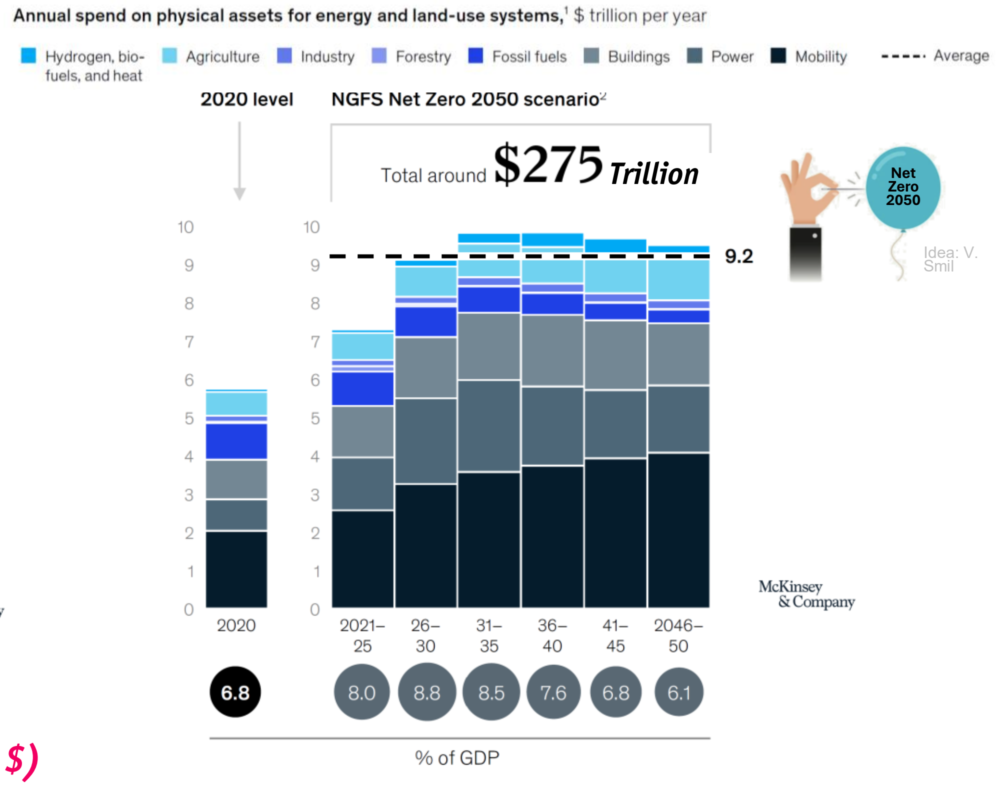
- *Challenge of Stepping Back from Oil & Gas*

Energy Transition Costs

- *≈ 9 Trillion USD Annual Spend on Physical Assets for Energy & Land-Use Systems in NGFS NZ 2050 Scenario*
- *Power | Industry | Mobility | Buildings | Agriculture | Forestry | Etc.*

NGFS — *Network for Greening the Financial System*, 114 Central Banks, 2017





- *Total Cost of U.S. "Moonshot" ≈300 Billion USD (in 2020 $)*

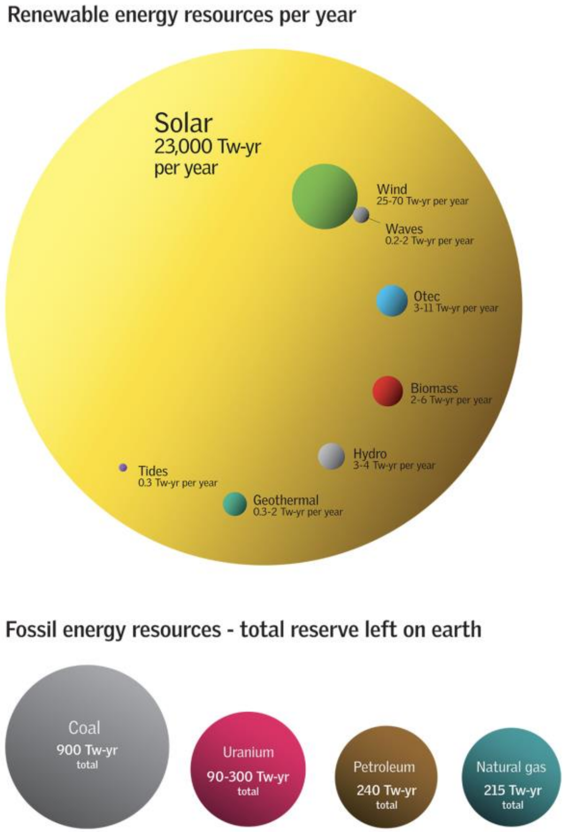
Utilizing Renewable Energy

Renewable Energy Sources
Long-Distance Transmission
Short & Long-Term Storage

The Opportunity

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

100% Conv. Efficiency
Excl. Oceans

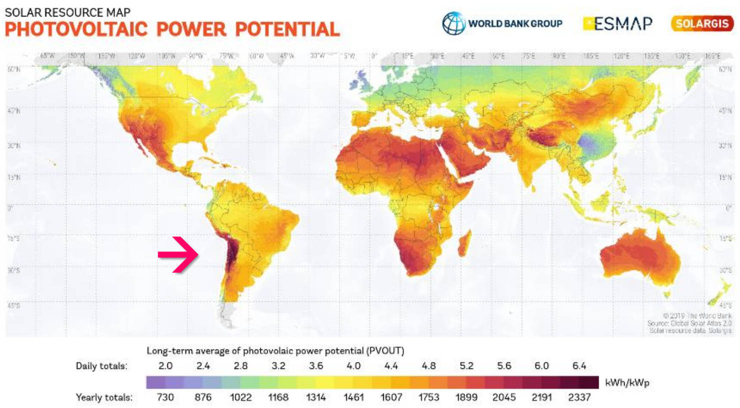


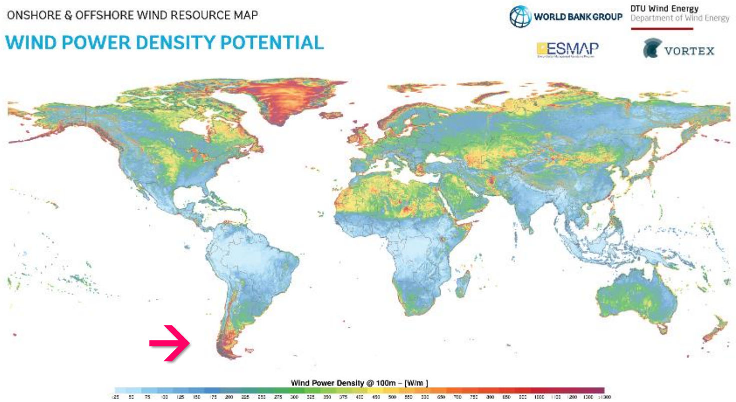
Note: Graphical Representation Assumes Spheres Not Circles

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*

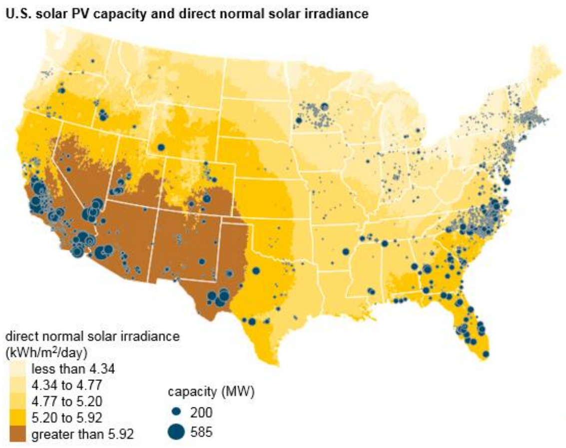


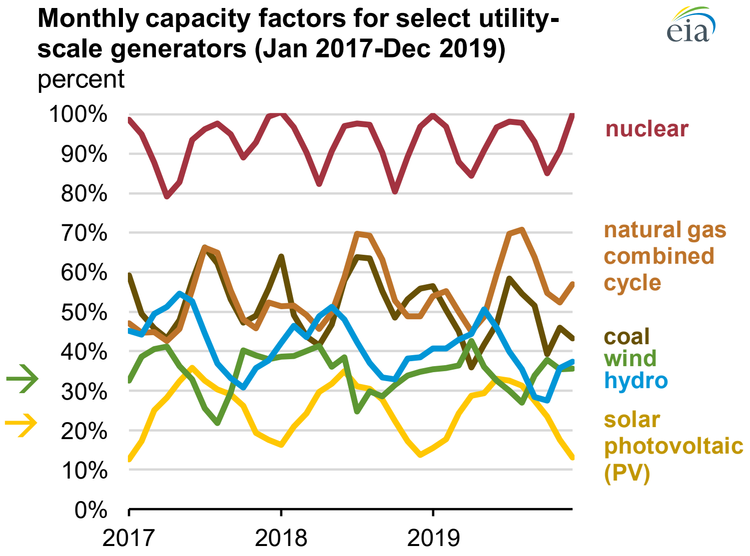


Challenge #1 – Low PV/Wind Capacity Factors

- *Ratio of Actual Energy Output Over Given Period of Time to Theoretical Maximum @ Full Nameplate Cap.*

$$\text{Capacity factor} = \frac{\text{Annual generation MW·h}}{(365\text{ days}) \times (24\text{ hours/day}) \times (\text{Nameplate capacity MW})}$$



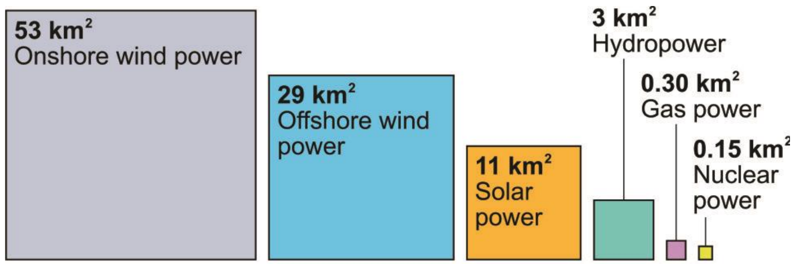


- *Capacity Factor of Renewables Dependent on Geogr. Location & Day/Night & Summer/Winter & Transm. Capacity*
- *PV & Wind Partly Complementary — Typ. Annual Avg. ≈30% for U.S. Wind | ≈20% for U.S. Solar (12% in Germany)*

Challenge #2 – Low PV/Wind Areal Energy Density

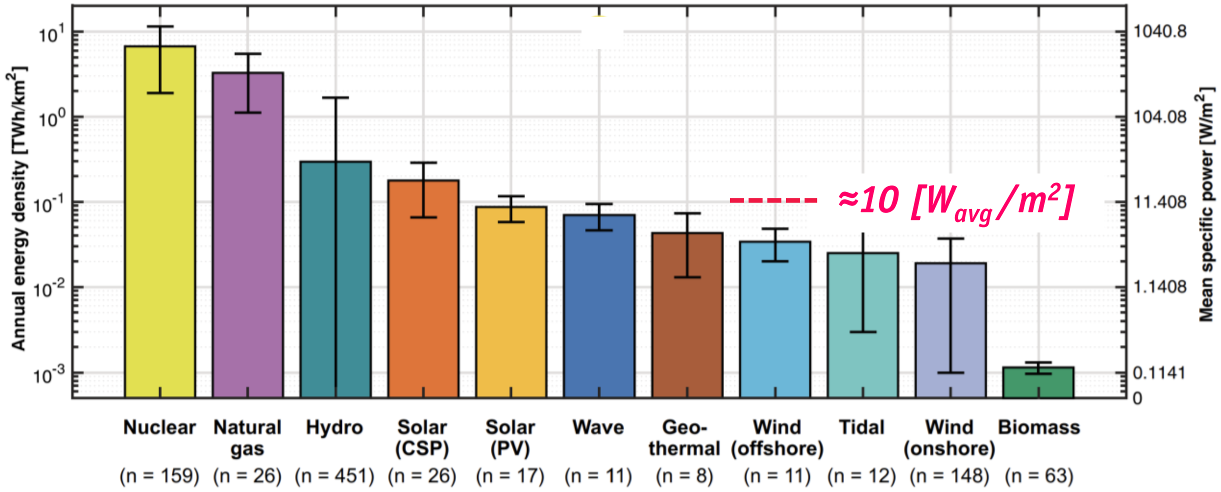
- *Energy Density — Determined by Power Density | Intermittency &/or Capacity Factor | Buffer Zones | Storage | etc.*
- *Land Footprint of Renewable Energy Sources Massively Larger Compared to Fossil Fuel / Nuclear Power Plants*

Annual Generation of 1 TWh (Smaller City)



Source: https://www.sciencenorway.no/
J. K. Nøland, NTNU, 2023

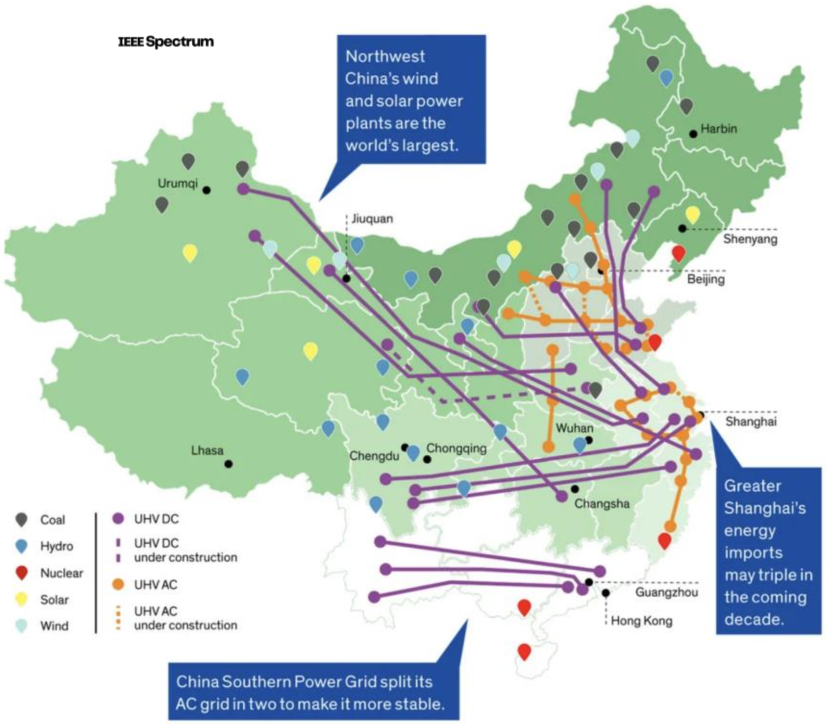
Source: nature, J.K. Nøland et al., 2022



- *Low Energy Density of RES — Large Land Use / Collection Grid / Long Distance Transmission for Powering Load Centers*
- *≈1.7 10^5 TWh of World´s Annual Energy Consumption (2023) — PV @ ≈0.09 TWh/km² → 1.9 10^6 km² ≈ Algeria*

Challenge #3 — Long Distance Transmission

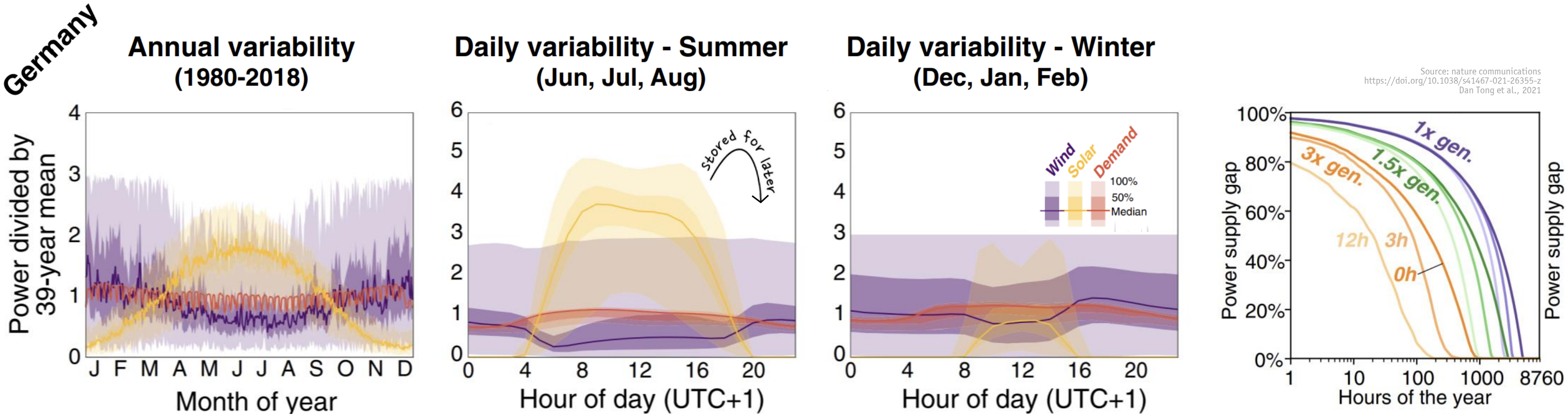
- *Growth of Transmission in Line w/ Growth of Electricity Generation Capacity | 10 TW → ≈10 Million km HV Lines*
- *U-HVDC Transmission Lines Connecting Megacities to Remote Wind & Coal-Fired Power Plants / Solar Farms etc.*



- *30´000 km U-HVDC Links Built Over Last Decade in China / Emerging Nationwide Super-Gird Interconn. Reg. Grids*

Challenge #4 – Storage Requirements 1/3

- *Variability of Renewables & "Dunkelflaute" — Batt. Storage | HVDC-Links | Sector Coupling | Gas/Coal/Hydro Plants*
- *World´s Largest Battery Storage / Pumped Hydro Storage — 3.3 GWh @ 0.875 GW / 40 GWh @ 3.6 GW*



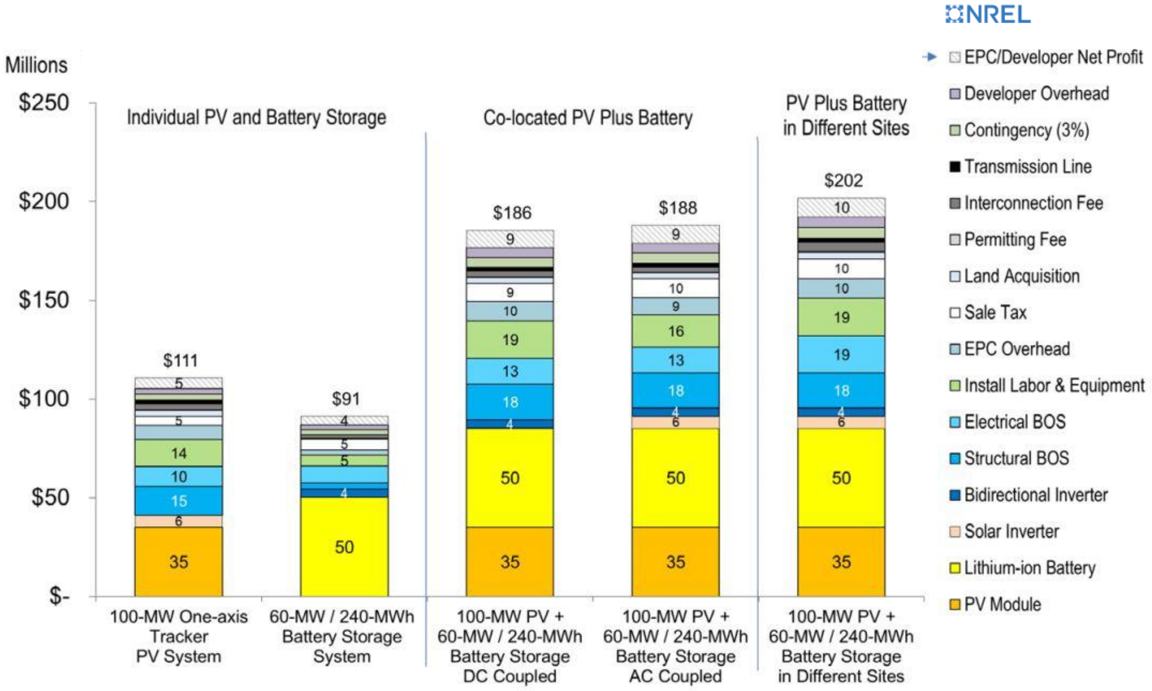
Source: nature communications https://doi.org/10.1038/s41467-021-26355-z Dan Tong et al., 2021

- *Considerable Overdesign of Optimal PV & Wind & 12 Hours Storage Still Leaves Considerable Power Supply Gap (Germany)*
- *Islanded Megacity → Power Supply of 10 Million People x 2.6 kW x 1 Hour = 26 GWh → 86´000 Tons of 300 Wh/kg Batteries*

Challenge #4 – Storage Requirements 2/3

- *U.S. Cost Benchmarks for Utility-Scale PV-Plus-Storage Systems (4 Hours) / DC-Coupled or AC-Coupled*

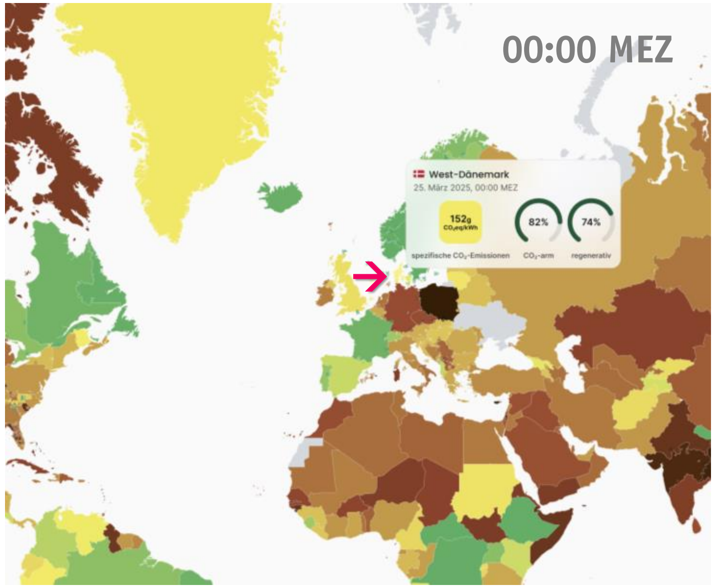
Source: TESLA

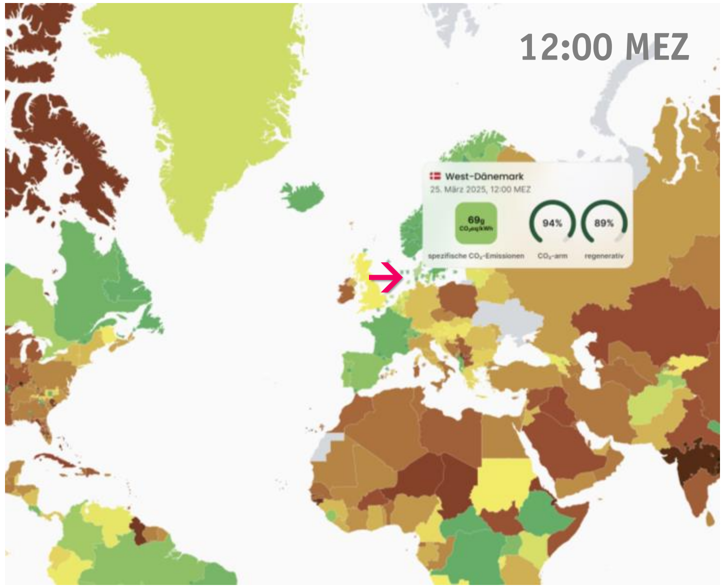


- *Comparison of PV & Fossil Fuel Power Gen. Must be Based on "LCOE" (Panels/Inverter/Cap. Factor/ Storage/Transmission etc.)*

Challenge #4 – Storage Requirements 3/3

- *Ensure Reliable Supply @ High Share of Intermittent RES — Power Balance on Different Time Scales*
- *Accurate Forecast / Local Storage / HVDC Interconnectors to Neighboring Countries / Sector Coupling*





