Advanced Mechatronic Systems Group

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Resource Efficient Circular Economy Compatible Power Electronics

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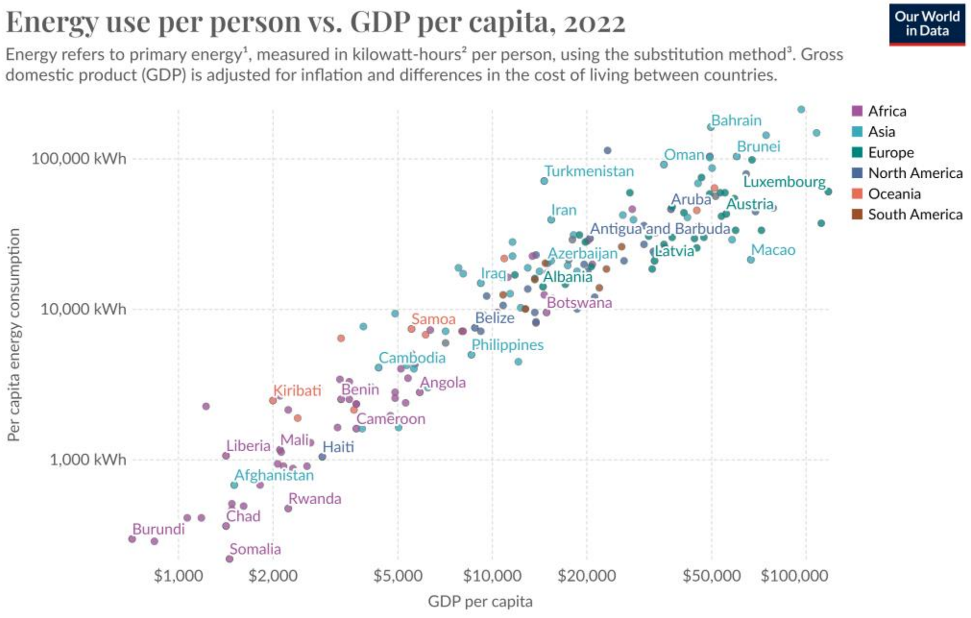
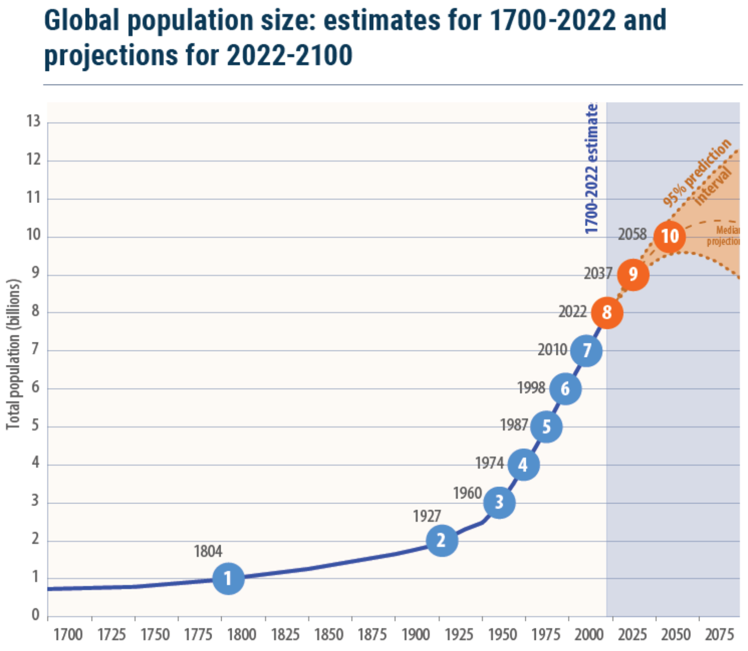
Outline

- Global Context & Challenges
- Renewable Energy
- Power Electronics 4.0: Do More with Less
- Power Electronics 5.0: Zero Waste

Future Growth of Energy Demand

- Relation of energy use & GDP/capita — **There are no low-energy rich countries (!)**
- Population growth and energy use per capita increase — 1980: 4.4 bn, 10 TW yr → 2022: 8 bn, 20.4 TW yr