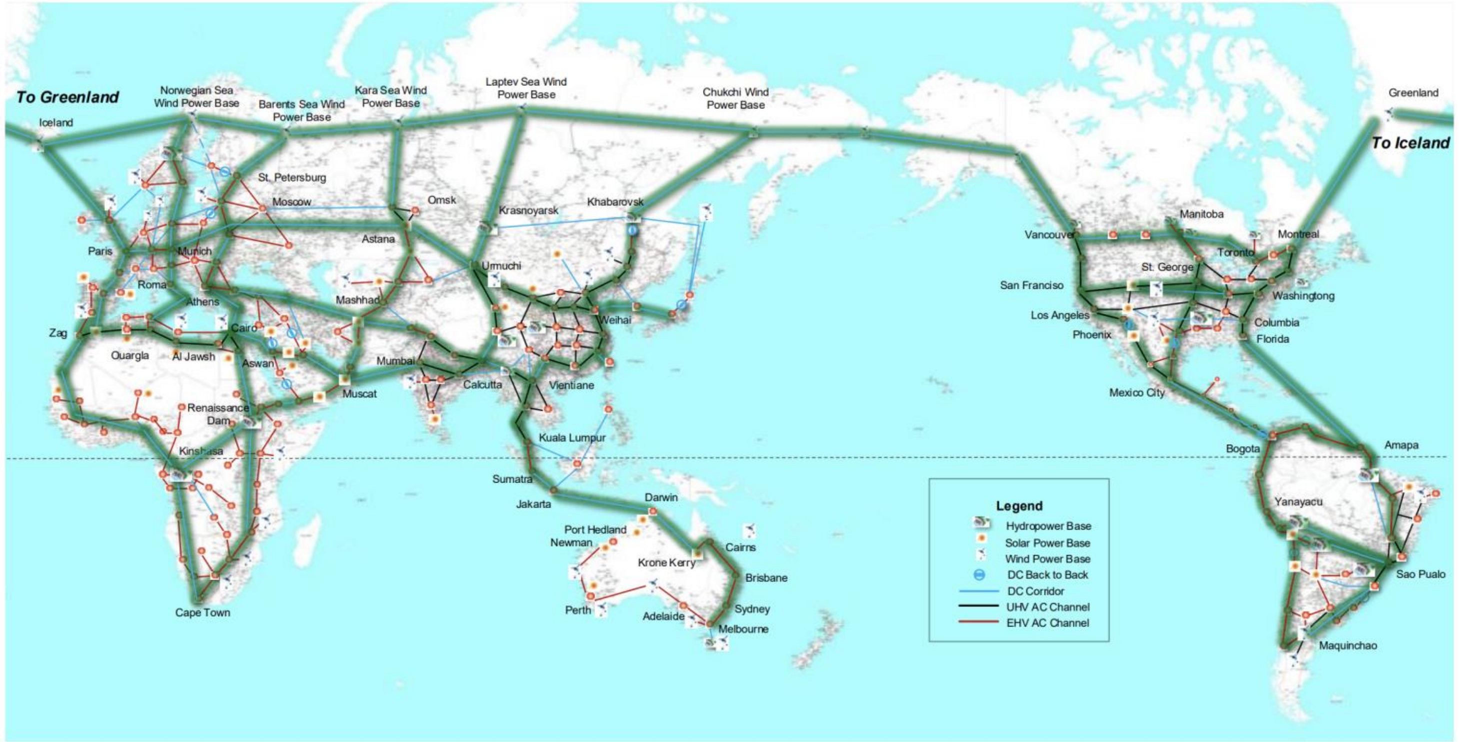
Source:
https://app.electricitymaps.com/map/72h/hourly

- *Opt. Use of Cross-Energy Sector Flexibility — Coupling of El. Power / Heating / Nat. Gas or H_2 or Methane*
- *Direct or Indir. Storage — Grid Conn. Batteries / CHP & Heat Storage / H_2 → Methane – Long Term Gas Store*

Remark The Global Grid

- *"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*

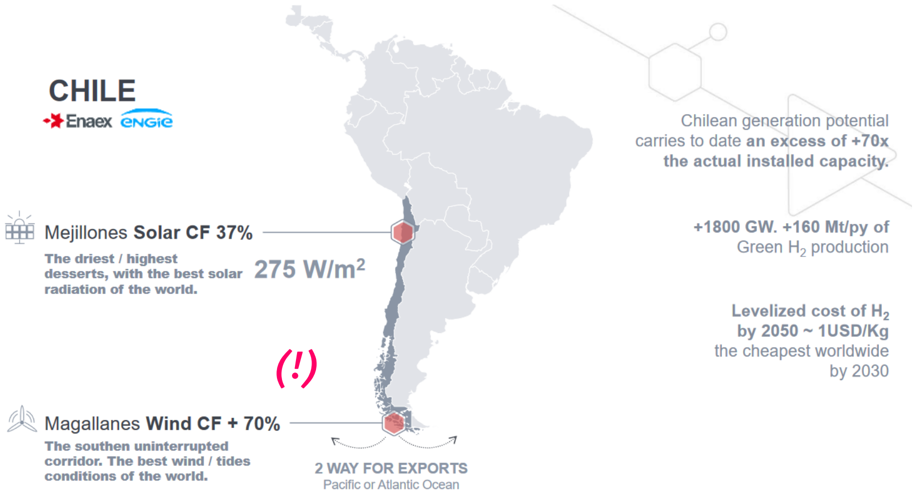
Source: GEIDCO 2018

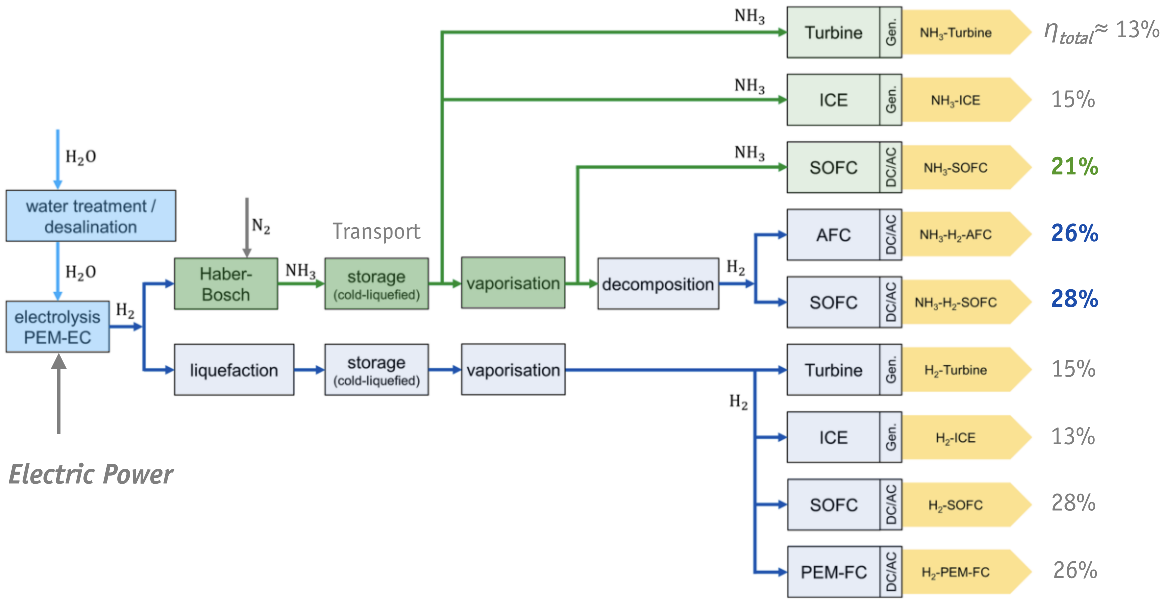


- *Example of the "Global Energy Interconnection Backbone Grid" (GEIDCO) Proposed by China in 2015*

Remark Power-to-X-to-Power

- *Hydrogen Economy — H_2 Produced & Used Directly or in Synthesis w/ Nitrogen or Carbon (Ammonia, Methanol, etc.)*
- *Prod. @ High RES Intensity Locations — NH_3 Transp. by Ships — Use for Long-Term Storage & Hard-to-Abate Sectors*





Storage/Boil-Off-Losses Not Considered

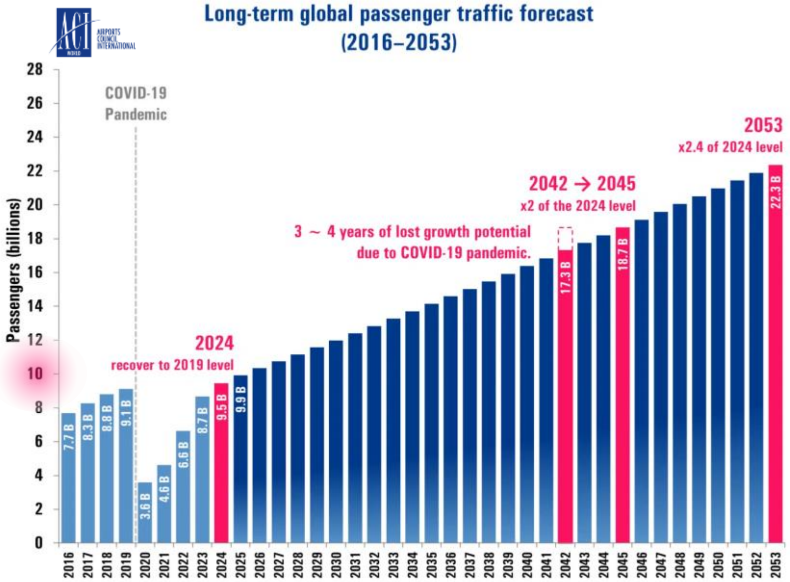
- *Hydrogen Hype — A Story of Energy Loss (?) / Direct Use of Electricity Clearly Superior if Possible (!)*
- *Low-Efficiency Processes — 60% Electrolysis / 70% Liquefying Hydrogen / 60% Fuel Cells / etc.*

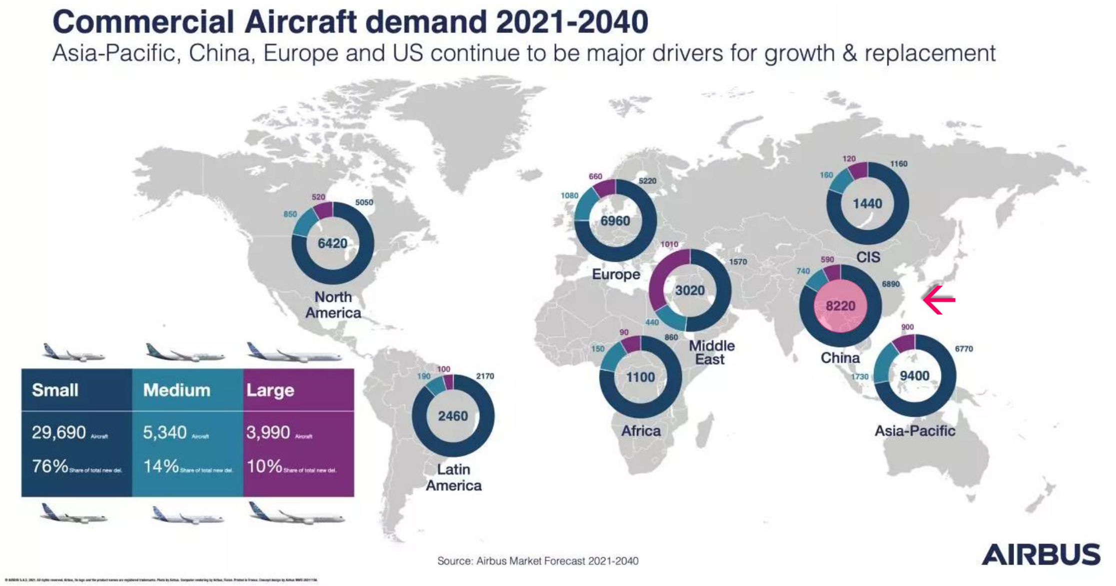
Multi-Carrier Energy System

Electricity / Heat / H_2 / E-Fuels / CO_2 Infrastructure
Aviation etc. / Green Steel / Cement / Chemicals

Hard-to-Abate Sector #1 – Aviation

- 2.5% of Global CO_2 Emissions / ≈1.2 Billion Liters of Aviation Fuel/Day in 2024 / ≈35% SAF by 2050
- 30´000 New Commercial Aircraft & Freighters in 2021–2040 incl. Replacements — 4.8 Trillion USD





- Growing Air Travel Demand Driven by Growing Middle-Class & Desire to Explore / Connect Globally
- E-Commerce Drives ≈5%/Annum Growth in the Freight Sector — 200 Million Tons of Global Air Cargo

Hard-to-Abate Sector #2 – Shipping

- *2.8% of Global CO_2 Emissions / ≈85% of World Trade Carried by Sea / 12.3 Billion Tons / 100´000 Vessels*
- *IMO Strategy on NZ shipping around 2050 incl. Green H_2 & Derivatives (E-Ethanol, E-Ammonia)*

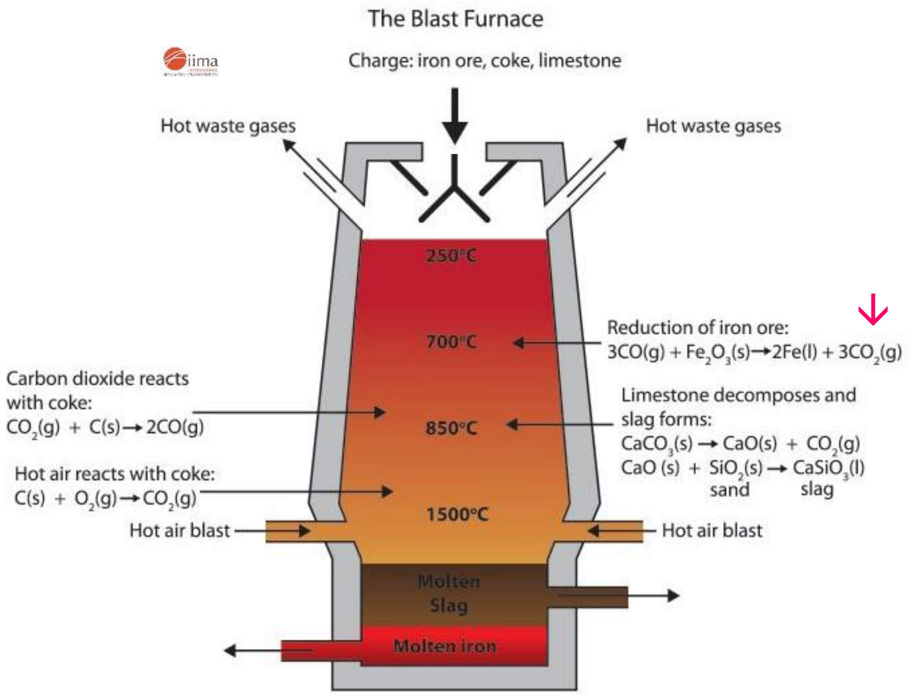
Source: https://www.ship-technology.com/

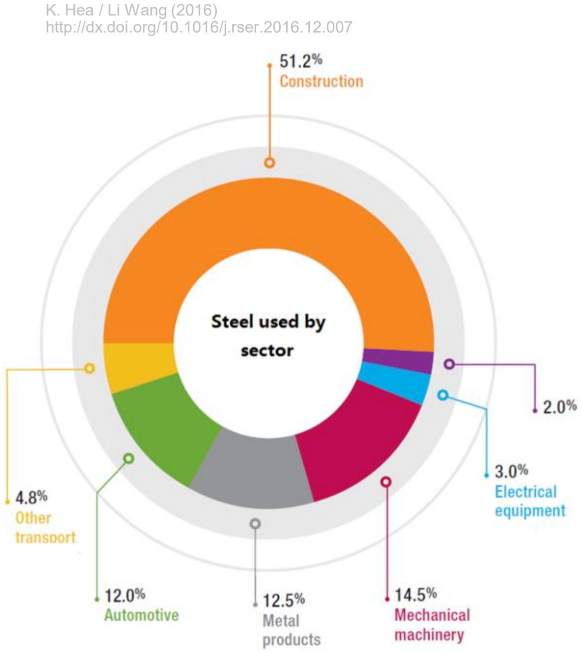
https://www.shipsnostalgia.com/

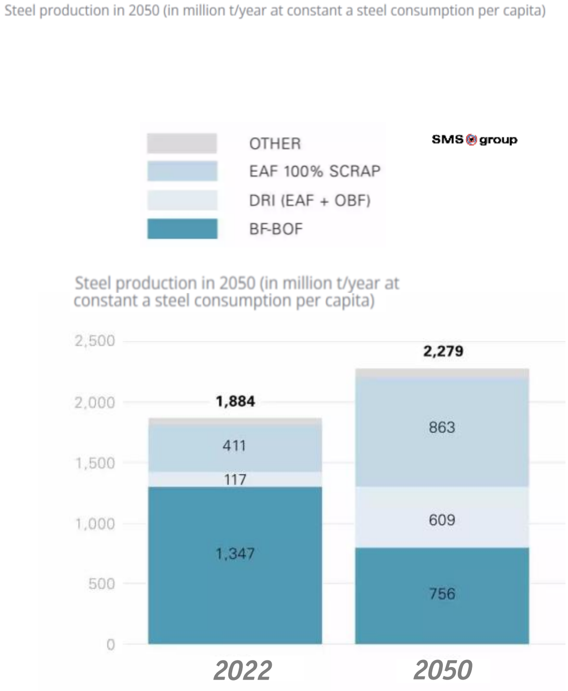
- *Ultra-Large Container Vessels (ULCVs) — 20´000 Twenty Foot Containers / 15´000 Liters of Heavy Fuel Oil per Hour*
- *80 MW @120 rpm / 2´300 Tons Largest Diesel Engine Used in ULCVs*

Hard-to-Abate Sector #3 – Iron & Steel

- *Crude Iron Production in Blast Furnaces Reliant on Coal/Coke as Reducing Agent to Extract Iron from Ore/Fe_2O_3*
- *Basic Oxygen Converter Turns Crude Iron into Easily Formable Steel / Electric Arc Furnaces Recycle Steel Scrap*



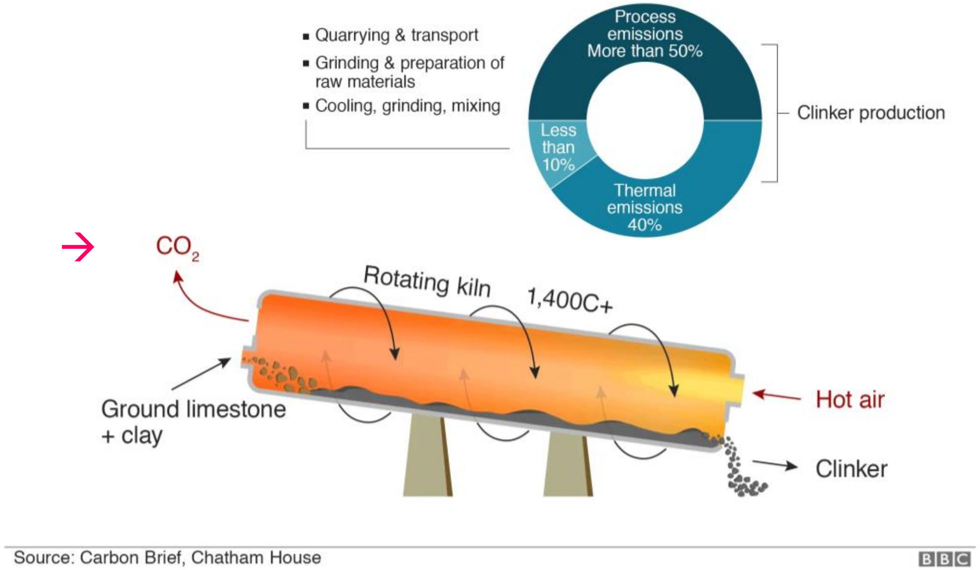


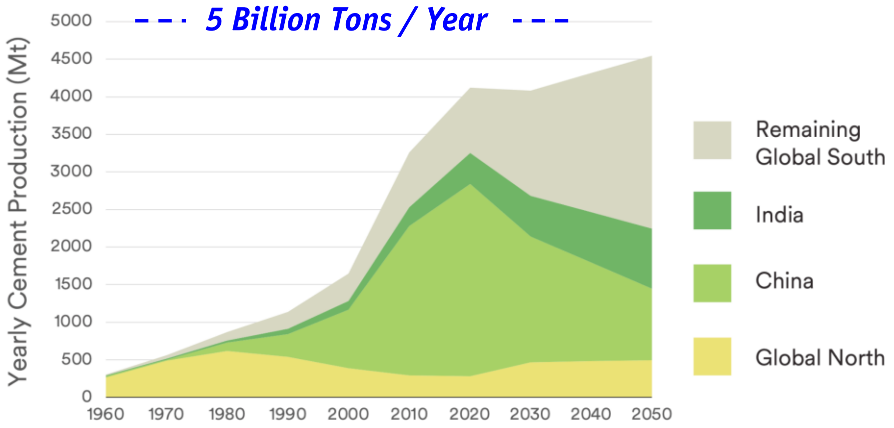


- *Steel Production Responsible for ≈8% of All Global Direct Emissions From Fossil Fuels*
- *Global Steel Demand Expected to Increase from ≈1.9 Billion Tons/a in 2021 to Over ≈2.3 Billion Tons/a by 2050*

Hard-to-Abate Sector #4 – Cement

- *Cement — Key Ingredient in Concrete / Chemical Process & High Heat / 8% of Global CO_2 Emissions*
- *Concrete is the Most-Consumed Human-Made Material on Earth / Buildings & Infrastructure etc.*

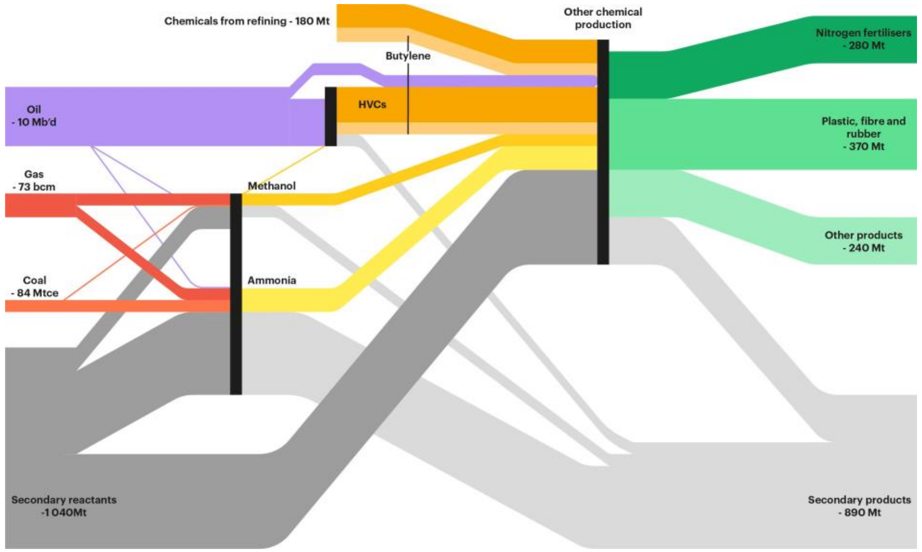


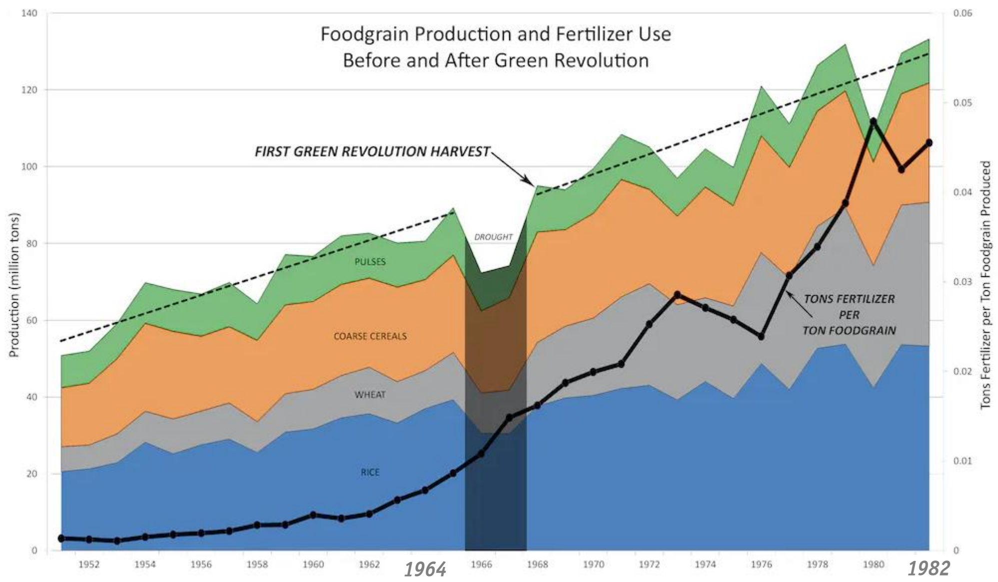


- *China & India Account for Around 50% of Global Cement Production*
- *Intensity of Cement Use Declines After Initially Rising w/ Increasing GDP/ Capita*

Hard-to-Abate Sector #5 – Chemicals

- *11%/8% Global Oil/Gas Used for Production of Chemicals — Fertilizers, Pharmaceutics, Plastics etc.*
- *50+% of Energy Input as "Feedstock" Finally Embedded in Products (Globally ≈1 Mio PET Bottles Sold/Minute)*

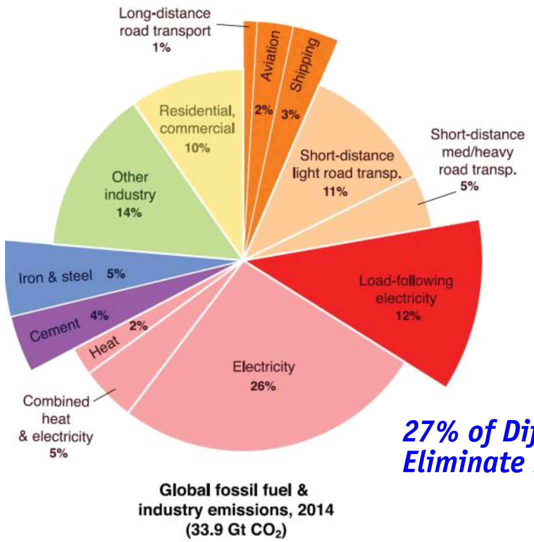




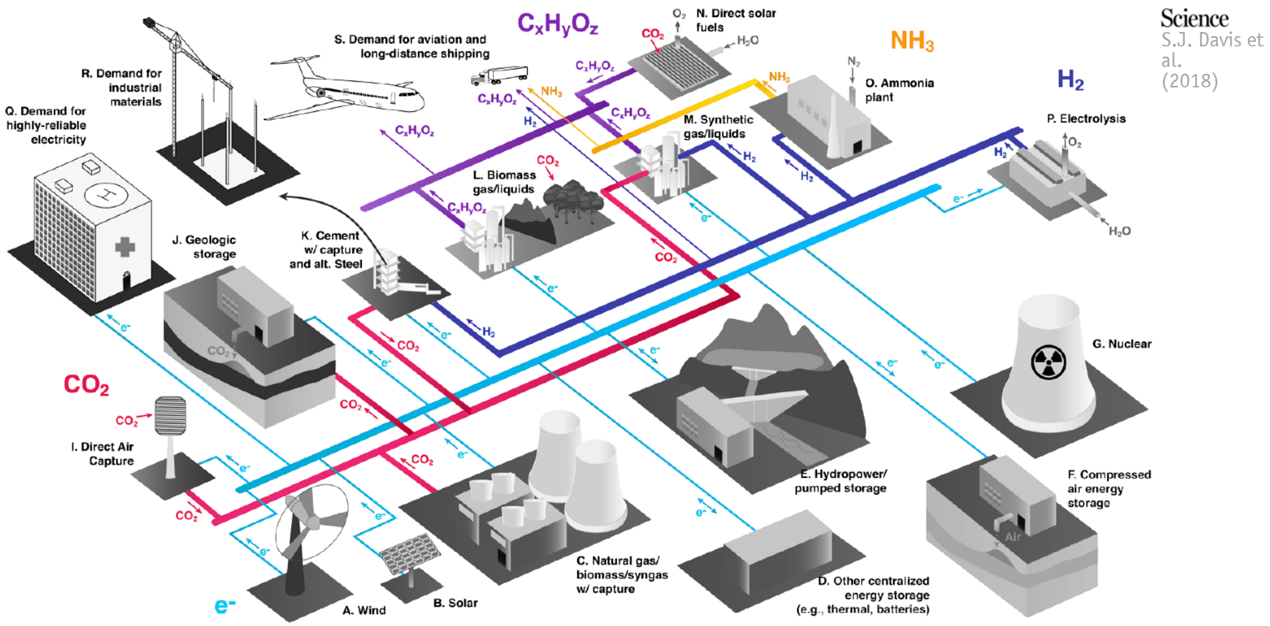
- *"Green Revolution" in Mid-20th Century — Higher Yield Due to Use of Fertilizers & Pesticides & Mechanization*
- *Chemical Sector — Largest Industrial Energy Consumer / 3rd Largest CO_2 Emissions after Steels & Cement*

Multi-Carrier Energy Society

- 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



27% of Difficult-to-Eliminate Emissions



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

Critical Raw Materials

"Blind Spot" of Clean Transition
Requirements & Geopolitical Dependencies
Mining Constraints

„Peak Minerals/Metals“ of Net-Zero Scenario 1/2

- *Minerals/Metals-Intensive Clean Energy Transition will Potentially Face Supply Deficits*
- *USD 2.1 Trillion Investment to Meet Net-Zero 2050 Demand / 6.5 Billion Tons of End-Use Materials*

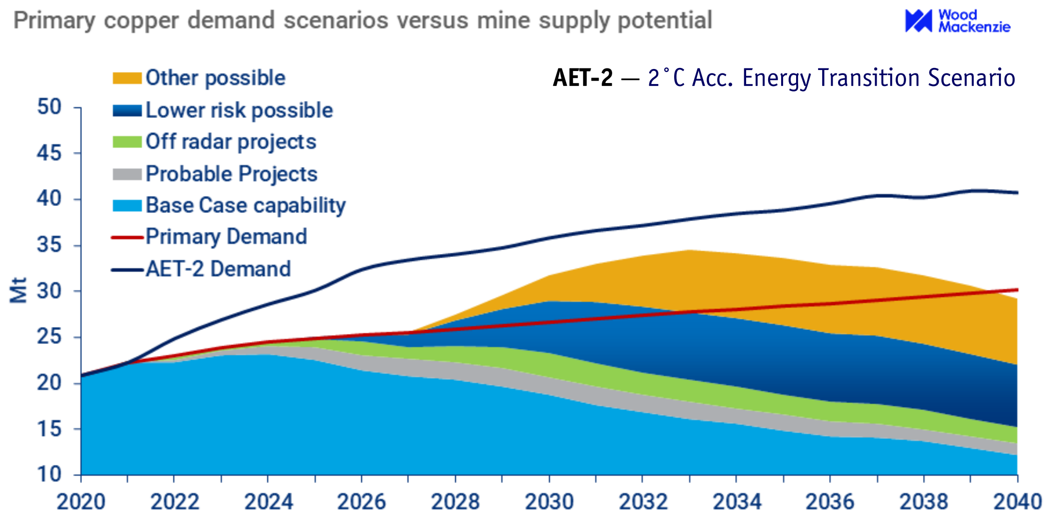
BloombergNEF

Figure 1: Market balances for energy transition metals under BNEF's Economic Transition Scenario and Net Zero Scenario – expected supply surplus and supply deficits

Metal	Scenario	2024-2030	2031-2040	2041-2050
Steel	ETS	2024		
	NZS	2024		
Aluminum	ETS	2024		
	NZS	2024		
Copper	ETS	2024		
	NZS	2024		
Lithium	ETS	2025		
	NZS	2025		
Graphite	ETS	2028		
	NZS	2026		
Nickel	ETS		2030	
	NZS	2028		
Cobalt	ETS			2050
	NZS		2034	
Manganese	ETS			
	NZS			

Source: BloombergNEF. Note: Year is the first year in which a given metal is expected to enter a supply deficit. Only primary supply is considered in this table. All supply is mined nameplate capacity, apart from that for aluminum, graphite, and steel.

2024 2050

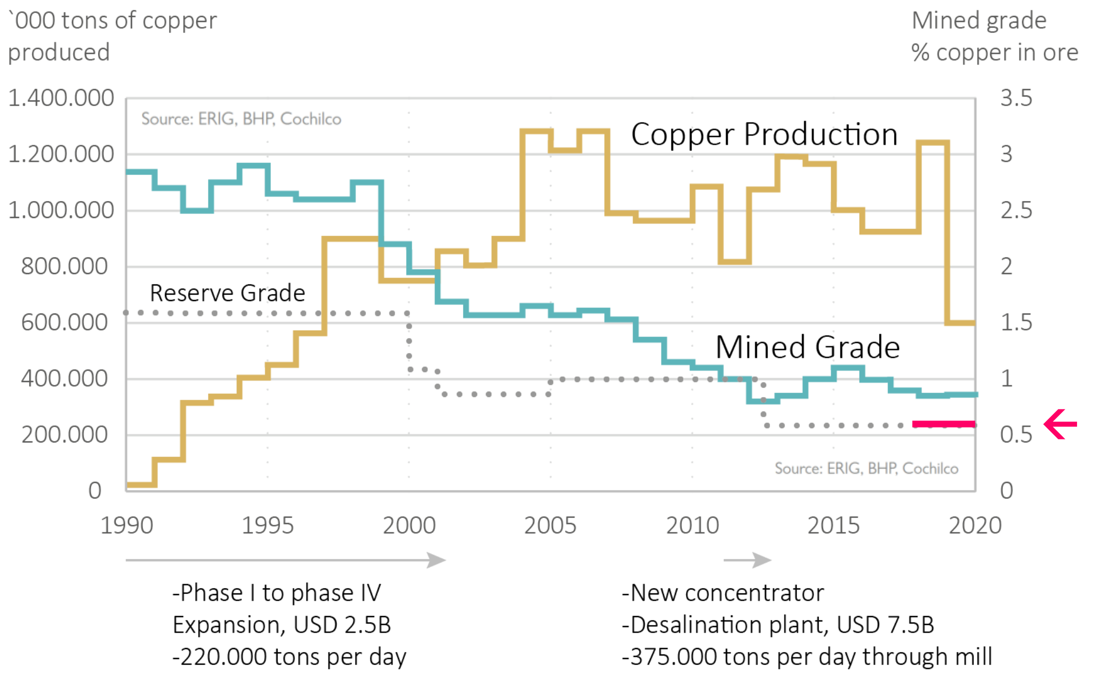


Source: Wood Mackenzie

- *50 New Lithium / 60 Nickel / 17 Cobalt Mines Required to Meet 2030 EV Battery Demand*
- *Development of a New Mine Takes 5…15 Years / x100 Million USD (!) – "Valley of Death"*

„Peak Minerals/Metals“ of Net-Zero Scenario 2/2

- *Declining Ore Body Grades Require Ever-Increasing Tonnage to be Moved & Processed*
- *Higher Production Costs / Declining Amount of Economically Extractable Mineral*

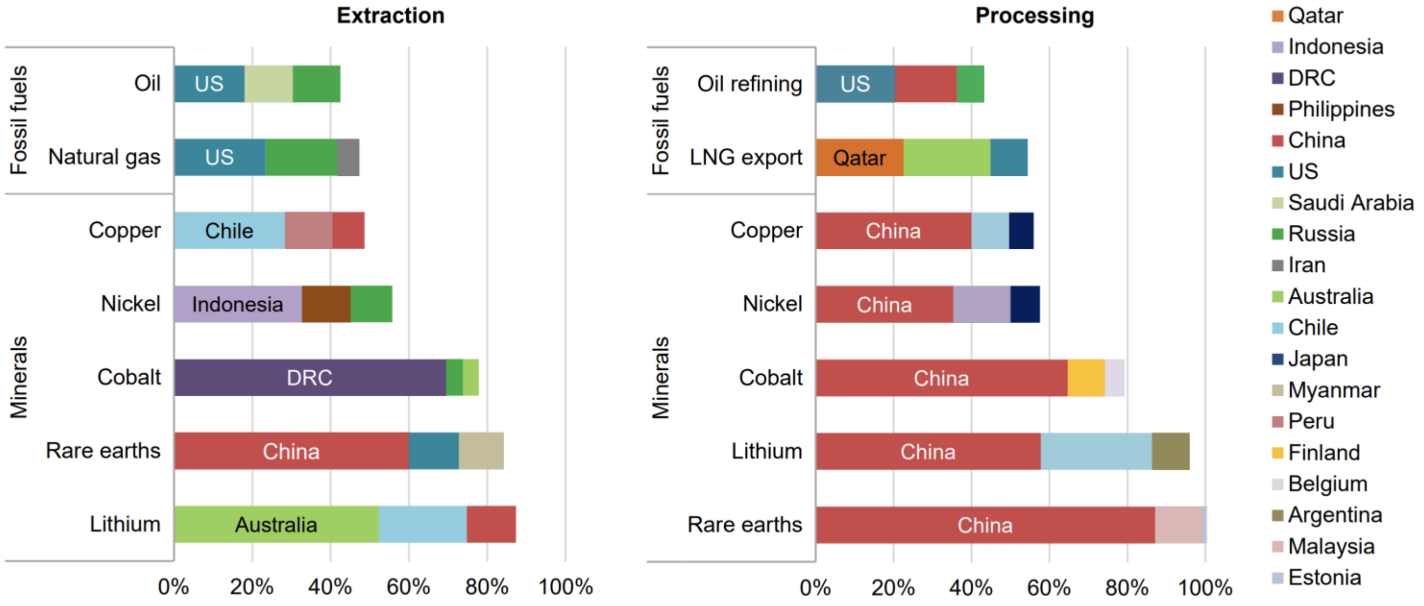


Caterpillar 797F — 350 tons payload / 3 MW

- *Higher Diesel Consumption of Truck/Shovel Fleet | Higher Energy Effort for Grinding/Extraction per Unit Metal*

Remark Critical Mineral Dependencies

- *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 (!)*

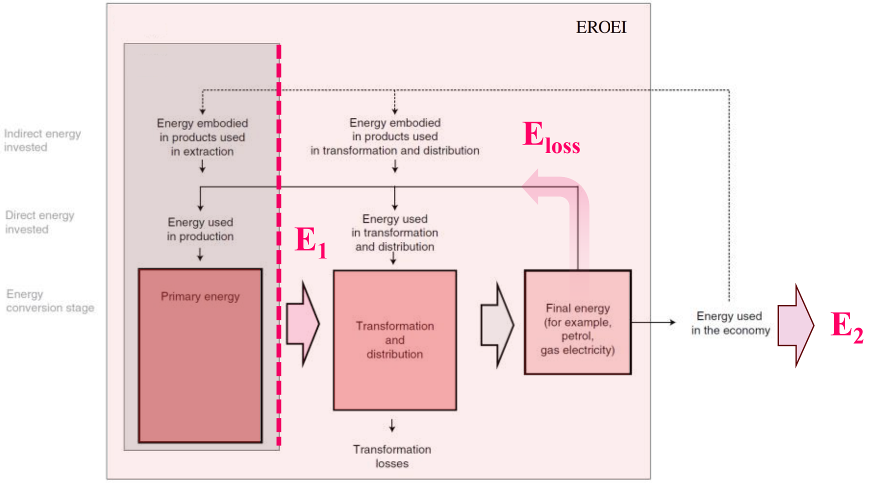
The "Net Energy Cliff"

Energy Return on Energy Invested
Fossil Fuels vs. Renewables

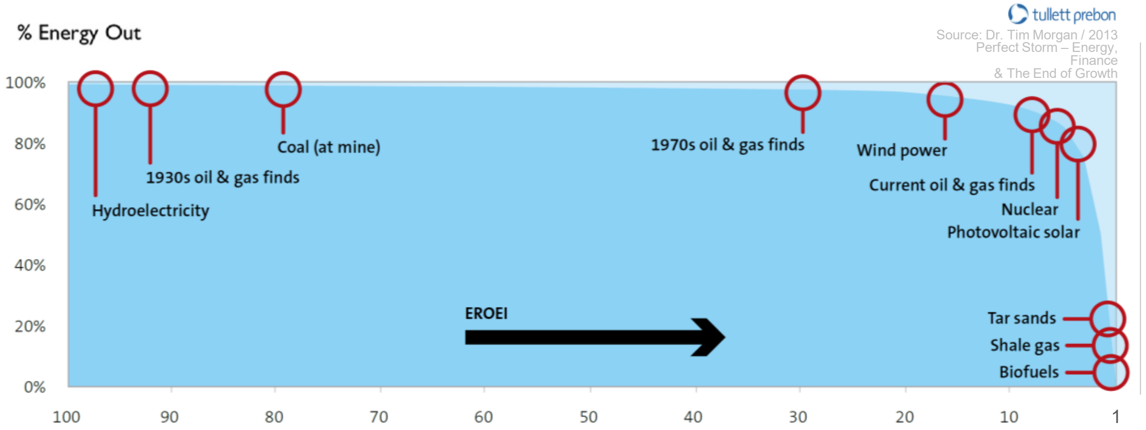
Energy Return on Energy Invested (EROEI)

- *Energy Supply Must Provide Sufficient Energy Surplus after Accounting for Own Energy Requirements*
- *Energy Invested for Production / Transformation / Transportation*

$$EROEI = \frac{\text{Energy Obtained}}{\text{Energy required to obtain that energy}} = \frac{E_1}{E_{loss}} \rightarrow E_2 = \text{Net Energy} = \text{Energy Obtained} \cdot \left(1 - \frac{1}{EROEI}\right)$$



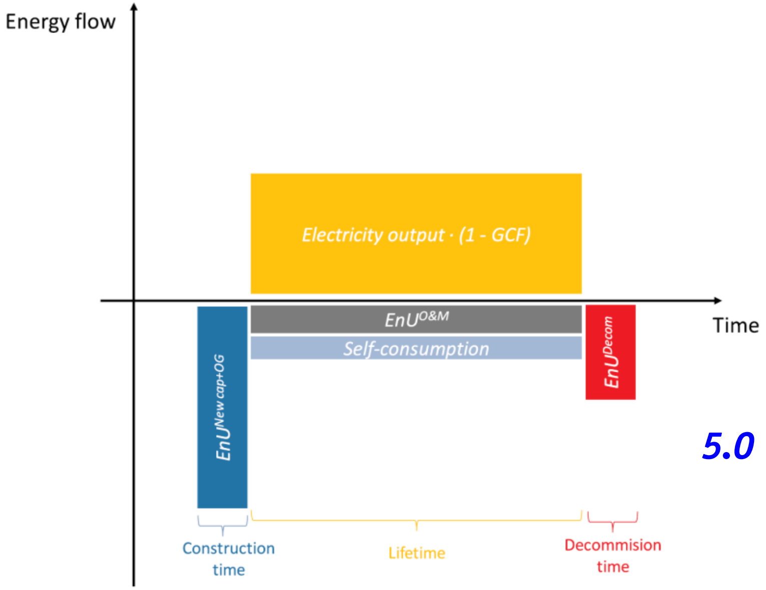
Source: K. Zhao et al. / 2021
doi.org/10.1007/s41247-021-00094-7



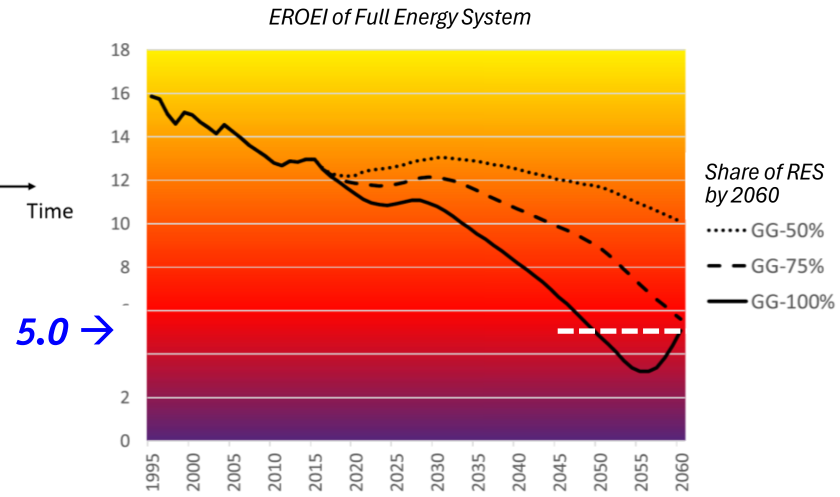
- *"Pyramids of Energy Needs" — Higher EROEI Values Enable Medical Care/Education/Technology Innovation/Art etc.*
- *The "Net Energy Cliff" Indicates the Minimum EROEI = 5…10 Required to Maintain a Complex Industrial Society*

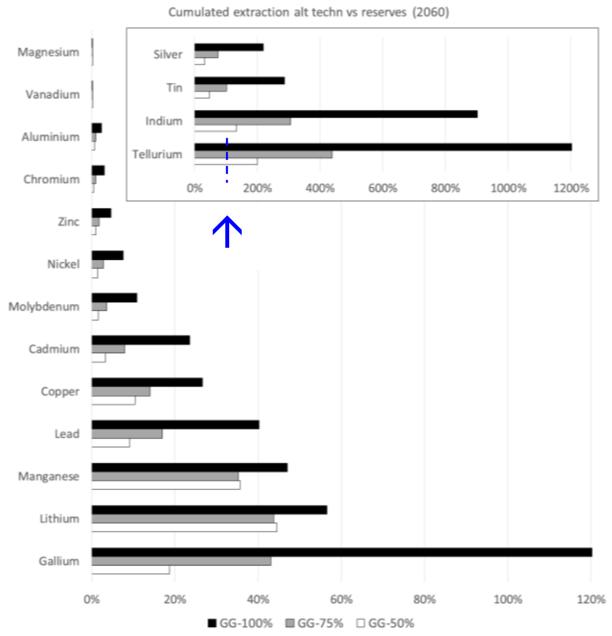
Falling-Off the „Net Energy Cliff“ (?)

- *Analysis of Energy & Material Investments for Global Transition from Fossil Fuels to RES in Electricity Sector*
- *Transition to 100% RES by 2060 Could Decrease EROEI from 12:1 to 3:1 by 2050 / Stabilizing @ 5:1*



Source: I. Capellan-Perez et al., 2019
doi.org/10.1016/j.esr.2019.100399





- *Resulting EROEI Level Potentially Below Threshold Required to Sustain Complex Industrial Society*
- *Transition Could Drive Substantial Re-Materialization of the Economy / Deplete Critical Mineral Resources*

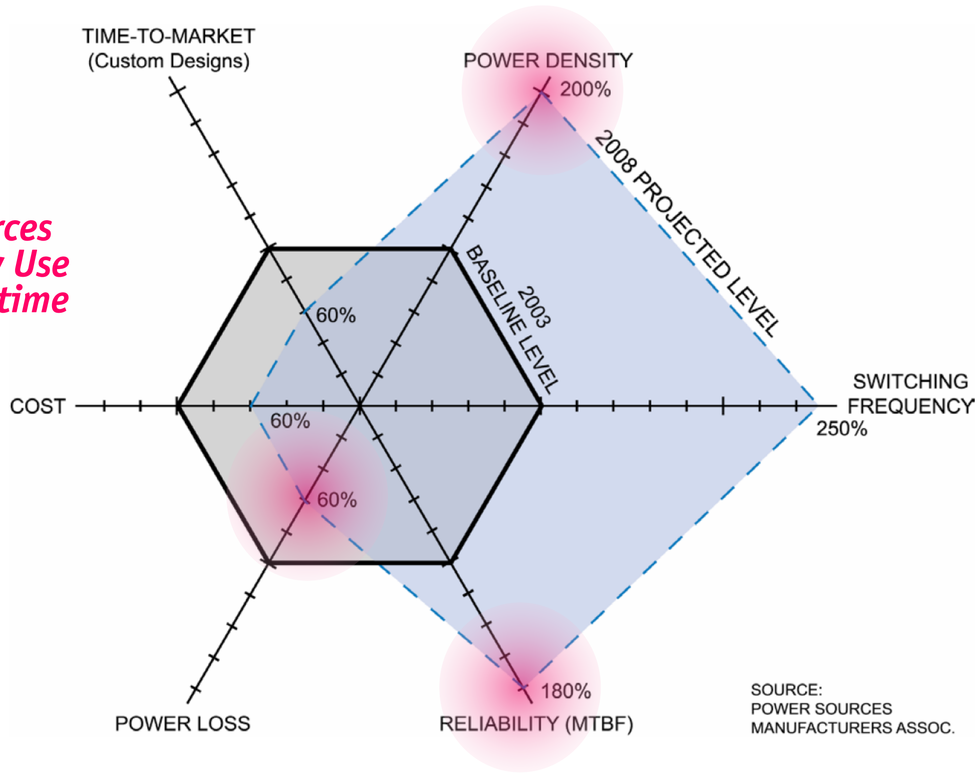
Power Electronics 4.0

"Do More with Less"

Power Electronics 4.0 — "Reduce-to-the-Max"

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

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

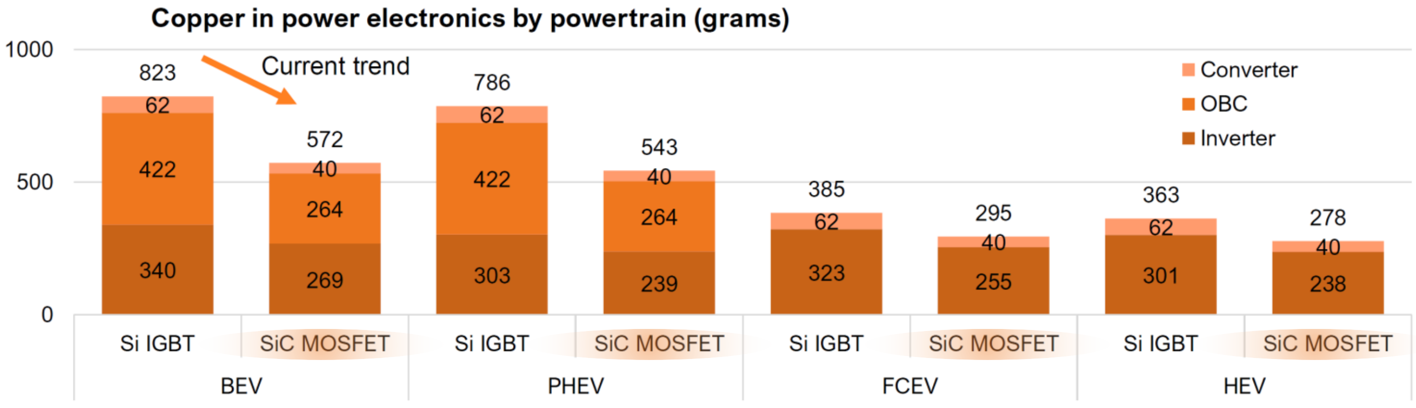


Power Sources Manufacturers Association
EPSMA

- *New Set of Key Performance Indicators Mandatory to Meet Future Environmental Compatibility Objectives*

Remark 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)*



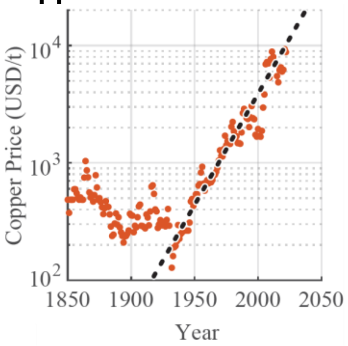
Source: IDTechEx

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

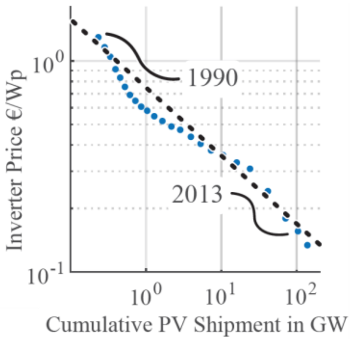
Remark Solid-State Transformers for MVac-LVdc Convers.

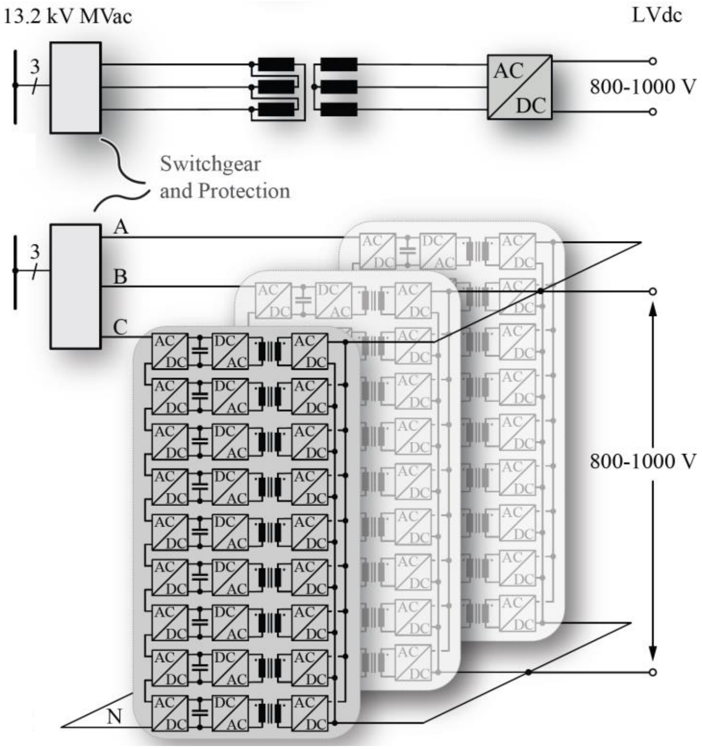
- Three-phase ac-dc **1.2 MW fully-modular solid-state transformers (SST)** with HF-isol. stages
- Comparative evaluation vs. conventional realization – 50 Hz transformer (LFT) & LV ac-dc converter

Copper Price

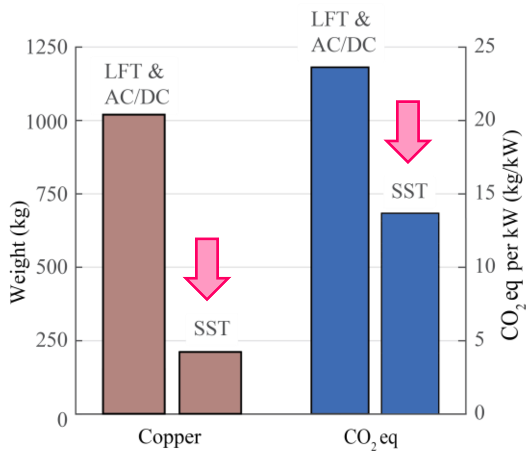


LV Power Electron. Learning Curve





Copper **Carbon Footprint**

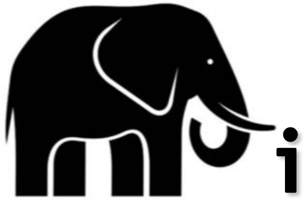


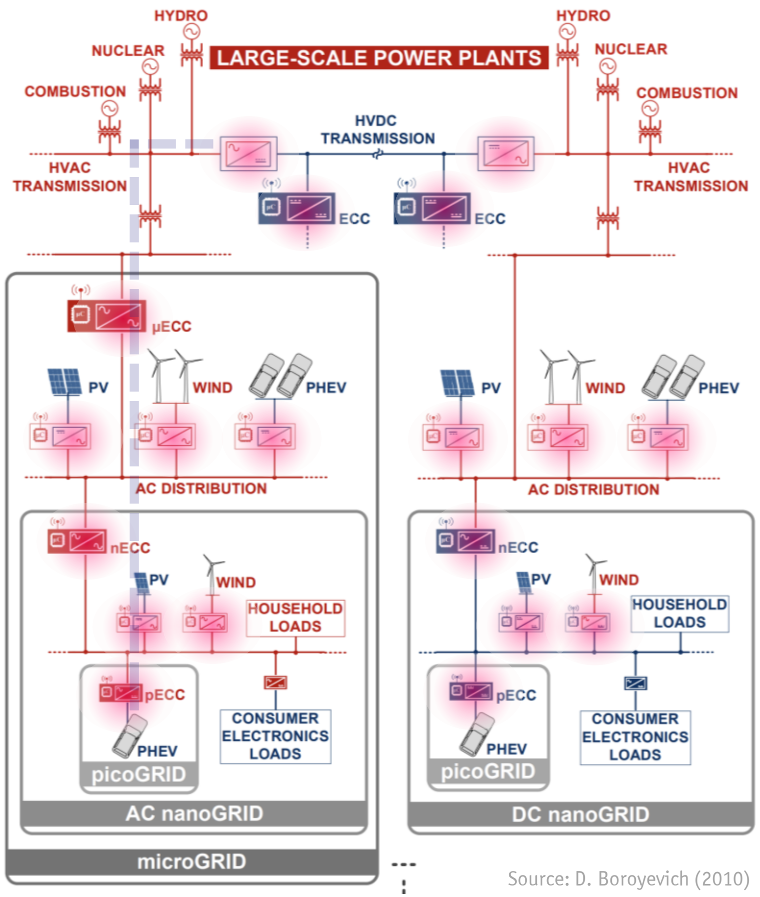
- **Lower raw material effort** / Lower impact of increasing raw material costs / **Lower carbon footprint**

Source: L. Imperiali, R. Wang, A. Anurag, P. Barbosa, J. W. Kolar, and J. Huber, "Comparative analysis of carbon footprints and material usage of solid-state transformers and low-frequency-transformer-based MVac-LVdc interfaces for high-power EV charging," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC),* Atlanta, GA, USA, Mar. 2025, pp. 1318–1325.

Power Electronics 5.0

"Zero-Waste" Paradigm

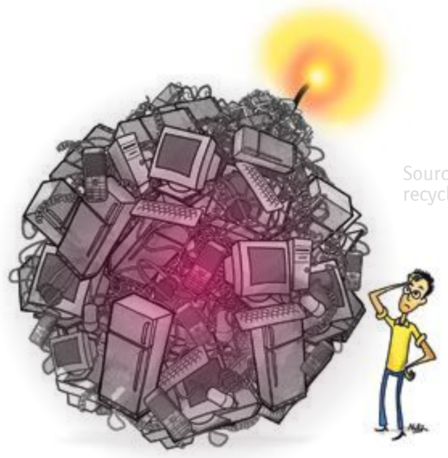
The  in the Room



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*

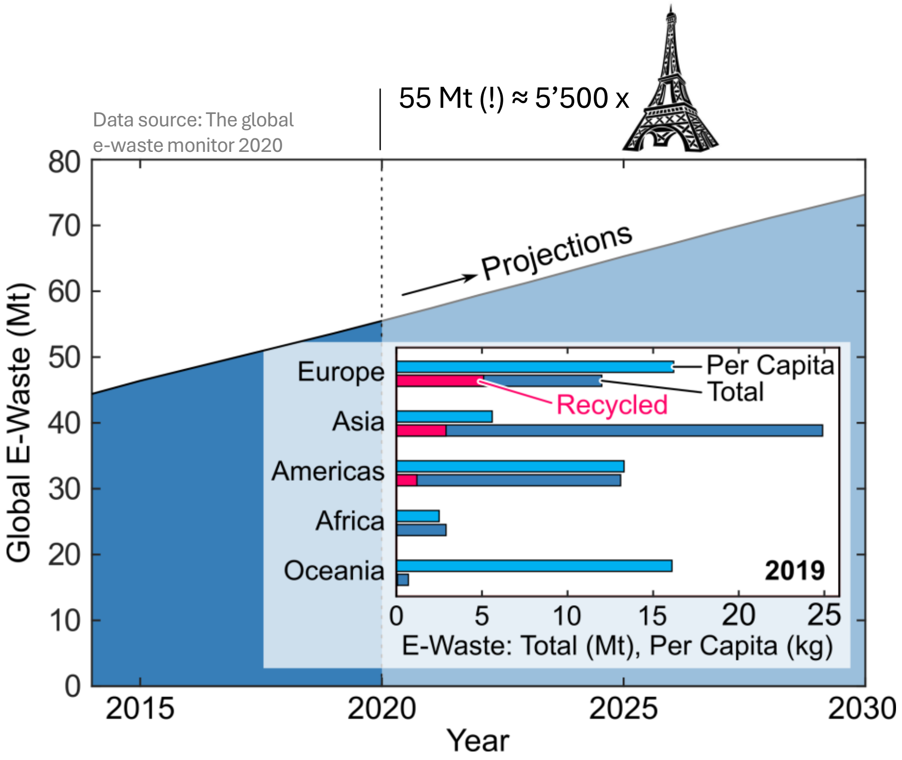


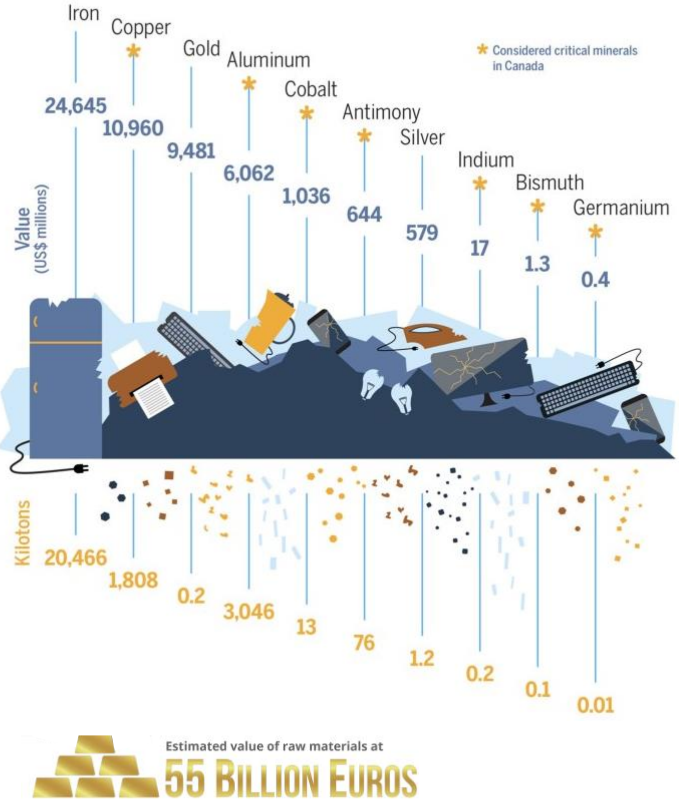
Source: www.e-waste-recyclers.co.in

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

Growth of Global E-Waste (1)

- **Growing global e-waste streams / < 20% recycling!**
- **120’000’000 tons of global e-waste in 2050**





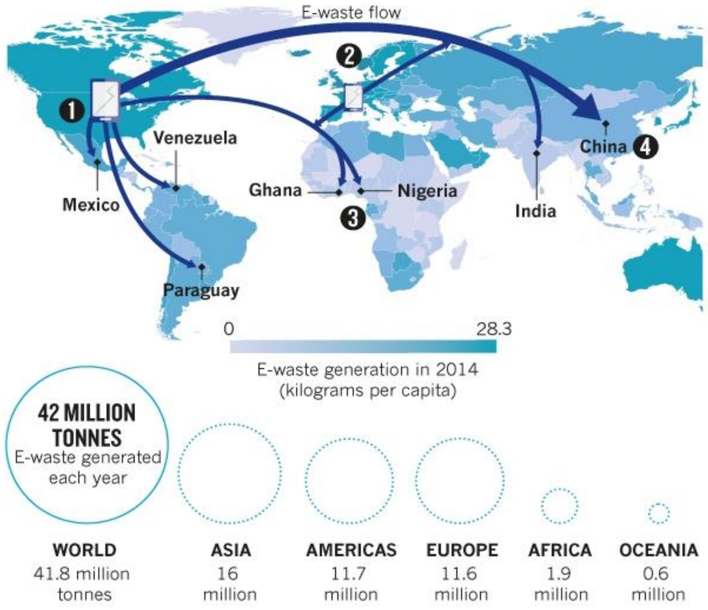
Source: Library of Parliament, Canada, 2019

Global, 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

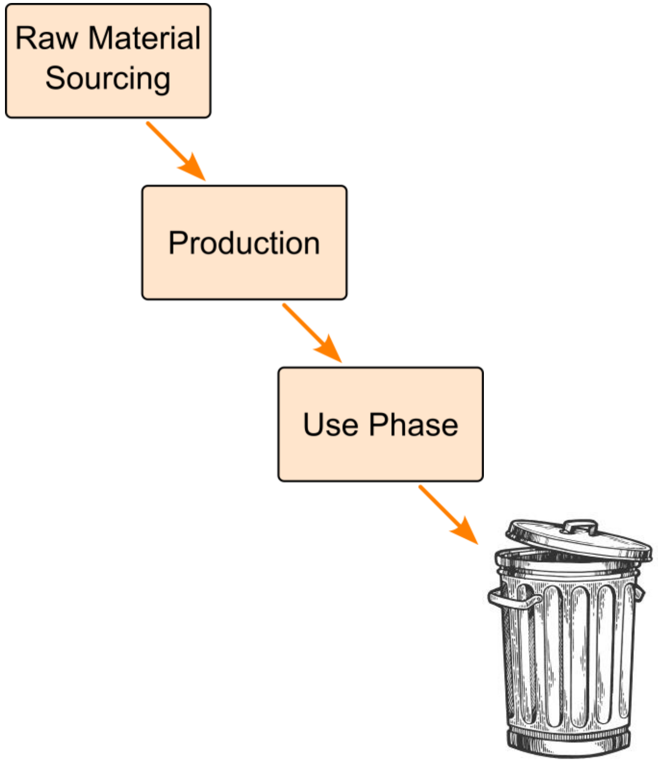
Source: Green IT Solution

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

The Paradigm Shift

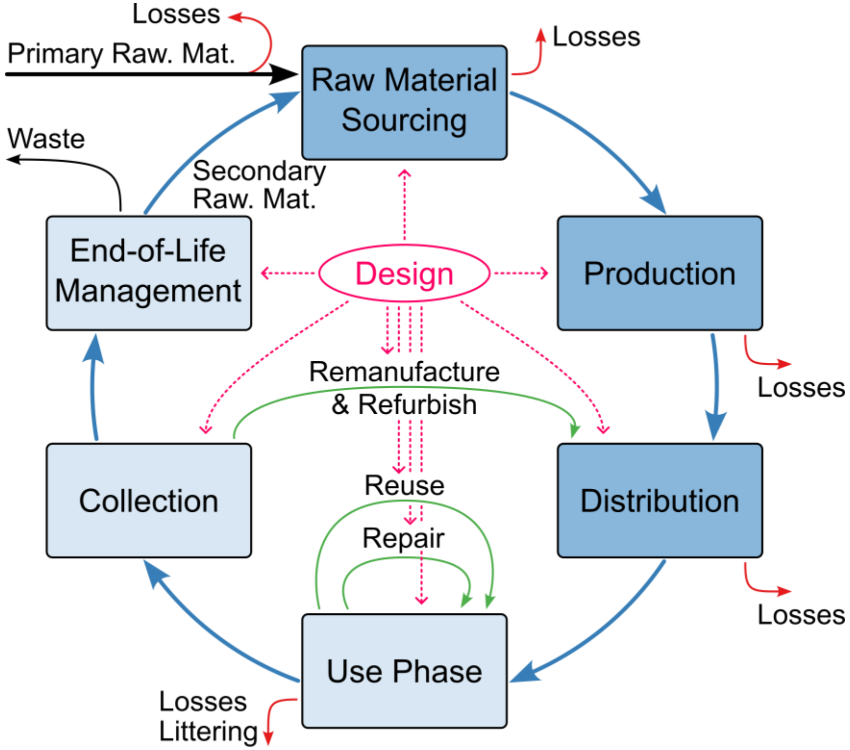
■ Linear Economy

- Take – make – dispose



■ Circular Economy

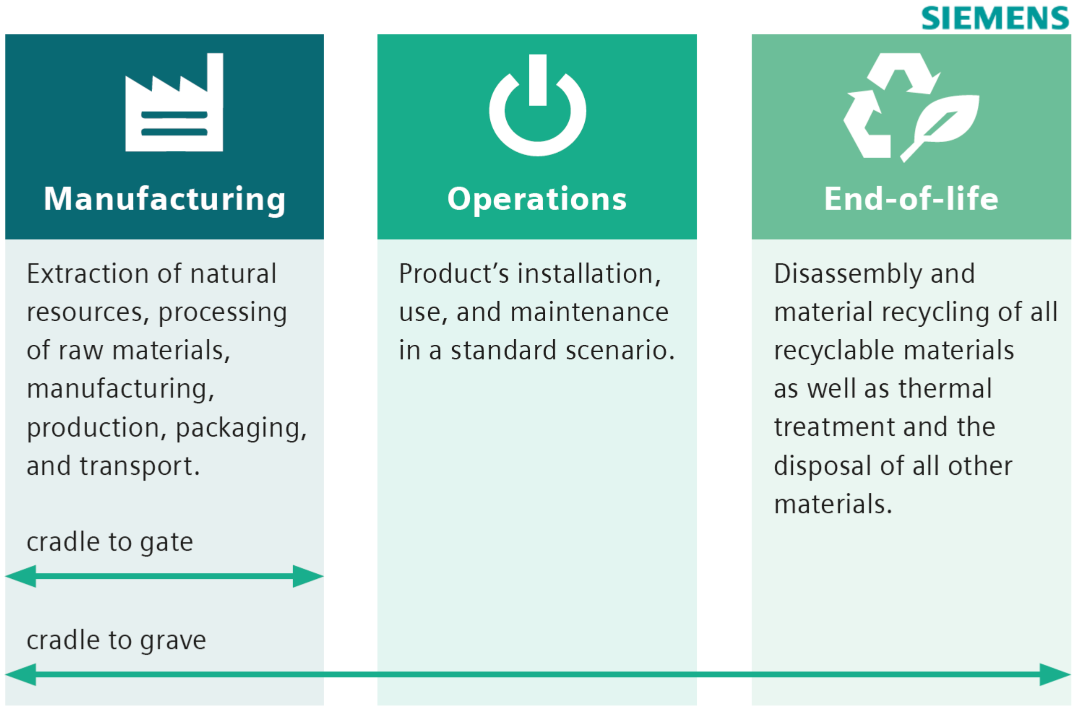
- Perpetual flow of resources



- Resources returned into the product cycle at end of life

LCA: Life Cycle Assessment (1)

■ **Quantification / benchmarking of eco-design & circular economy approaches**



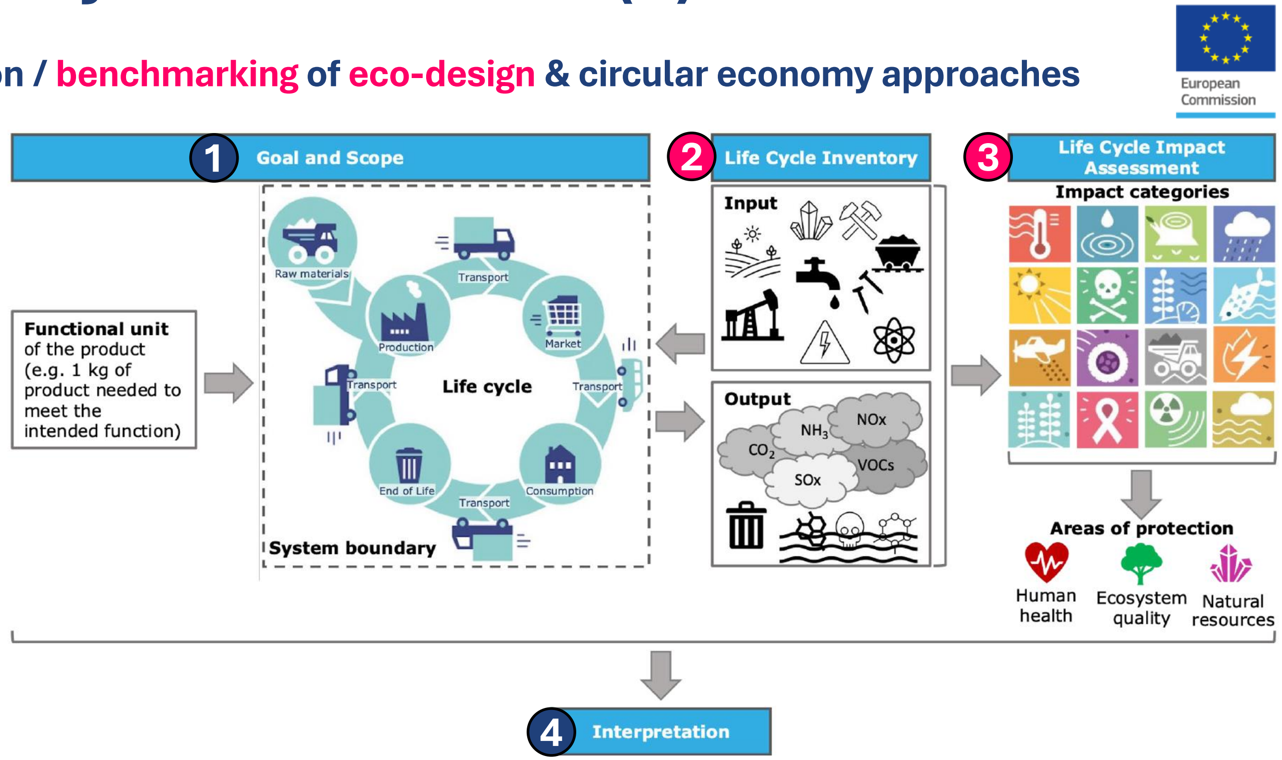
■ **Scope of LCA can include**

- **All** life-cycle phases (**cradle to grave**) or
- **Individual** life-cycle phases (**cradle to gate** or gate to gate)

Image source: SIEMENS AG, "Ecodesign: Multiplying impact, shaping the world." 2023. https://assets.new.siemens.com/siemens/assets/api/uuid:f7d929ad-971f-44df-ac51-7783cc28dac7/Ecodesign-WP.pdf

LCA: Life Cycle Assessment (2)

- Quantification / benchmarking of eco-design & circular economy approaches



2 LCI – Life Cycle Inventory
Compilation & quantification of inputs and outputs for a product throughout its life cycle

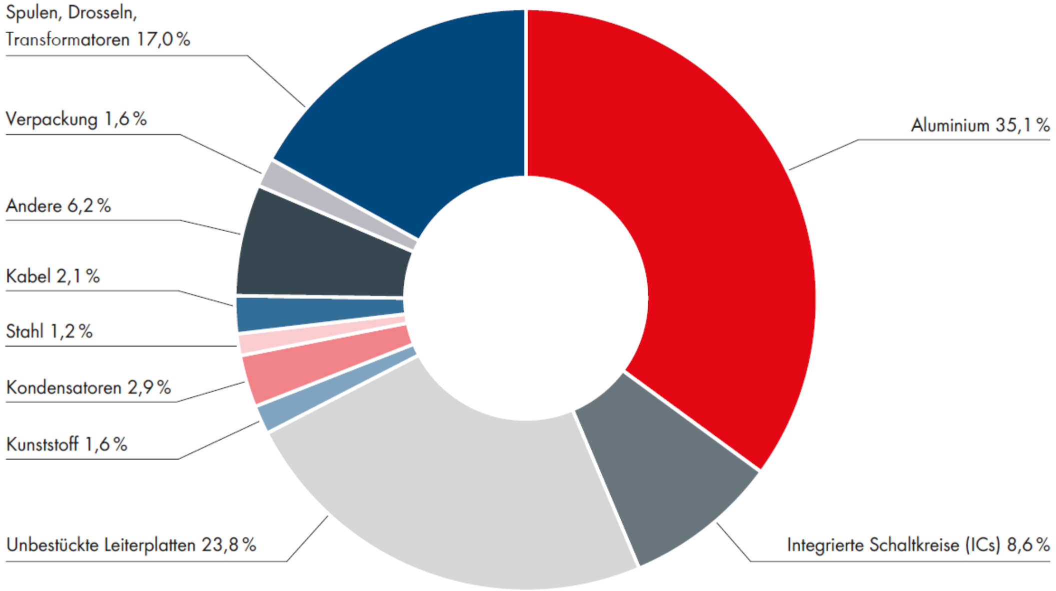
3 LCIA – Life Cycle Impact Assessment
Assignment of LCI results to (environmental) impact categories / Aggregation involves weighting factors & value choices

Source: M. Damiani, N. Ferrara, and F. Ardente, "Understanding product environmental footprint and organisation environmental footprint methods," Publications Office of the European Union, Luxemburg, JRC129907, 2022. https://data.europa.eu/doi/10.2760/11564

LCA Example: Carbon Footprint of a 150-kW PV Inverter

- **Production phase** / embodied carbon footprint of **903 kg CO_2eq** (15…20% of life-cycle carbon footprint)
- **Use phase** contributes **>80% to life-cycle carbon footprint** (conversion losses & standby/night consumption)

Embodied Carbon Footprint

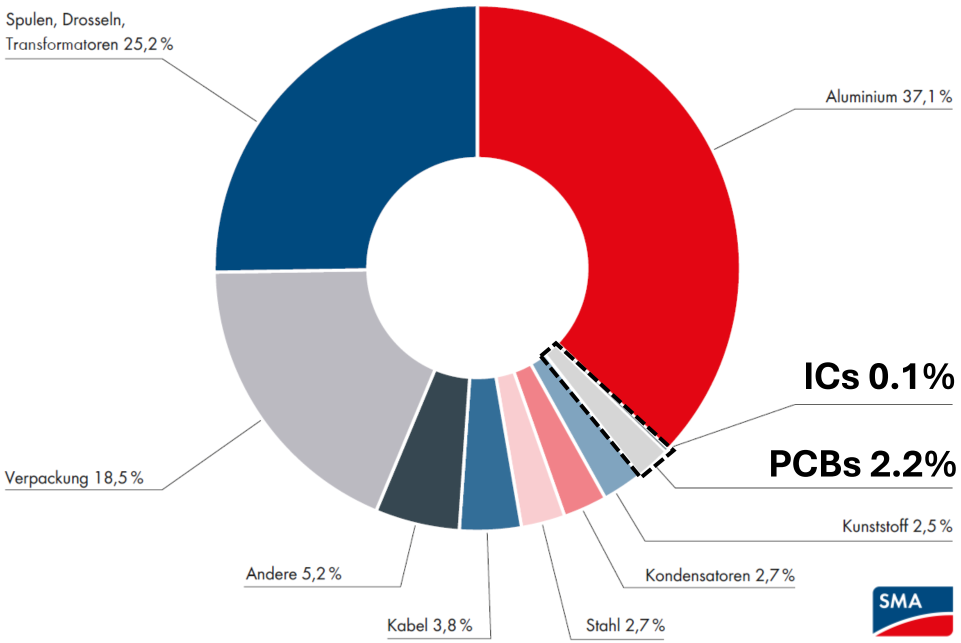


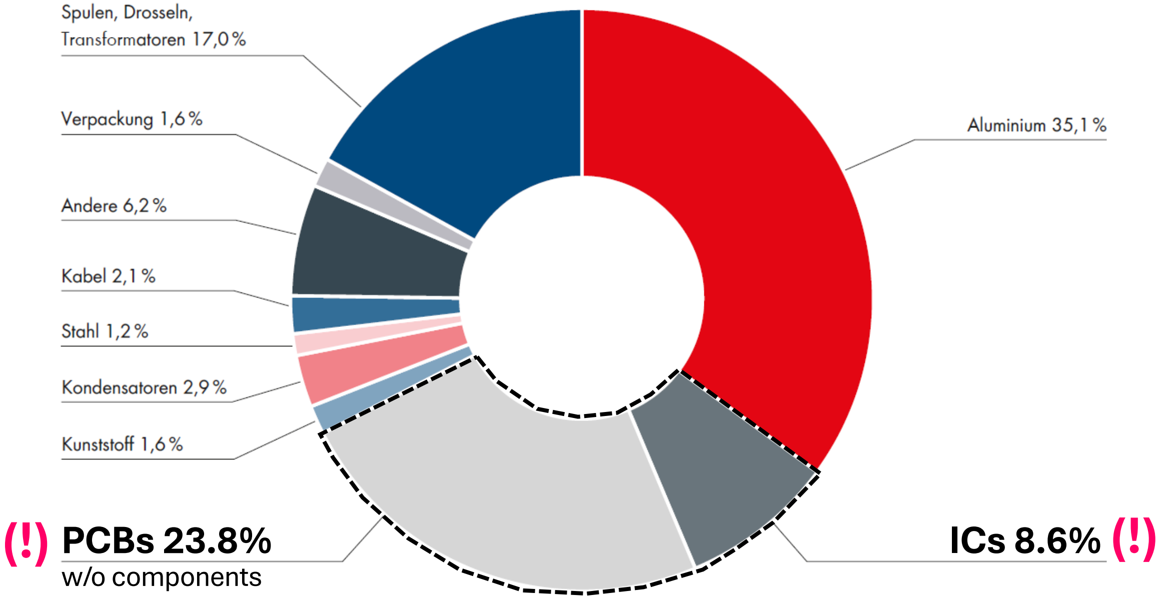
- 150 kW rated power for typ. 225 kW_p PV system

Source: SMA Solar Technology AG, "Sunny Highpower PEAK3 life cycle assessmnet (LCA)," 2023. https://files.sma.de/assets/280662.pdf

LCA Example: Carbon Footprint of a 150-kW PV Inverter

- Production phase / embodied carbon footprint of 903 kg CO_2eq (15...20% of life-cycle carbon footprint)
- Use phase contributes >80% to life-cycle carbon footprint (conversion losses & standby/night consumption)





- Small / lightweight components with large contributions to carbon footprint (!)

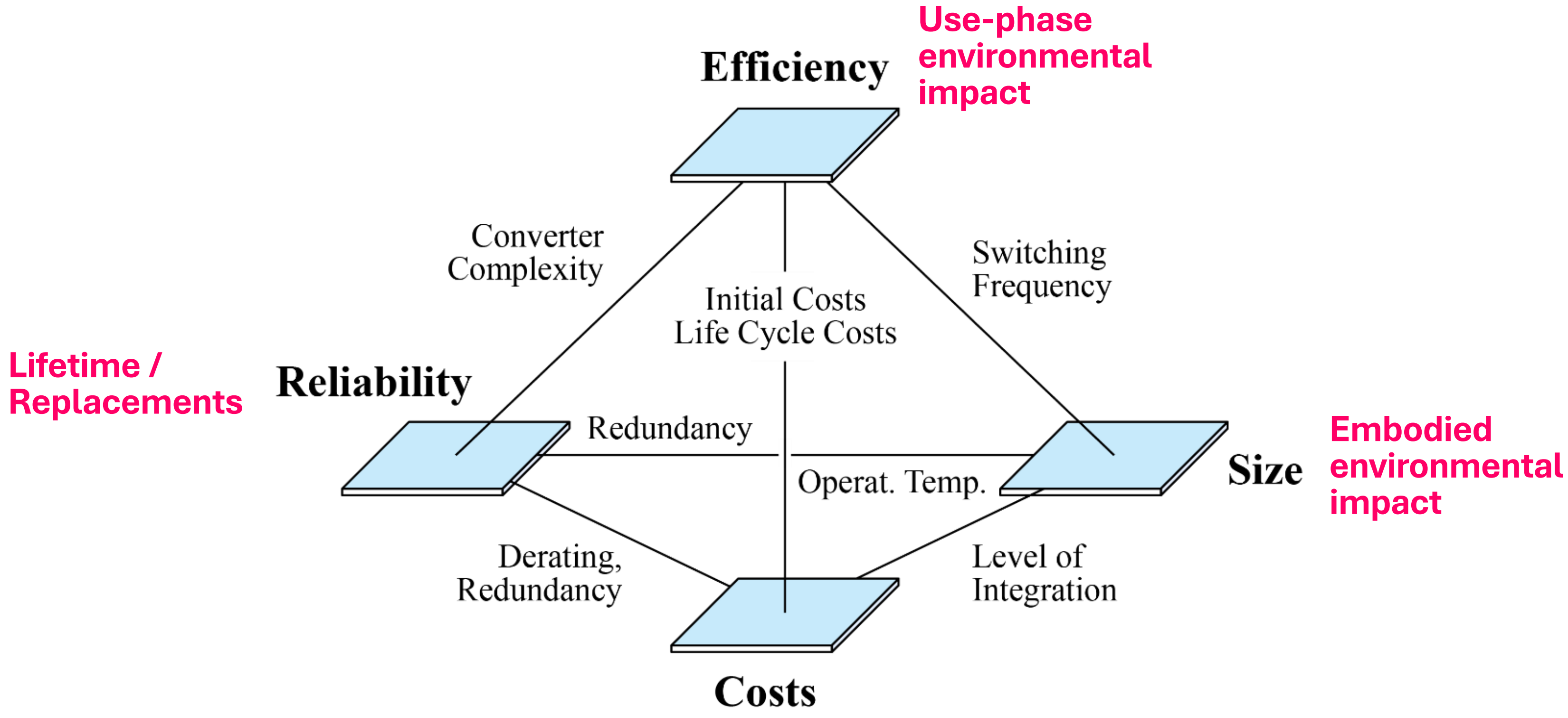
Source: SMA Solar Technology AG, "Sunny Highpower PEAK3 life cycle assessment (LCA)," 2023. https://files.sma.de/assets/280662.pdf

New Holistic Design Procedure

Multi-Objective Optimization with Environmental Impacts as New Performance Indicators

System Design Challenge

- **Mutual coupling of performance indicators → Trade-off analysis!**



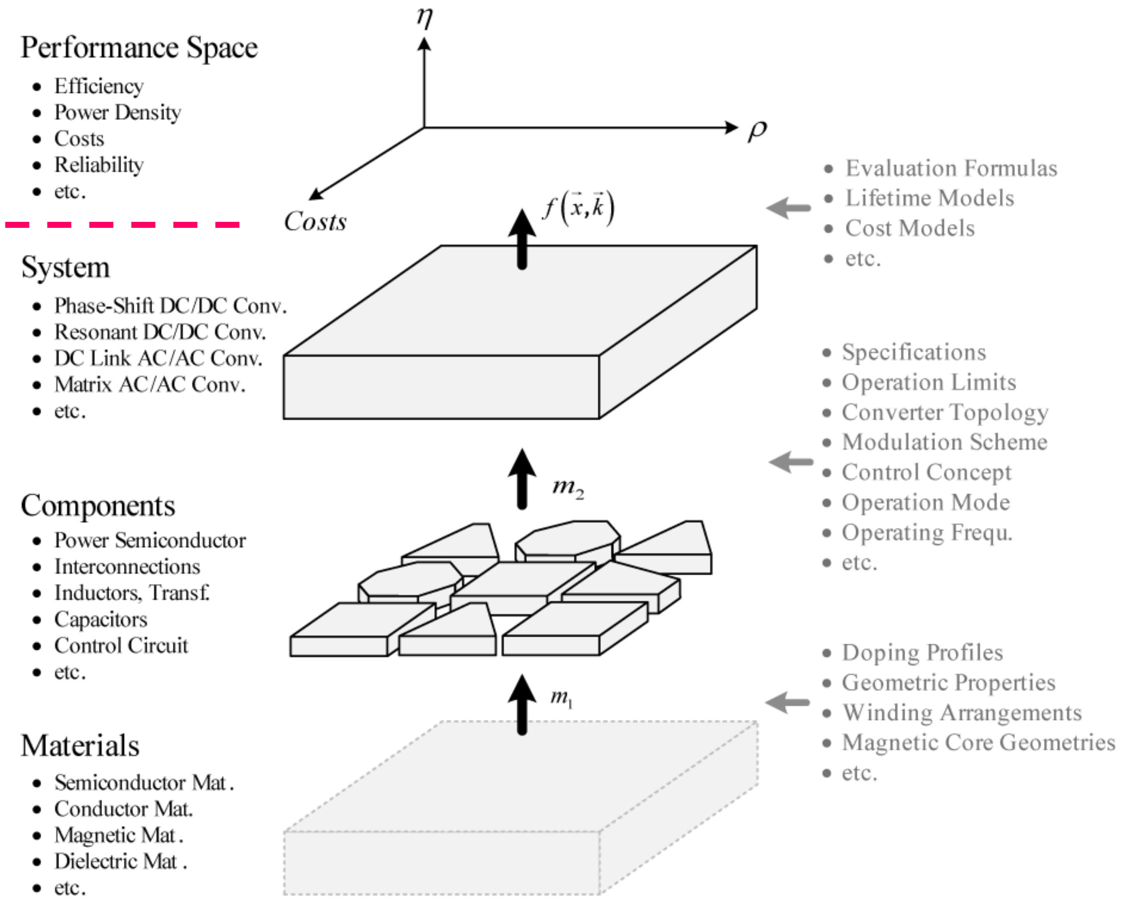
- **For optimized systems, it is not possible to improve several perf. indicators *simultaneously***

Source: J. W. Kolar, F. Krismer, H. P. Nee, “What are the "Big CHALLENGES" in Power Electronics?,” *Presentation at the 8th Int. Conf. Integr. Power Electron. Syst. (CIPS),* Nuremberg, Germany, Feb. 2014. .

Abstraction of Power Converter Design

Performance space

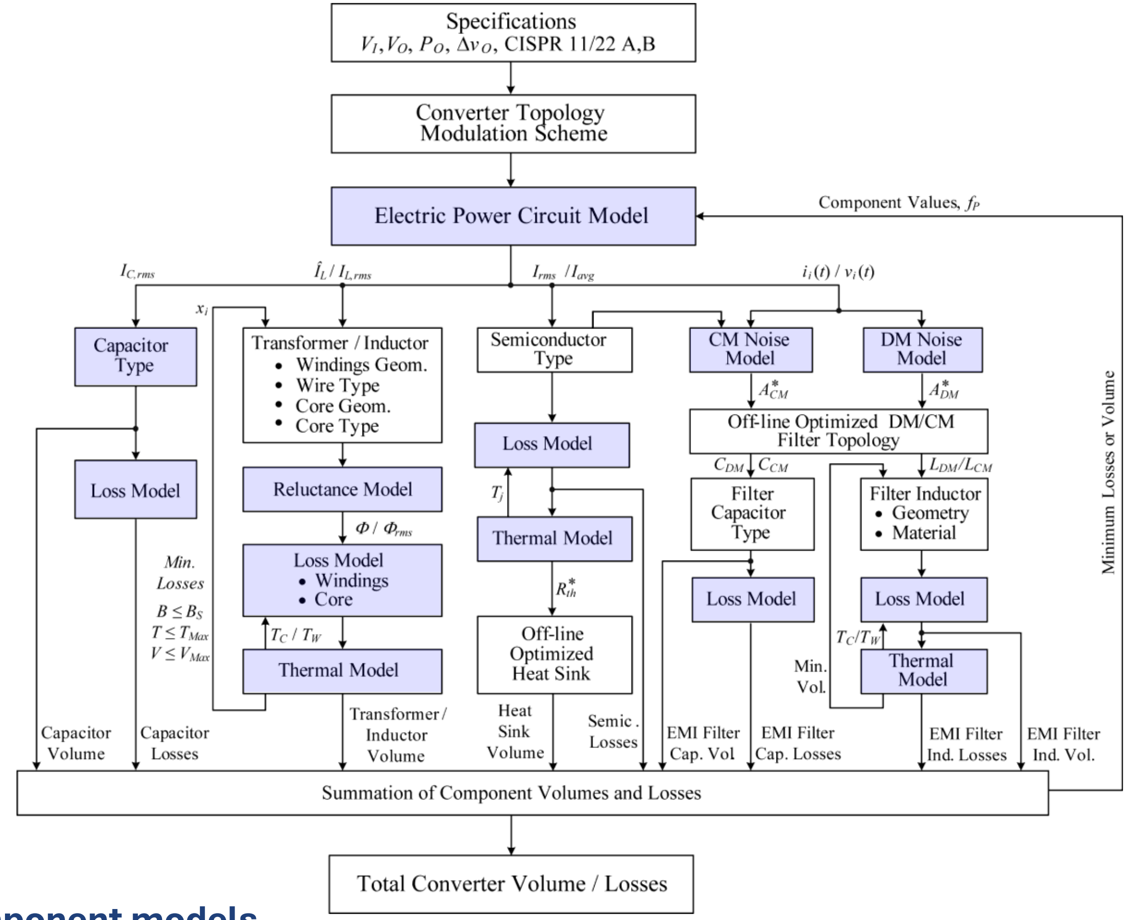
Design space



- **Converter Design: Mapping of multi-dimensional design space into a multi-dimensional performance space**

Source: J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner, "Performance trends and limitations of power electronic systems," in *Proc. 6th Int. Integr. Power Electron. Systems Conf. (CIPS)*, Nuremberg, Mar. 2010.

Modeling of Converter Designs

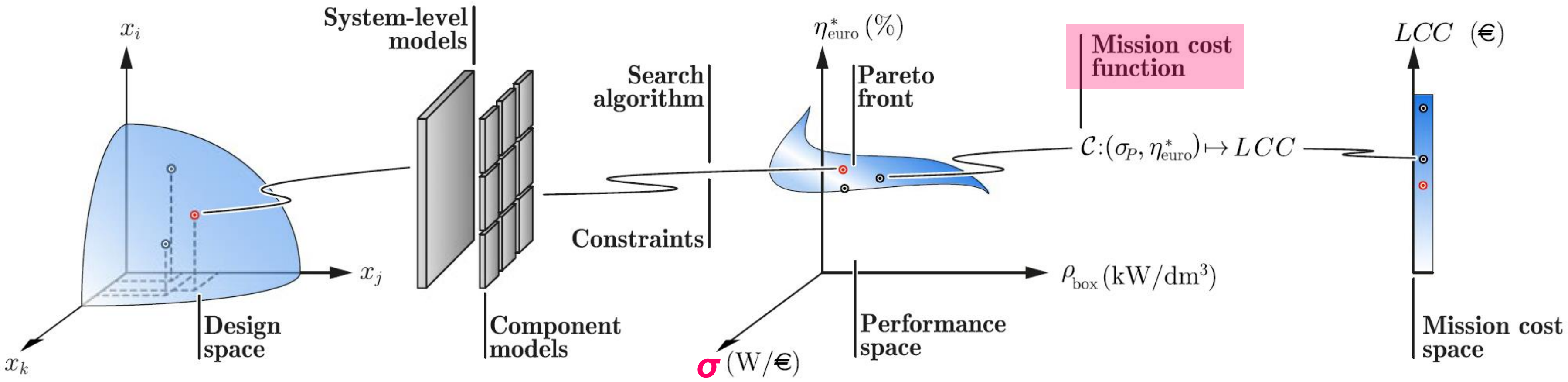


- System/circuit & component models
- Iteration over all combinations of design degrees of freedom

Source: J. W. Kolar, J. Biela, S. Waffler, T. Friedli, and U. Badstuebner, “Performance trends and limitations of power electronic systems,” in *Proc. 6th Int. Integr. Power Electron. Systems Conf. (CIPS)*, Nuremberg, Mar. 2010.

Multi-Objective Optimization of Converter Designs

- **Pareto front: Boundary of the feasible performance space**
- **Mission profiles: Power loss → Energy loss / Life-cycle *cost* (!)**

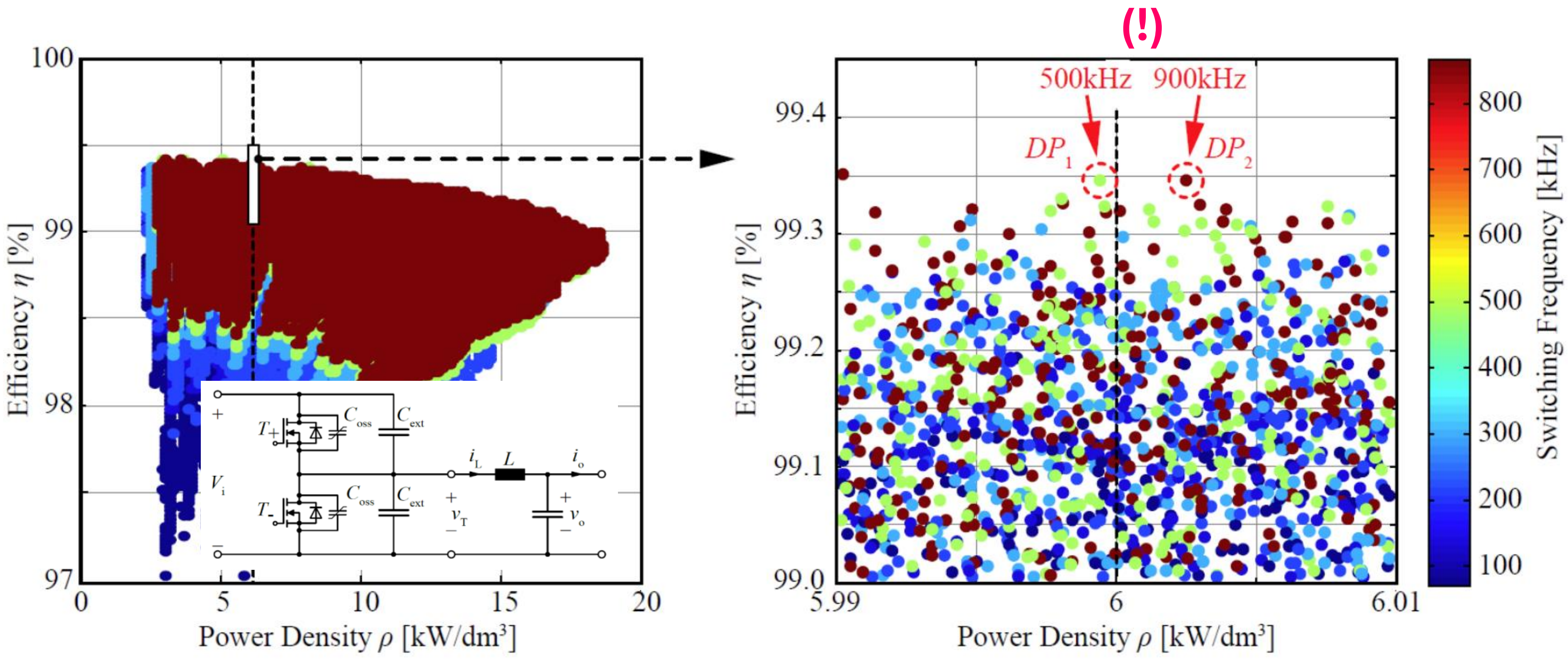


- **Typically considered performance indices:**
  - η Efficiency in %
  - ρ Volumetric power density in kW/dm^3
  - γ Gravimetric power density in kW/kg
  - σ **Cost density in W/€**

Source: R. M. Burkart and J. W. Kolar, “Comparative life cycle cost analysis of Si and SiC PV converter systems based on advanced η-ρ-σ multiobjective optimization techniques,” *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4344–4358, Jun. 2017.

Design Space Diversity

- Very **different design space coordinates** map to very **similar performance space coordinates**



- Example: Google Littlebox design optimization w. PWM operation / Mutual comp. of HF and LF loss contrib.

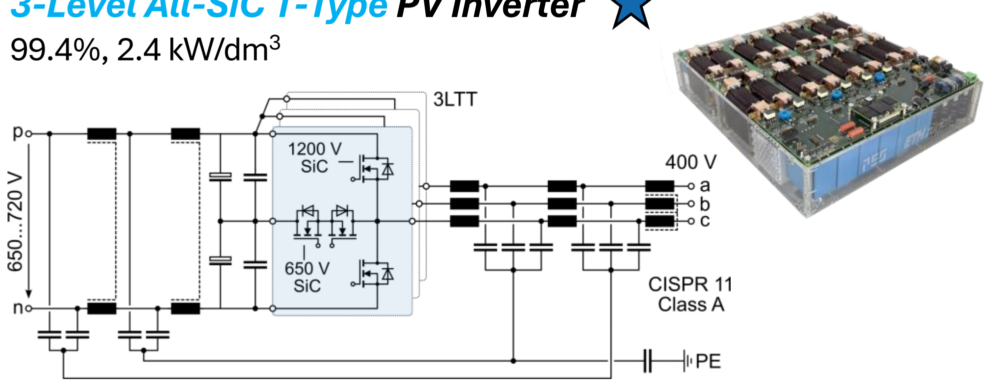
Source: J. W. Kolar, D. Neumayr, D. Bortis, M. Guacci, and J. Azurza Anderson, "Google Little-Box Reloaded," *Keynote at the 10th Int. Conf. Integr. Power Electron. (CIPS)*, Stuttgart, Germany, Mar. 2018.

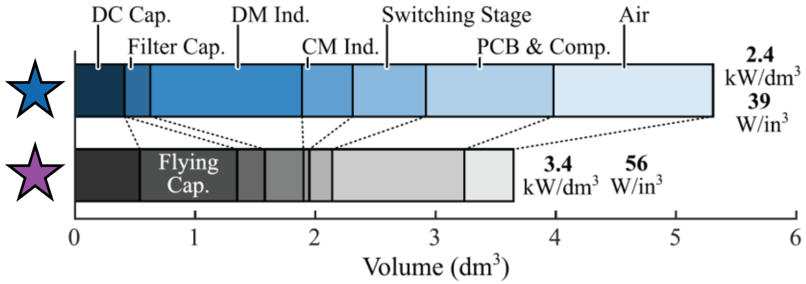
Design Space Diversity: 3L & 7L PV Inverters

- **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

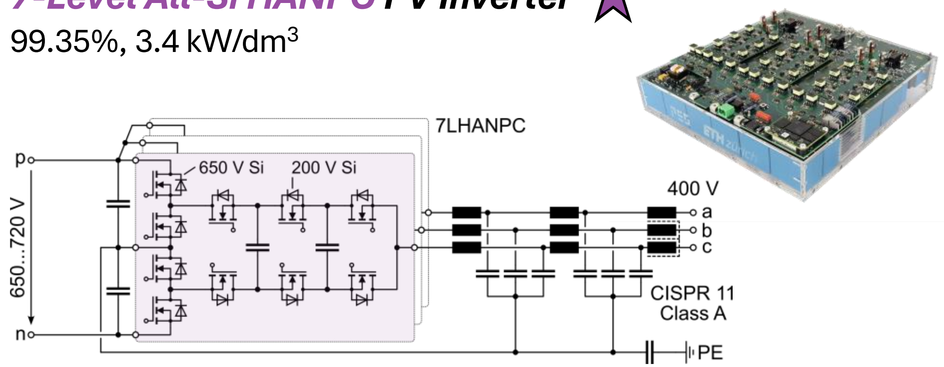
99.4%, 2.4 kW/dm³

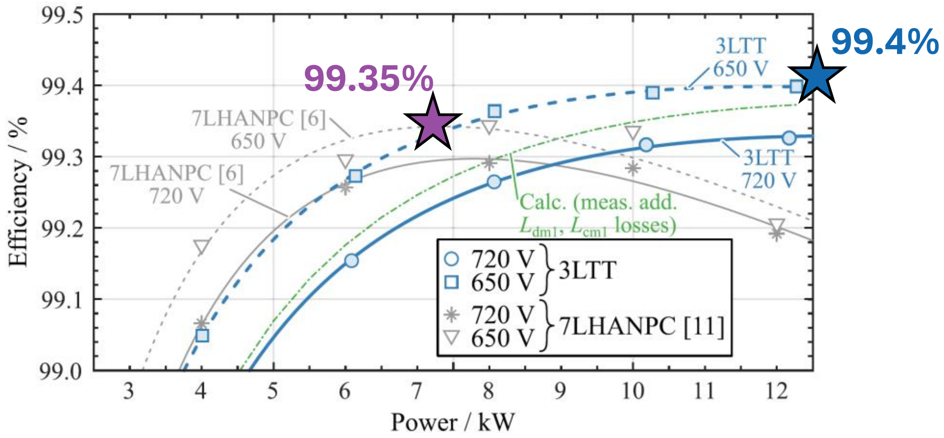




7-Level All-Si HANPC PV Inverter

99.35%, 3.4 kW/dm³





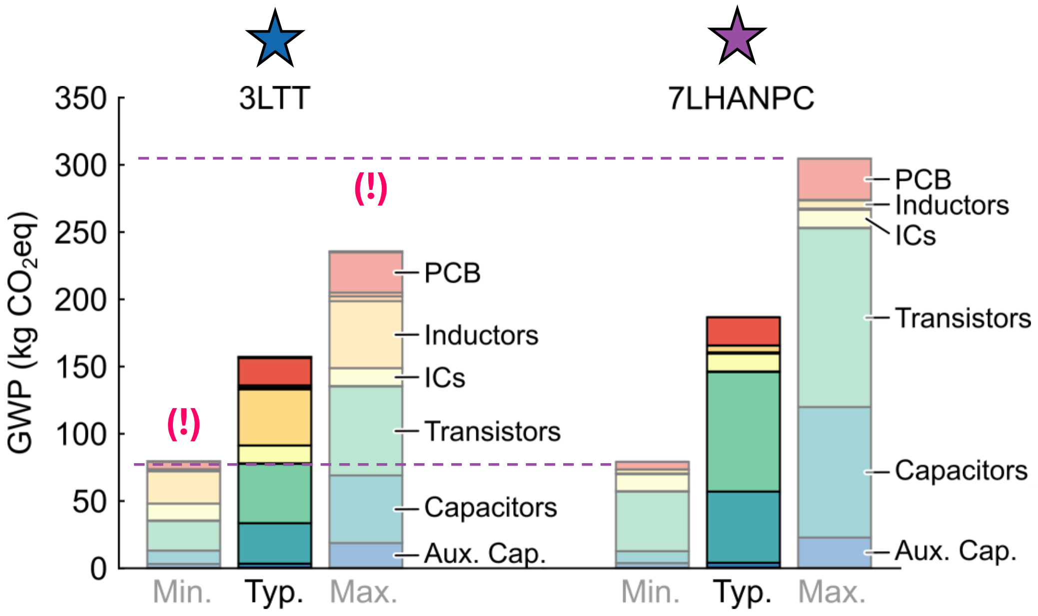
- **Differences in environmental impact?**

Source: J. A. Anderson, D. Marciano, J. Huber, G. Deboy, G. Busatto, and J. W. Kolar, "All-SiC 99.4%-efficient three-phase T-type inverter with DC-side common-mode filter," Electron. Lett., vol. 59, no. 12, p. e12821, 2023, doi: 10.1049/ell2.12821.

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/dm³, 11.8 kg



3.4 kW/dm³, 4.6 kg

GWP: Global Warming Potential

- **Generic comp. models / ecoinvent database & lit. → Widely varying embodied carbon footprint (GWP) res. (!)**
- **Data availability / quality as key challenge!**

Carbon Footprint is Not Enough!

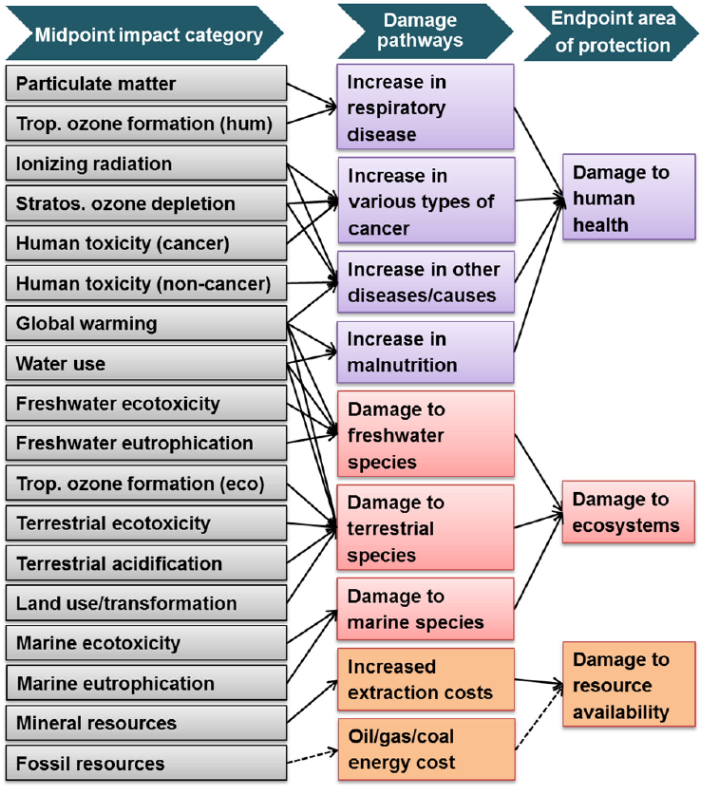
- Life cycle impact assessment (LCIA) phase of LCA — Environmental profile w. wide range of perf. indicators

- 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 ($)

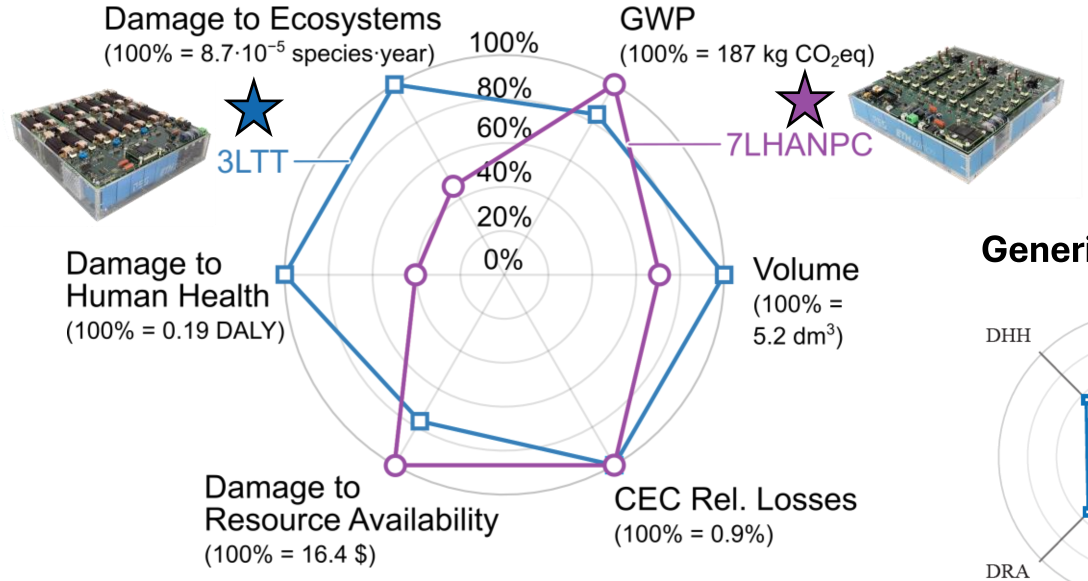


Source: Huijbregts et al., ReCiPe 2016 v1.1 Report

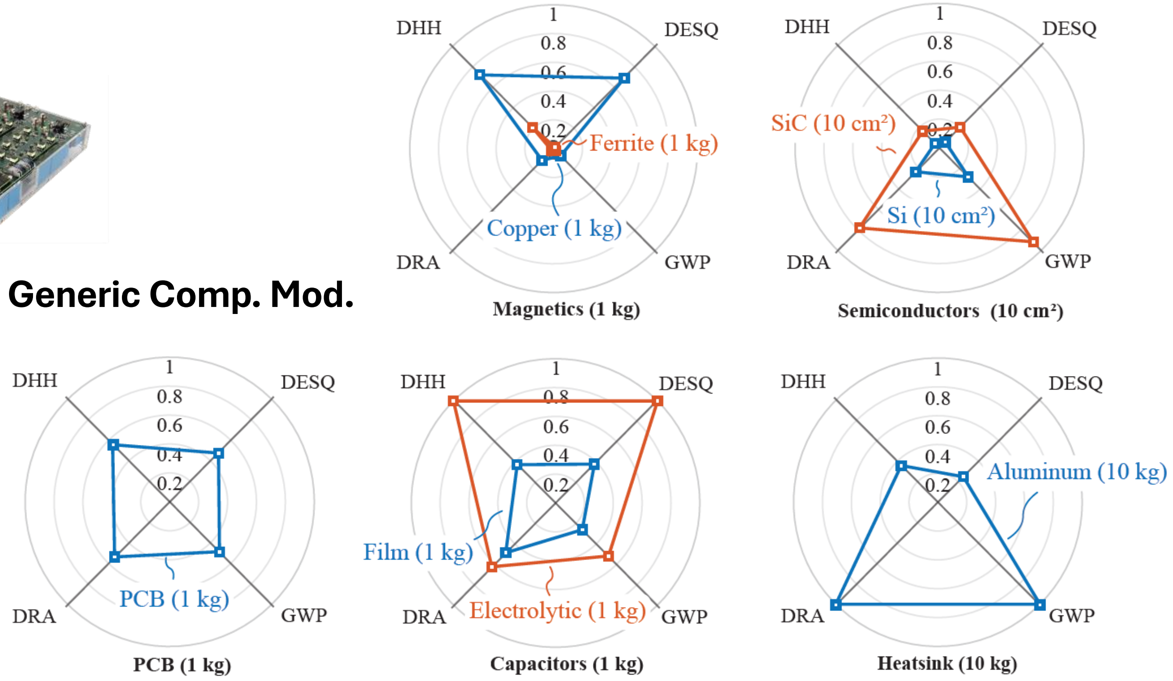
- Value choices (individualist / hierarchist / egalitarian) affect time horizon, included effects, etc.
- Alternative frameworks like EU Environmental Footprint (EF 3.1) exist

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)



Generic Comp. Mod.



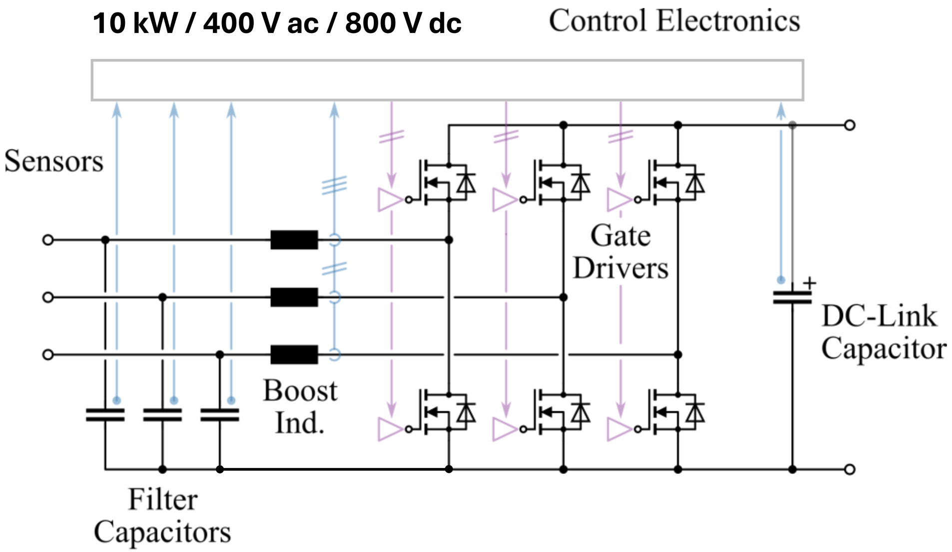
Normalized scales due to ecoinvent licensing restrictions.

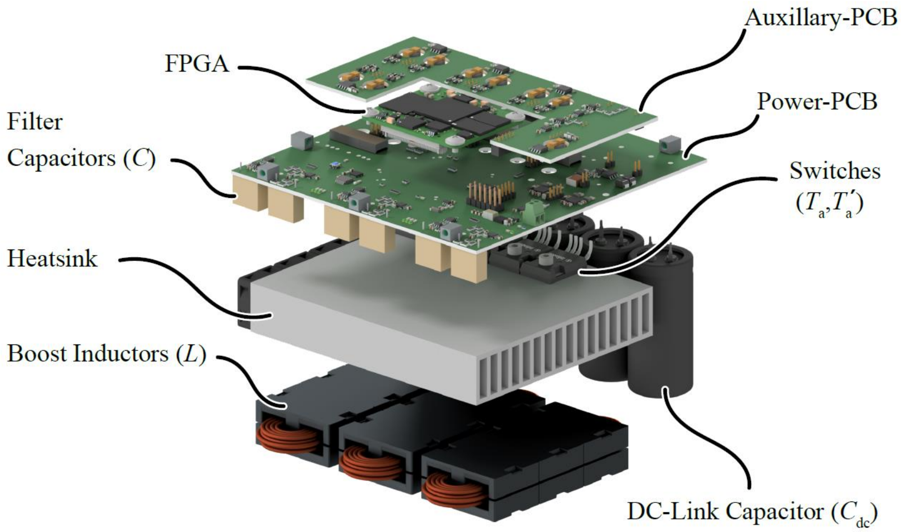
- **Environmental footprint of converter as aggregate of components' environmental footprints**

A Priori Consideration of Environmental Impacts in the Design Process? →

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

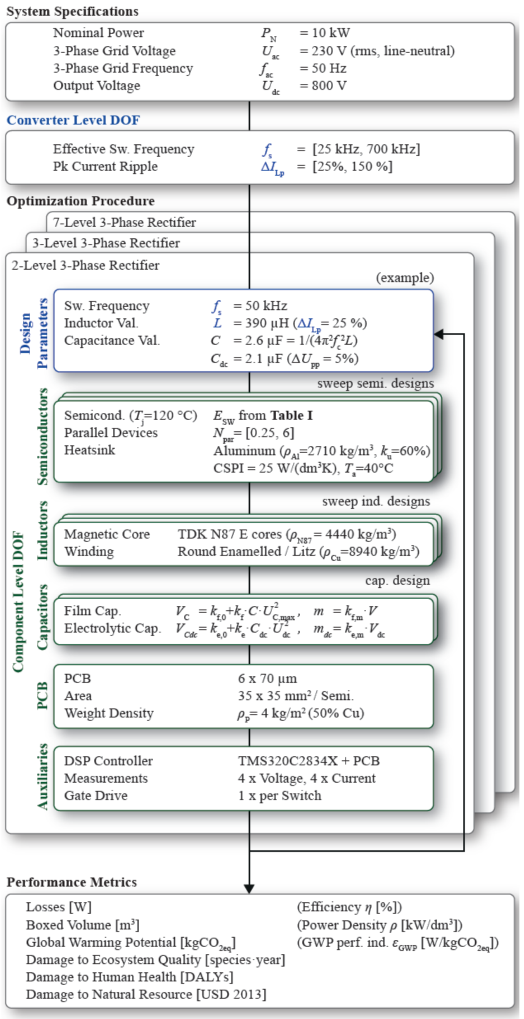
- Key power electronic building block (PEBB) for three-phase PFC rectifiers & inverters

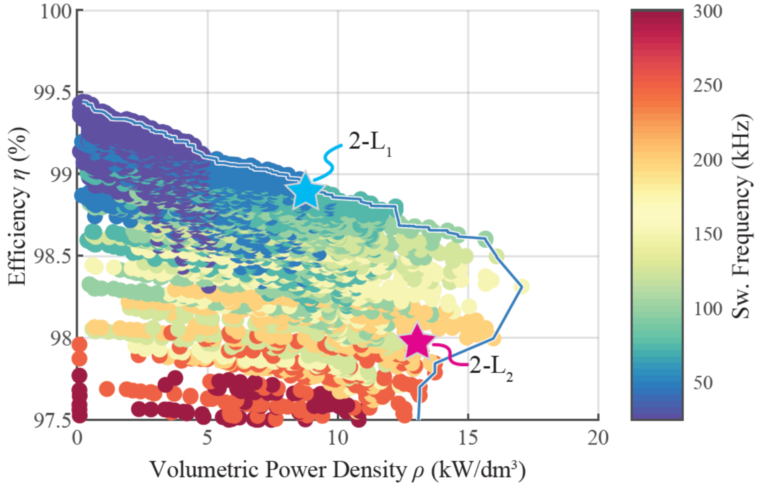


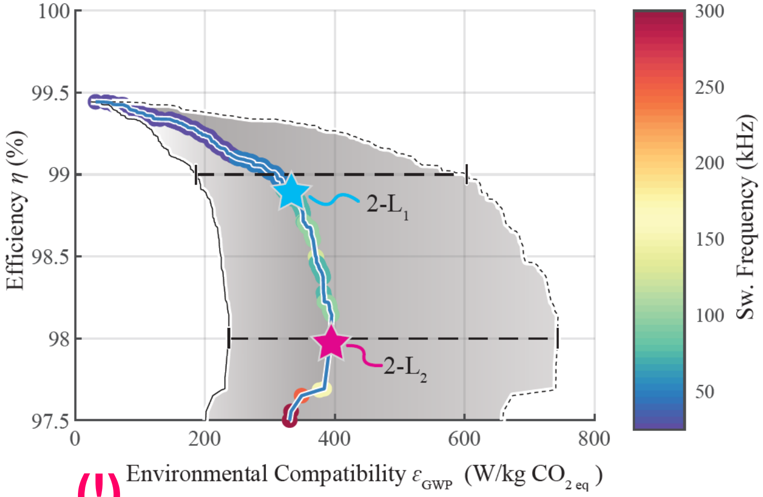


- **Degrees of freedom:**
  - Switching freq. [25...700 kHz]
  - Rel. Ind. Peak cur. ripple [0.25...1.5]
  - Var. transistor chip area
  - Variable ind. size (N87; solid/litz)
- **Assumptions:**
  - Junction temp. @ 120 °C
  - Ambient temp. 40 °C
  - Necessary heat sink vol. via CSPI = 25 W/(K dm^3)

Multi-Objective Optimization Including Env. Impacts (1)



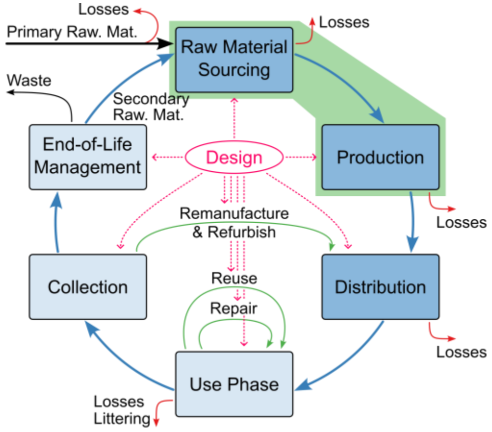




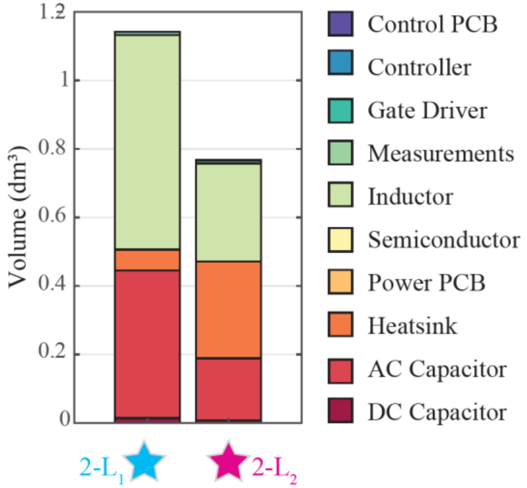
(!)

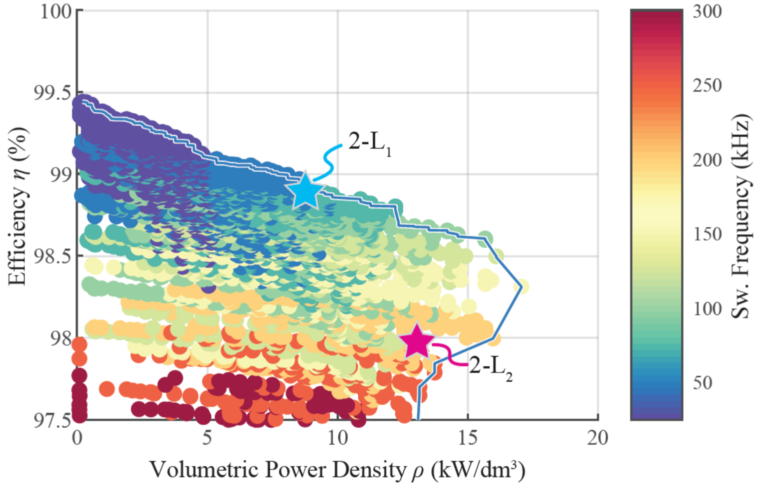
- **Trade-Offs**
  - Efficiency vs. power density
  - Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)

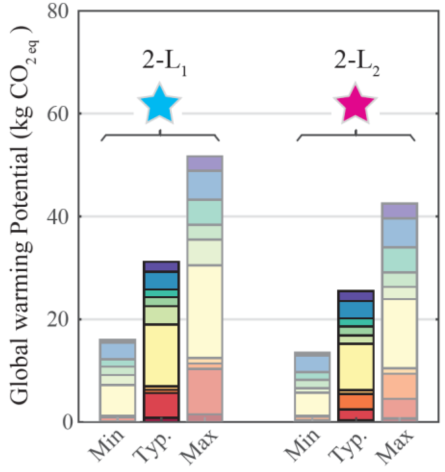
- **Env. Impacts with high uncertainties due to data availability/quality**

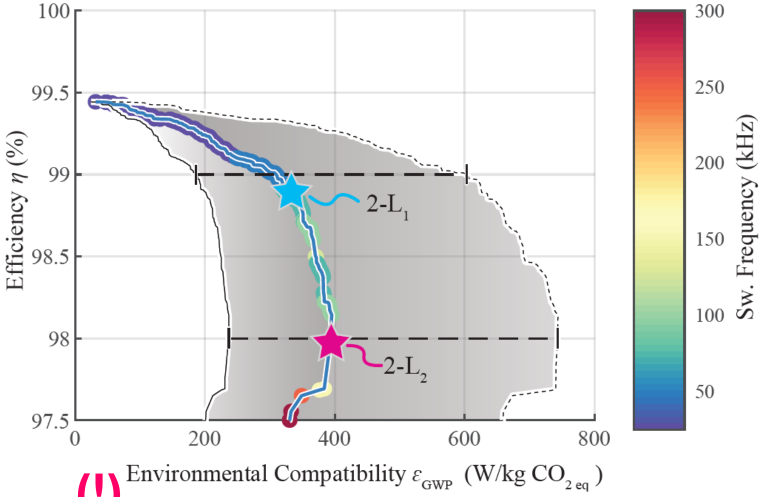


Multi-Objective Optimization Including Env. Impacts (2)



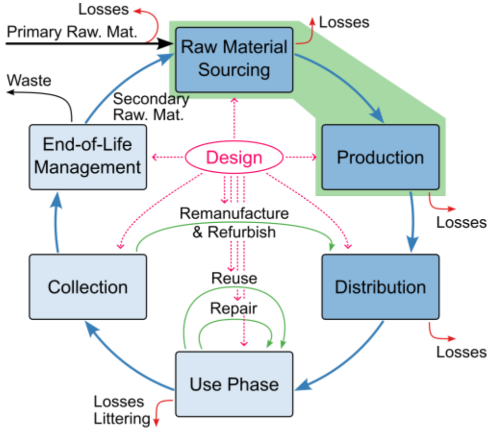






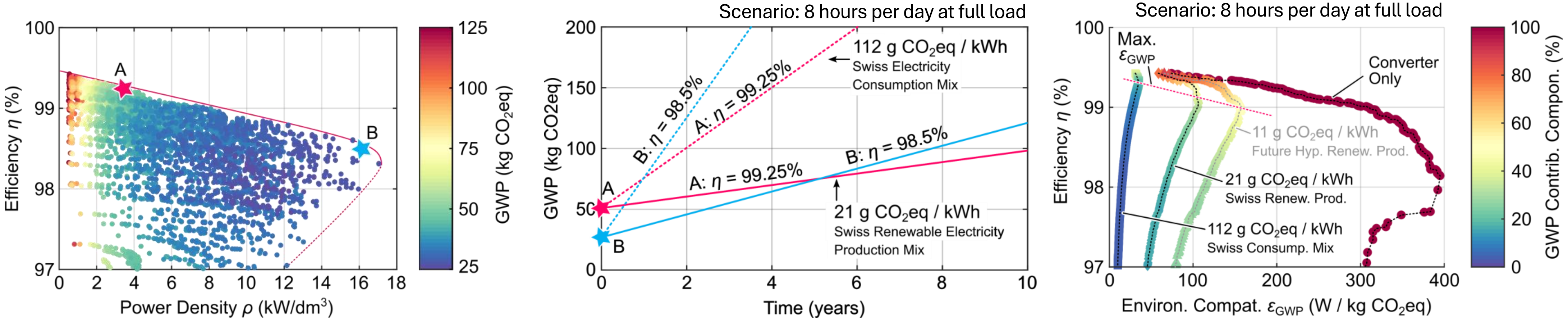
(!)

- **Trade-Offs**
  - Efficiency vs. power density
  - Efficiency vs. environmental compatibility regarding embodied GWP (carbon footprint)
- **Env. Impacts with high uncertainties due to data availability/quality**



Multi-Objective Optimization Including the Use Phase

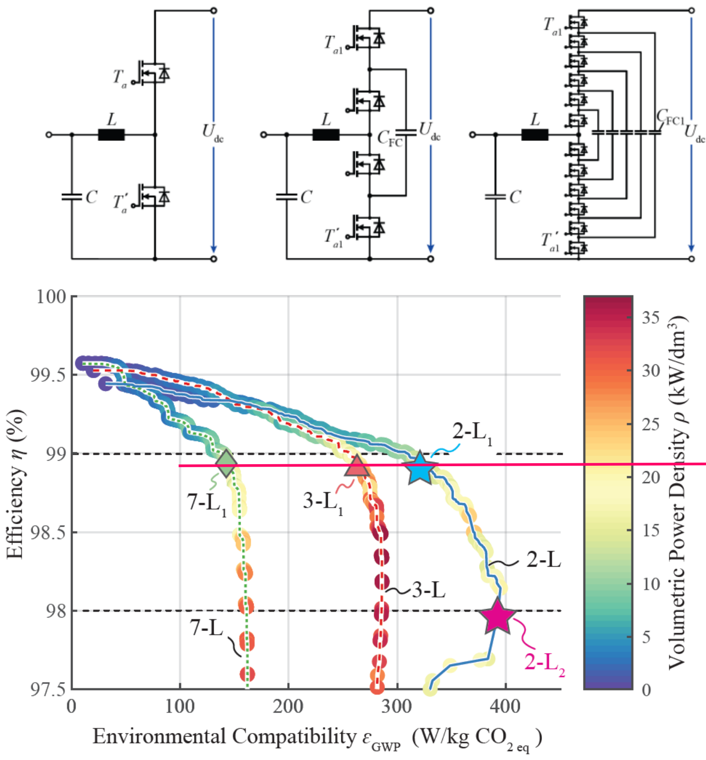
- Life-cycle carbon footprint strongly depends on electricity mix and mission profile / usage intensity

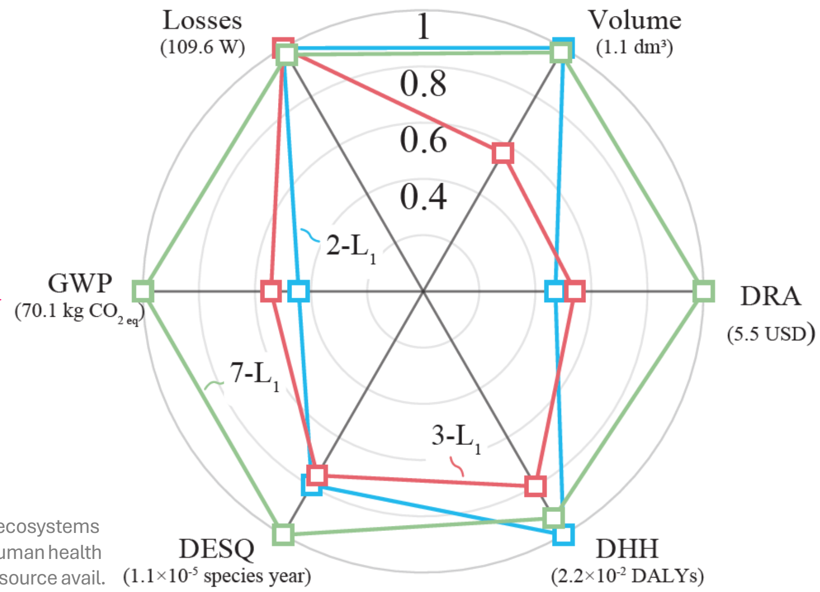


- Design should consider use phase for best life-cycle performance
- Analogy to total cost of ownership (TCO) perspective

Comprehensive Environmental Impact Profiles

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





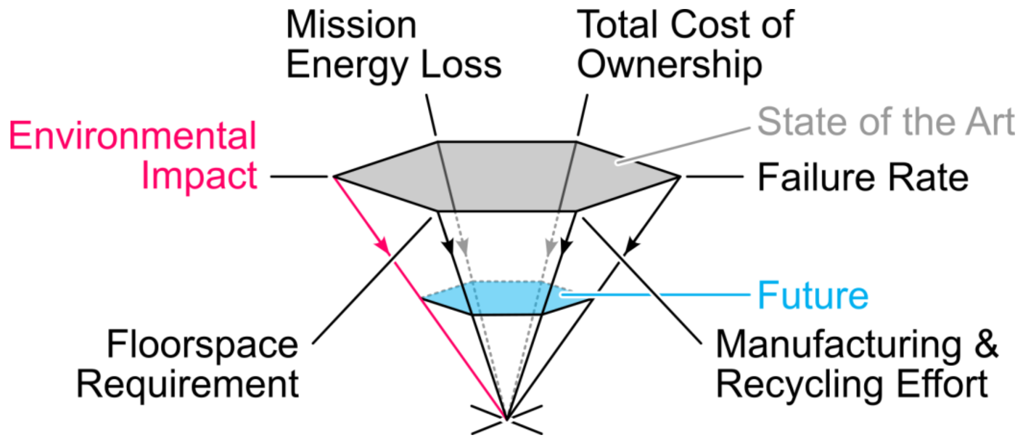
ReCiPe 2016:
DESQ—Damage to ecosystems
DHH—Damage to human health
DRA—Damage to resource avail.

- Embod. env. 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**

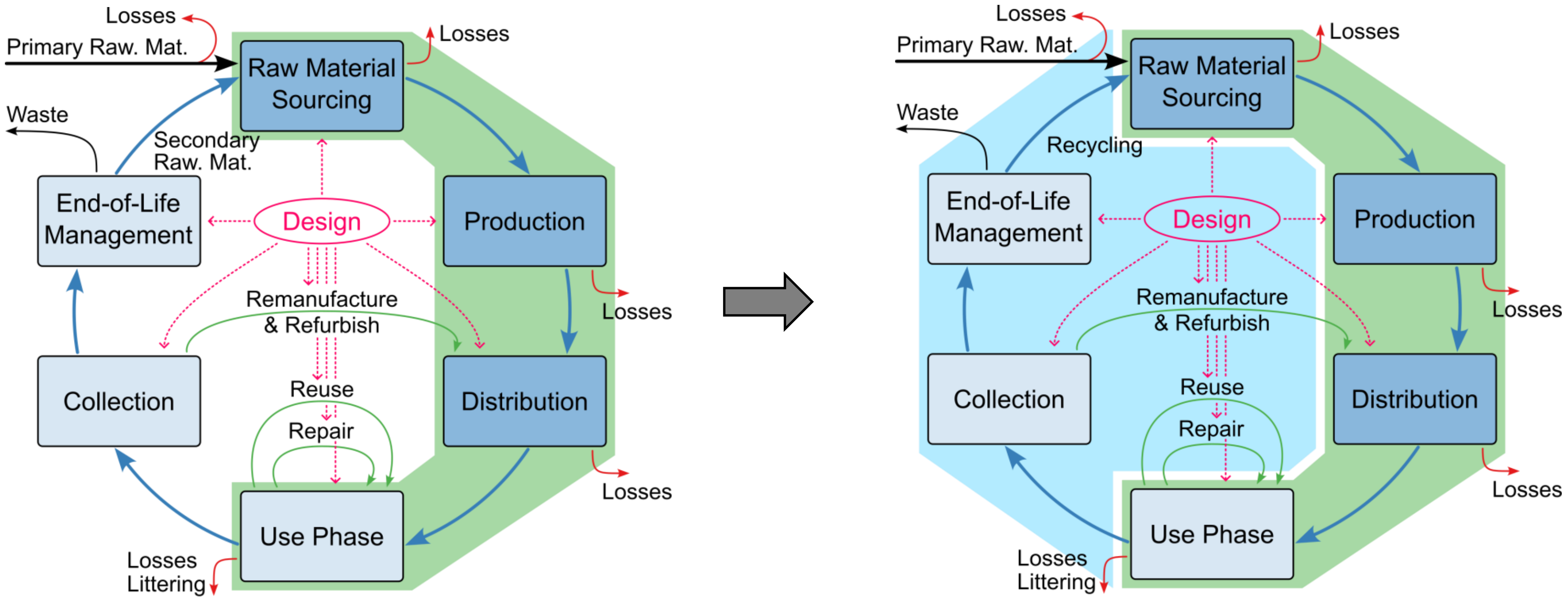
- **Complete set of new performance indicators**
  - Environmental impact [kg CO_2eq / kW, ...]
  - Resource efficiency [kg_{xx} / kW]
  - Embodied energy [kWh / kW]
  - TCO [$ / kW]
  - Power density [kW/dm^3, kW/dm^2]
  - Mission efficiency [%]
  - Failure rate [h^{-1}]



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

Power Electronics 5.0: “Zero Waste”

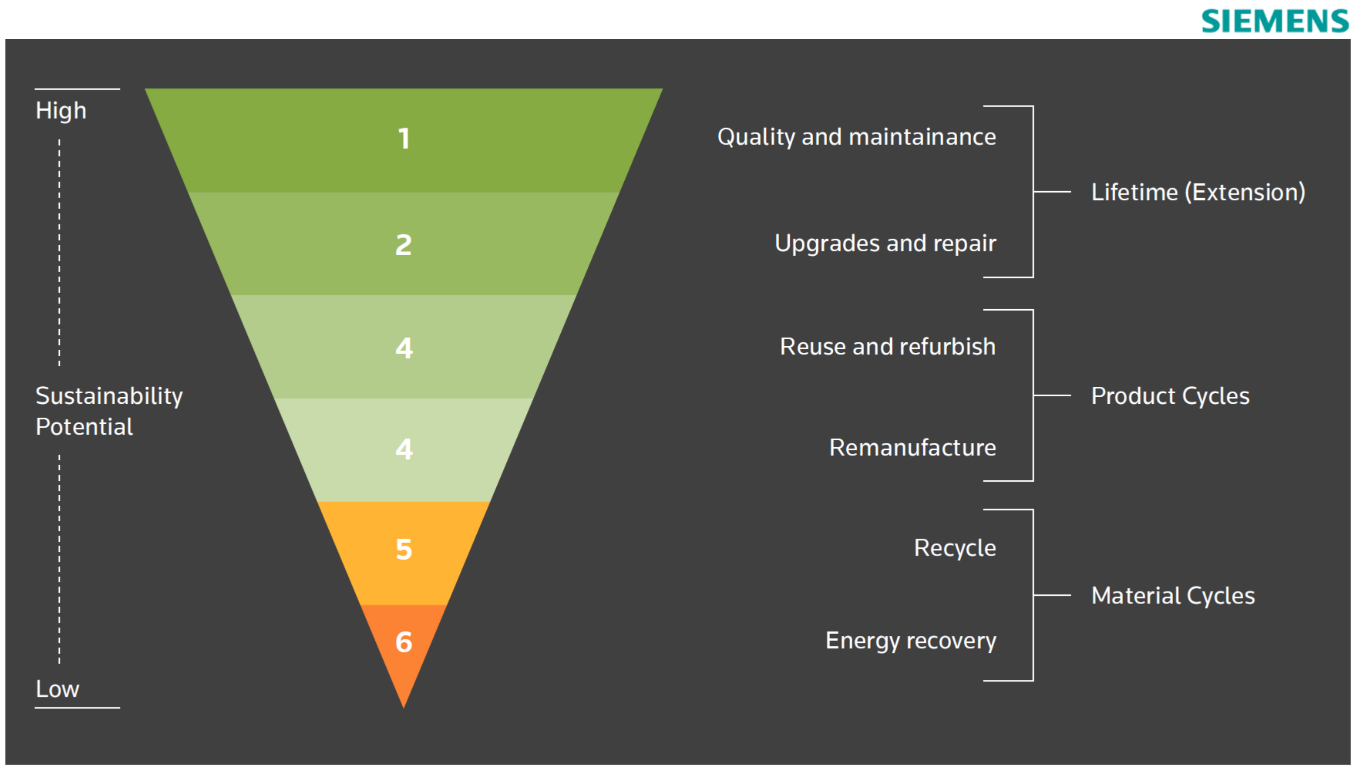
- Including 4R into the design process — Repair / Reuse / Refurbish / Recycle
- Lifetime extension / reliability considerations are a key design aspect



- Life-cycle cost perspective — Potentially advantageous for suppliers & customers

Sustainability Potential

- 2nd ELLEN MACARTHUR FOUNDATION circular economy principle: Circulate products and materials at their highest values



- High reliability / lifetime extension → Lifetime / aging modeling

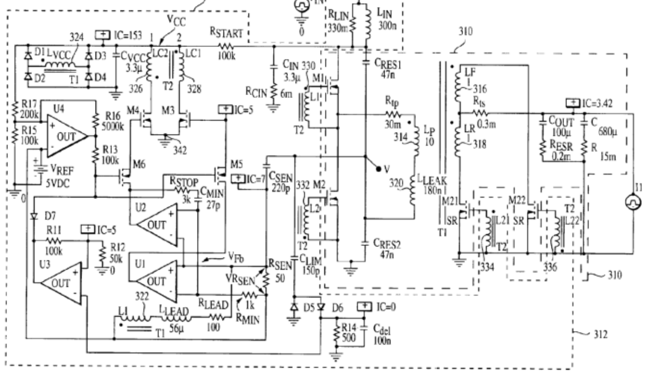
Source: SIEMENS AG, "Towards a circular economy for industrial electronics." Reuters Events, Jun. 2023. https://www.siemens.com/global/en/company/about/businesses/smart-infrastructure/downloads-events/towards-a-circular-economy-for-industrial-electronics-white-paper.html

Integration: Minimize Size / Initial Resource Usage

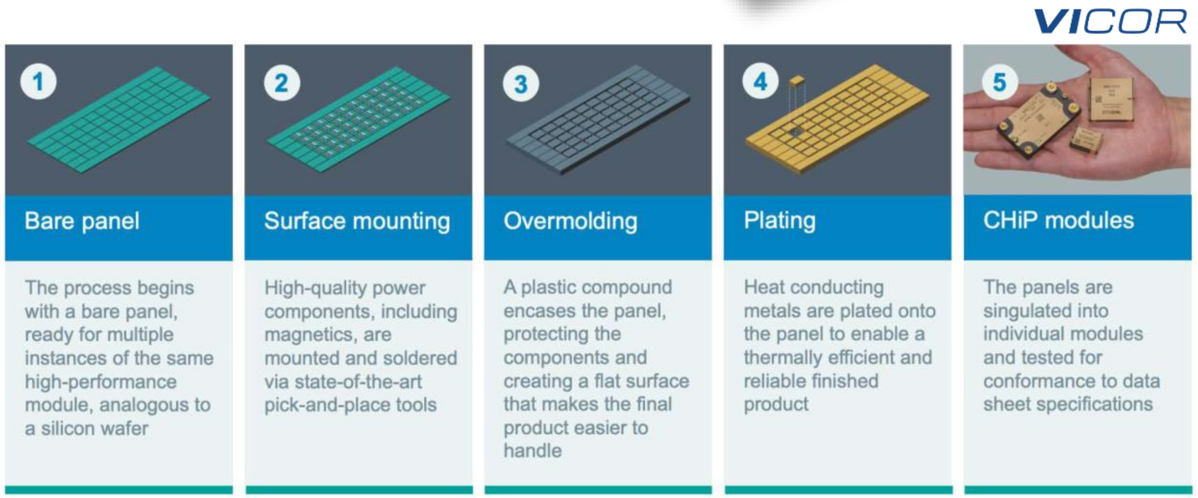
- **Maximum integration facilitates extreme power densities (10…100 x conv.)**
  - Example: 30 kW non-isolated fixed-ratio conversion (400 V to 800 V) in 92 x 80 x 7.4 mm^3 — 550 kW/dm^3 and 130 kW/kg

- **Low initial material usage ↔ Difficult material separation**
- **Importance of recyclability?**

FIG. 35



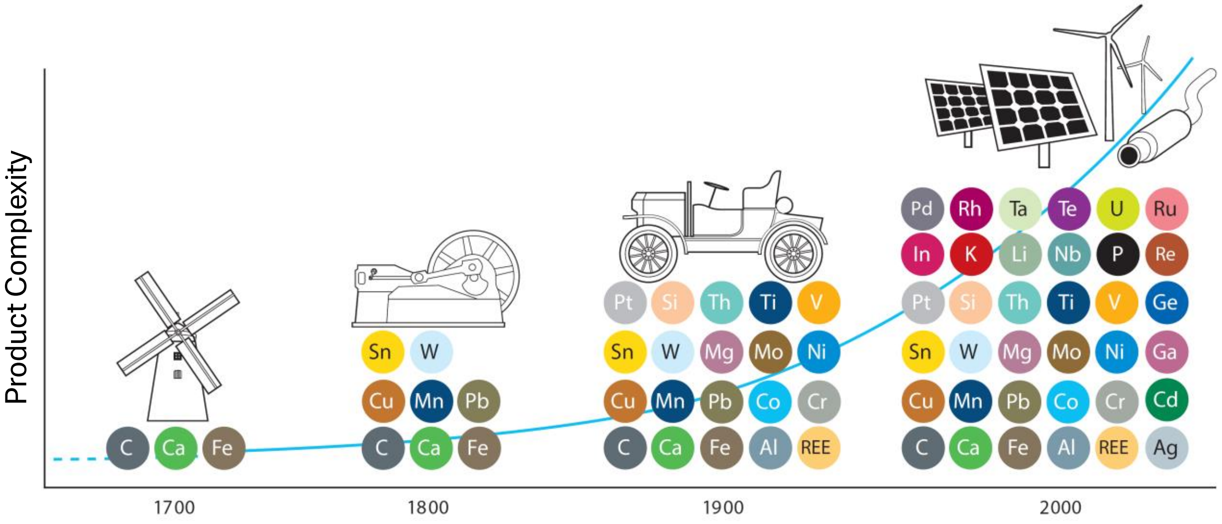
Example: Isolated dc-dc



Sources: vicorpower.com, US6930893B2

The Complexity Challenge

- Technological Innovation — Increasing level of complexity & diversity of modern products
- Exponentially accelerating technological advancement (R. Kurzweil)



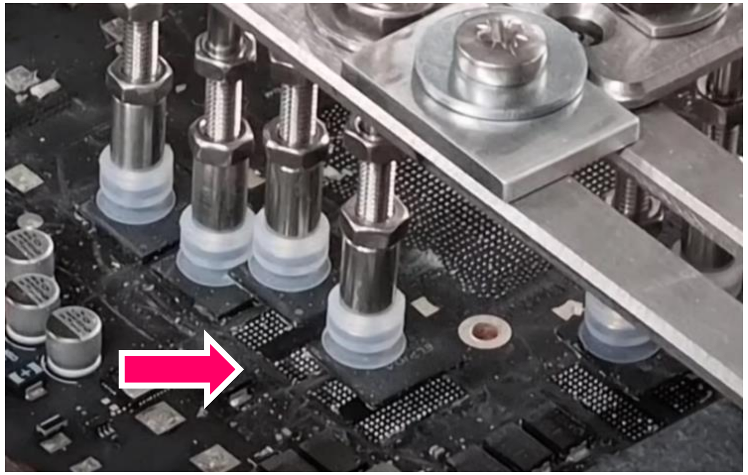
Source:
Materials Critical
to the Energy Industry
An introduction

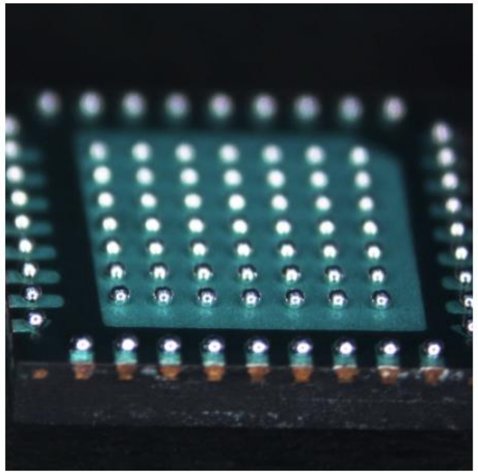
- More than 60 Metallic Elements Involved in Pathways for Substitution of Conv. Energy Systems
- Ultra-compact systems / functional integration — Major obstacle for material separation!?

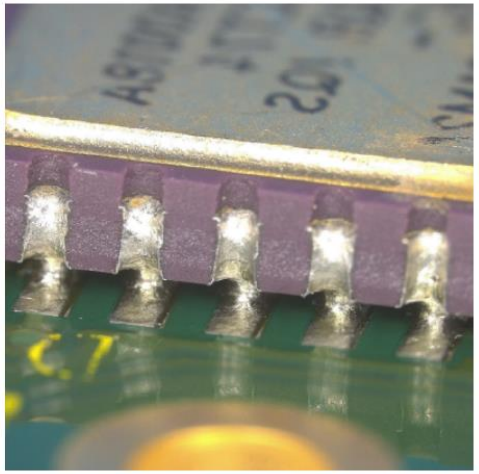
Remark: Electronic Component Reclaim / Reuse

- Electronic waste recycling today: Shred / incinerate / extract most valuable resources — if at all!
- Alternative: Reclaim & refurbish / Desolder & re-ball

RETRONIX
A JABIL COMPANY





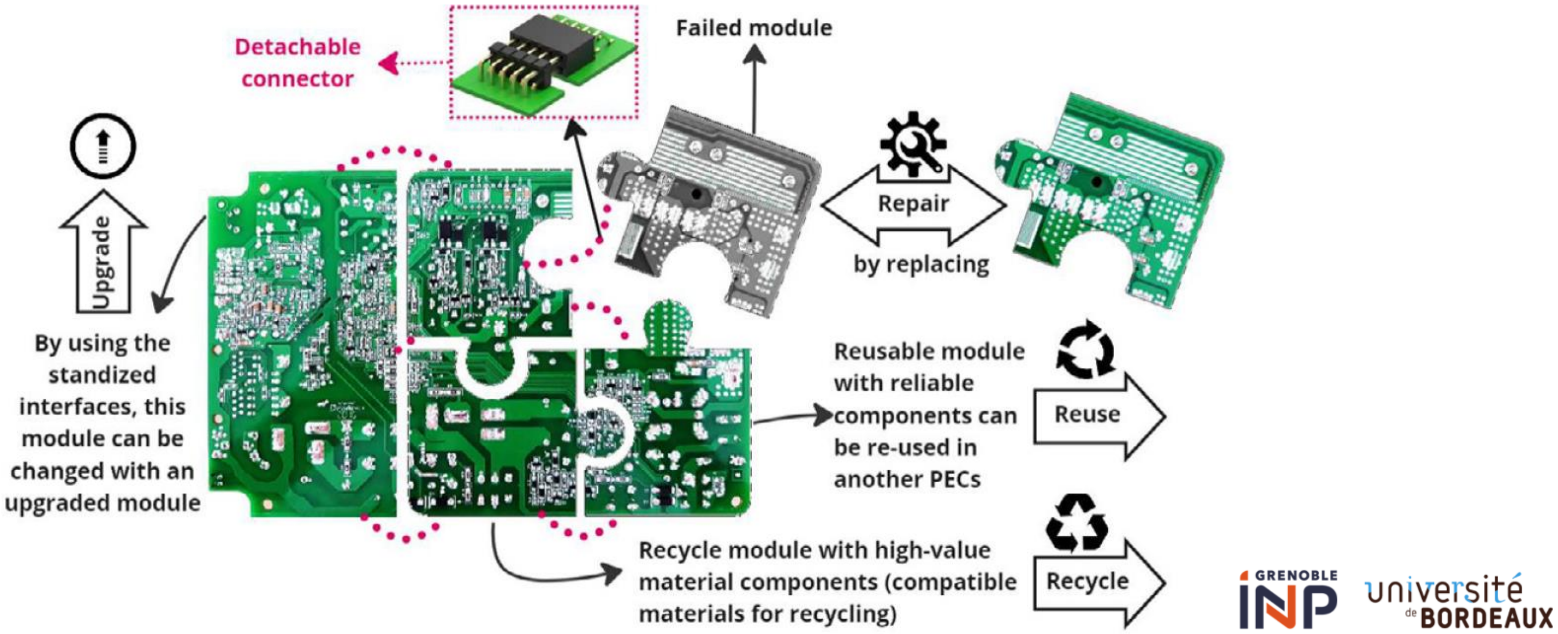


- Challenging logistics etc. for reclaiming PCBs from customers / Circular economy thinking needed
- Business case today especially for scarce / valuable components

Source: https://retronix.com/component-reclaim/

Modularity: Upgrade, Reuse, Repair, ...

- Module design for ease of disassembly: Maintainability, upgradability, repairability, reusability, recyclability



- Grouping of components according to reliability level and expected lifetime / level of reusability or recyclability / ...
- Standardized interfaces / Mechanically loose connections ↔ Electrical characteristics
- Potential for leveraging economies of scale to compensate interface costs

Source: T. T. Romano, T. Alix, Y. Lembeye, N. Perry, and J.-C. Crebier, "Towards circular power electronics in the Perspective of modularity," *Procedia CIRP,* vol. 116, pp. 588–593, Jan. 2023, doi: 10.1016/j.procir.2023.02.099.

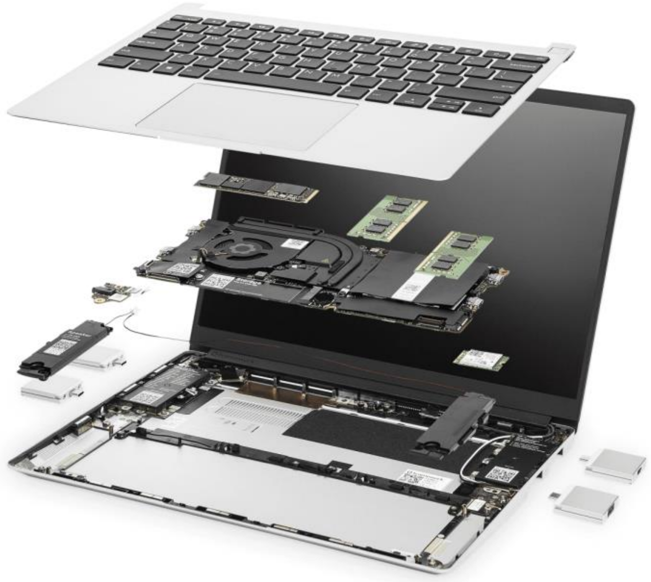
Design for Repairability & Circularity

- **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 (!)

5 YEARS WARRANTY

Source: www.ligman.com/

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



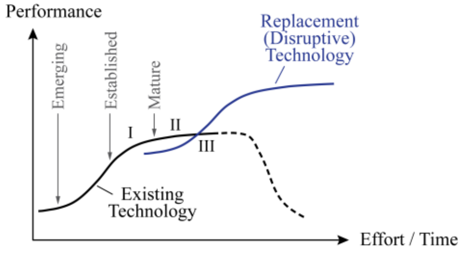
Source: Life Cycle Assessment of the Framework Laptop 2022, Fraunhofer IZM

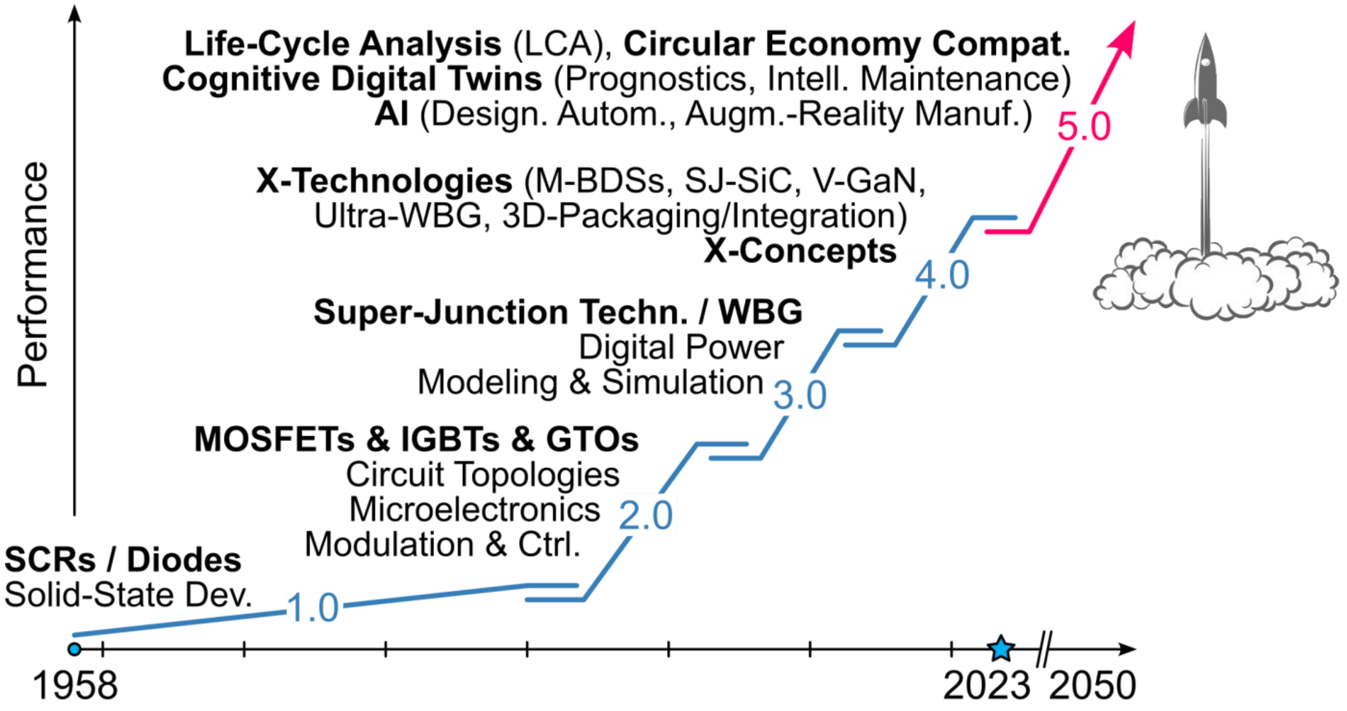
- **FAIRPHONE** — Modular design / man. replaceable parts / 100% recycl. of sold products / fairtrade materials
- framework laptop **"You should be able to fix your stuff."** — Modular design / man. replaceable parts
- **"80% of environmental impact** of products are **locked-in at the design stage"** — J. Thackara, *In the bubble: Designing in a complex world*. Cambridge, MA, USA: The MIT Press, 2006.

Conclusion & Outlook

Power Electronics 5.0

- Power Electronics 1.0 → Power Electronics 5.0
- X-Technologies & X-Concepts
- New main performance indicators (!)





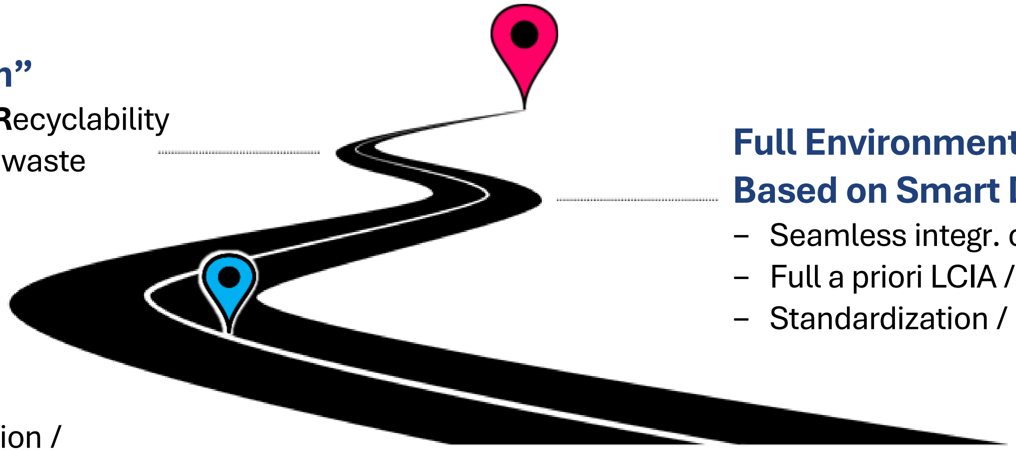
- Life-cycle analysis / circular economy compatibility are key for sustainable Power Electronics 5.0

Source: 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.

CEC Power Electronics Roadmap

- **Environmental awareness as integral part of environmentally conscious 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

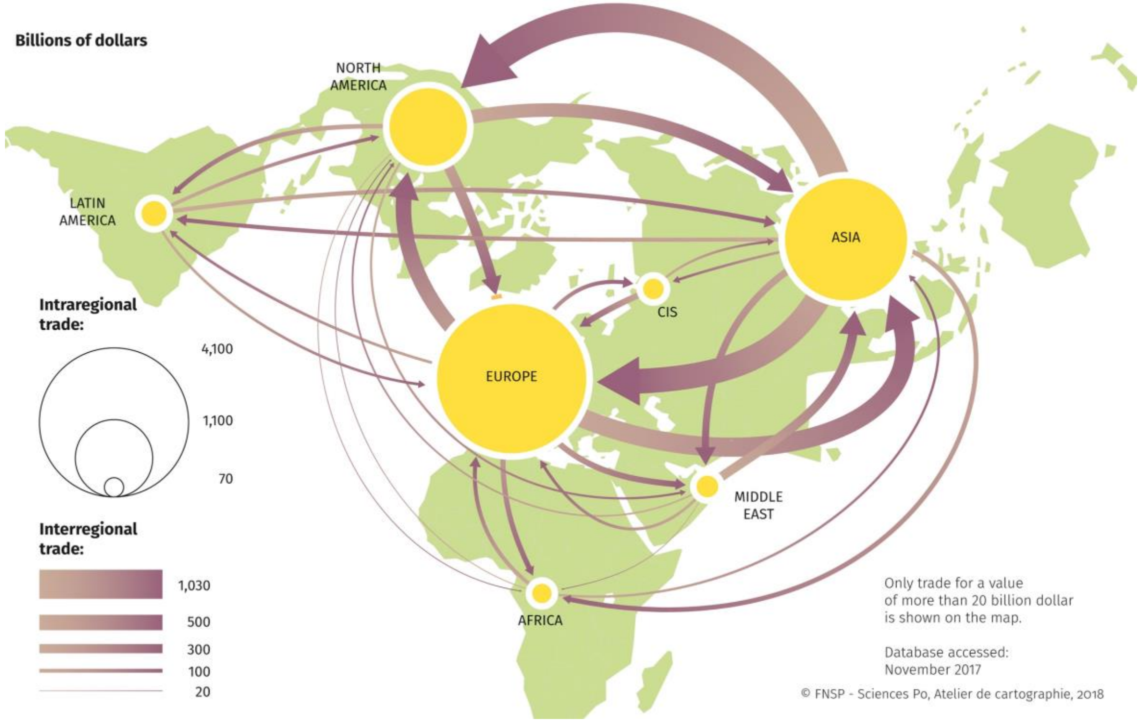
Generic Life-Cycle Impact Analysis (LCIA)
- New KPIs in multi-obj. opt.
- Data sources / quality / abstraction / generalization as key challenges

Classical $\eta\rho$-Pareto Optimization / Design
- Manual a posteriori LCA of complete converters

- **Automated design | On-line monitoring | Preventive maintenance | Digital product passport**

Economic Challenges of NZ by 2050

- *Globalization / Global Trade — Complex Couplings / Interdependencies of Main Economies*
- *No Immediate Reward BUT Massive Costs / Political Challenges of NZ-by-2050 Trajectories*



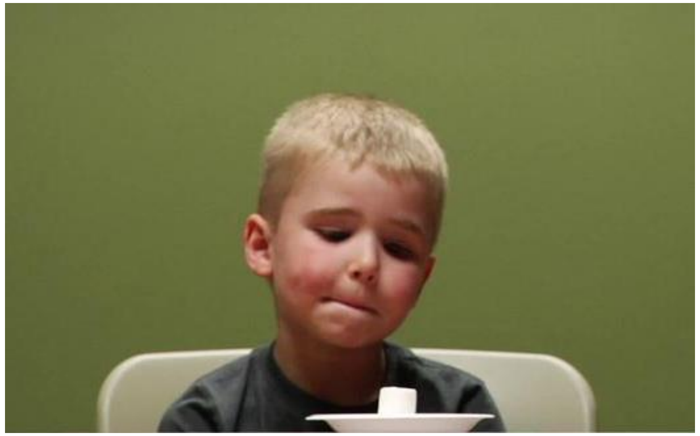
- *Environmental Impact Aggregates Over Time — No Serious $$$-Consequences / "Tragedy of Commons"*
- *"Prisoner´s Dilemma" — Why Take Action If You Can´t Be Sure Other Countries Will Act As Well?*

Remark The NZ-by-2050 “Marshmallow Test”

- *“You Can Have One Marshmallow Now, OR, If You Wait, You Can Have Two” (!)*
- *Experiment Measuring Children’s Ability to Self-Control / Delay Gratification (W. Mischel / Stanford / 1960s)*

Source: https://www.edbatista.com/

HIGHBROW



- *“You Can Have One Marshmallow Now, OR, If You Wait, Others Will Take It” (!)*
- *“Instant-Effortless-Everything”- Society Might Face Serious Challenges Passing the NZ-by-2050 Marshmallow Test*

Develop a Global "Clean Energy Moonshot Spirit"

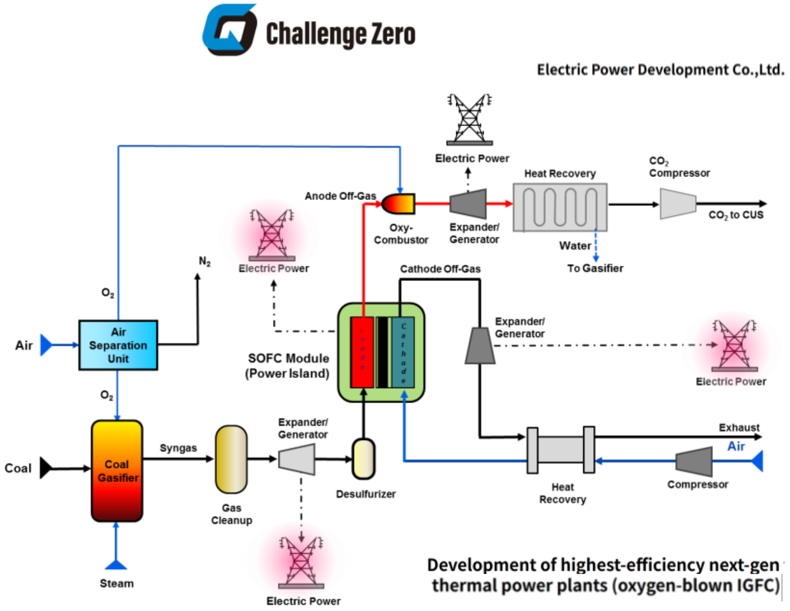
- *Aim for a Net-Zero/Environmentally-Neutral Integrated Multi-Carrier Energy System*
- *Full "Circularity" (Closed Carbon Cycle & Raw Materials Cycle, etc.) / Sustainability / etc.*

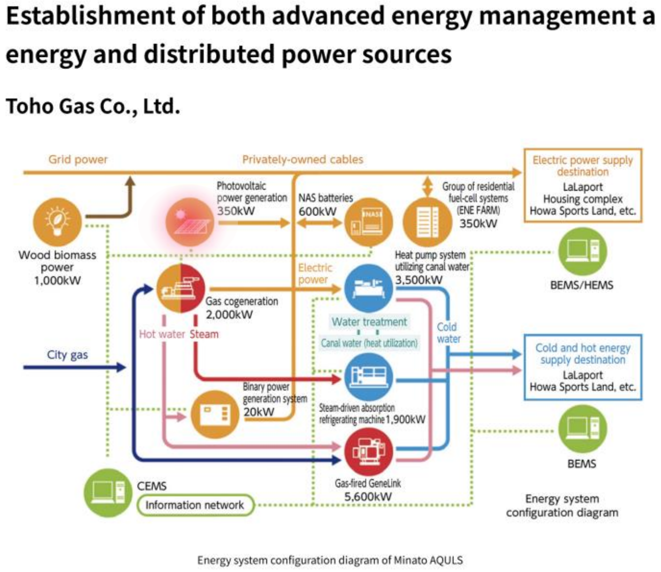
„We choose to go to the Moon in this decade, ..., not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our engineers and skills – because that challenge is one we are willing to accept, one we are unwilling to postpone, and one we intend to win!"

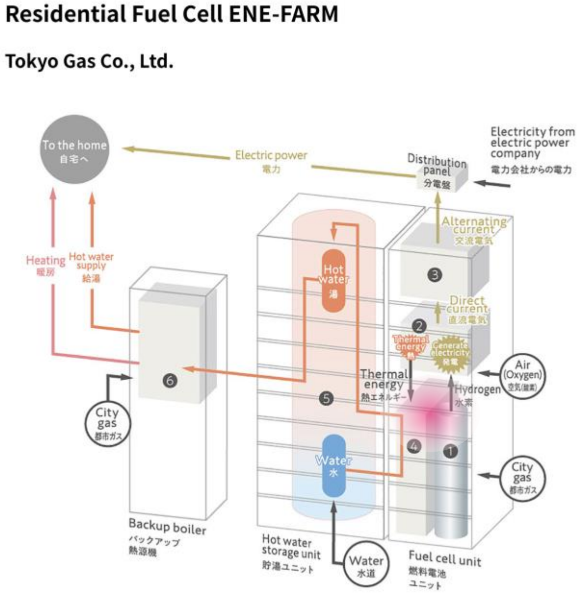
- *Power Electronics Engineers are the Rocket Scientists of the 2020´s (!)*
- *"Transformational Industrial Clusters" (El. Energy, Chemistry, Microbiology, etc.) & "First Mover Coalitions"*

Challenge Zero & "Green Growth" Strategy Japan

- "Challenge Zero" — A New Action by Japanese Industry in the Field of Climate Change (2020)
- 200 Members / 400 Projects on Zero Emission & Transition Technologies



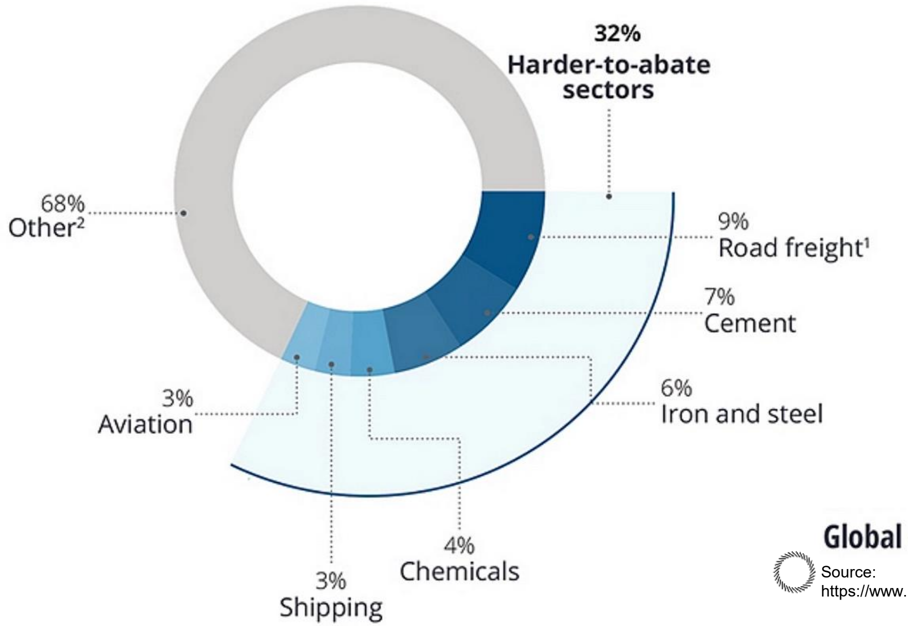




- Very Wide Range of Topics — WBG Power Semiconductors / Power-to-Chemicals / Red.-CO_2 Steel etc.
- "Green Growth" Strategy — 14 Focus Areas Announced (2021) – Asia Zero Emission Community (2023)

Power Electronics for New / "Hard-to-Abate" Sectors

- *Sometimes Named "Horseman of the Climate Apocalypse" — 30 Trillion USD to Achieve NZ by 2050*
- *Collectively Responsible for ≈30% of World´s CO_2 Emissions (Cement, Steel, Chemicals, Aviation etc.)*



Global carbon dioxide emissions by sector in 2018

Source: https://www.innovationen

- *Highly Interdisciplinary BUT Fascinating Opportunities for Future Power Electronics Applications (!)*
- *High-Eff./High-Dyn. Chemistry — Plasma Techn., Microwave Reactors, Pulsed Power, Cryog. Power Electr., etc.*

Thank You!

Further Reading

- L. Imperiali, R. Wang, A. Anurag, P. Barbosa, J. W. Kolar, and J. Huber, "Comparative analysis of carbon footprints and material usage of solid-state transformers and low-frequency-transformer-based MVac-LVdc interfaces for high-power EV charging," in *Proc. Appl. Power Electron. Conf. Expo. (APEC),* Atlanta, GA, USA, Mar. 2025.

- 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.

- J. W. Kolar, L. Imperiali, D. Menzi, J. Huber, and F. Musil, "Net zero CO_2 by 2050 is NOT Enough (!)," *Keynote at the 25th Europ. Conf. Power Electron. Appl. (EPE),* Aalborg, Denmark, Sep. 2023.