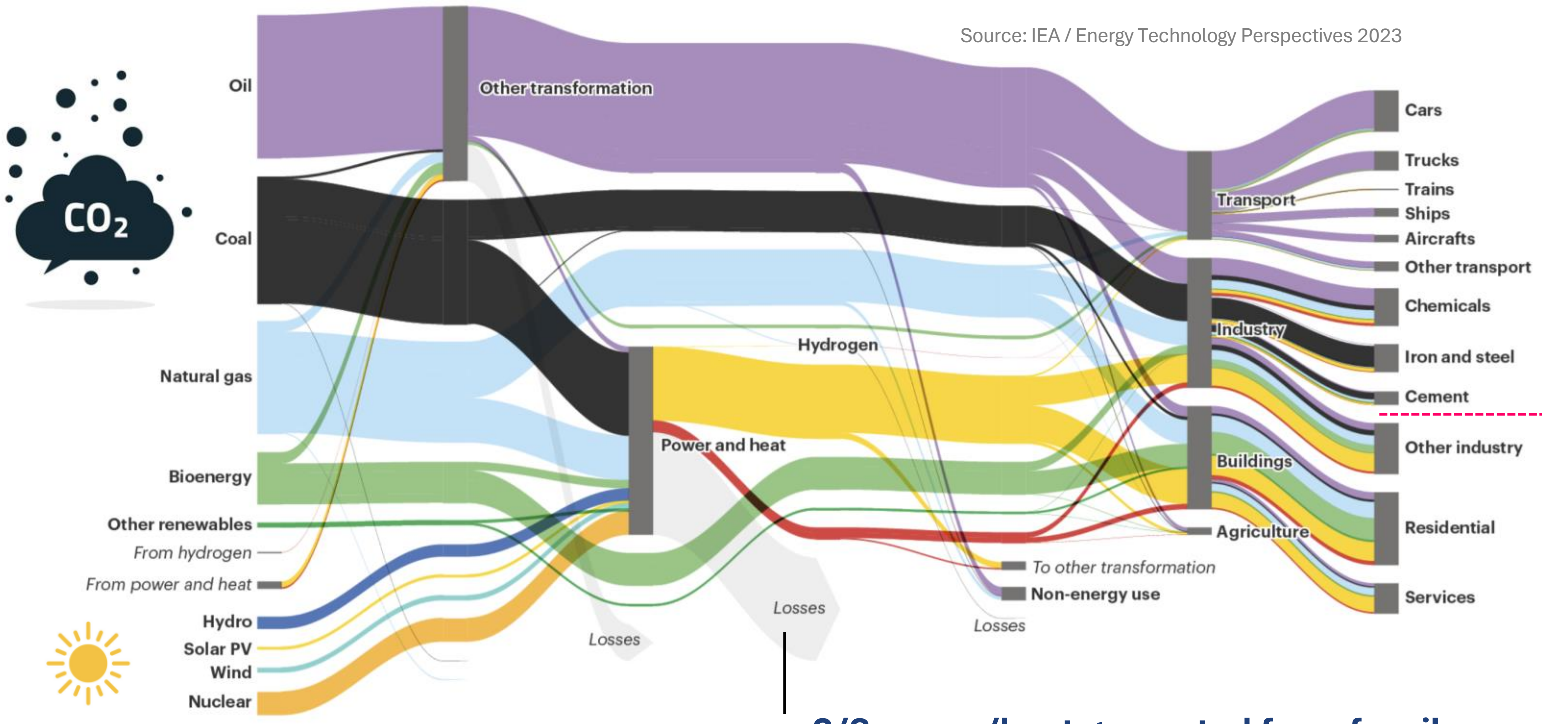
Source: United Nations, DESA, Population Division (2022). World Population Prospects 2022.

ENERGY TRANSITIONS COMMISSION

- Growing population & GDP — Increasing demand for energy services in developing countries
- +22% Population | +92% GDP/capita | -37% Energy intensity → **+50% Energy demand by 2040 globally**

Global Energy Use Today

- Global energy flows 2021



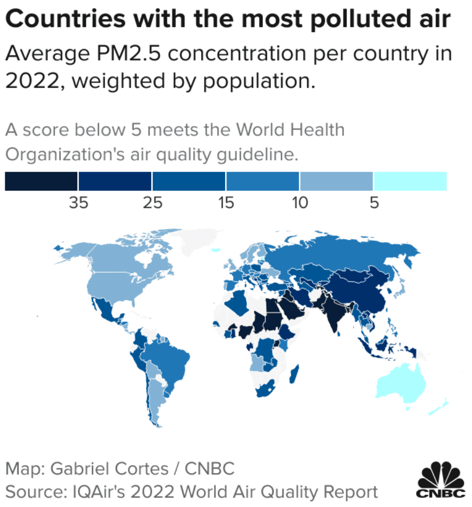
- Direct fossil fuel use in essential industries
  - **Transportation**
  - **Chemicals** (e.g., fertilizer)
  - **Steel** production
  - **Cement** production

- 2/3 power/heat generated from fossil fuels with low efficiency

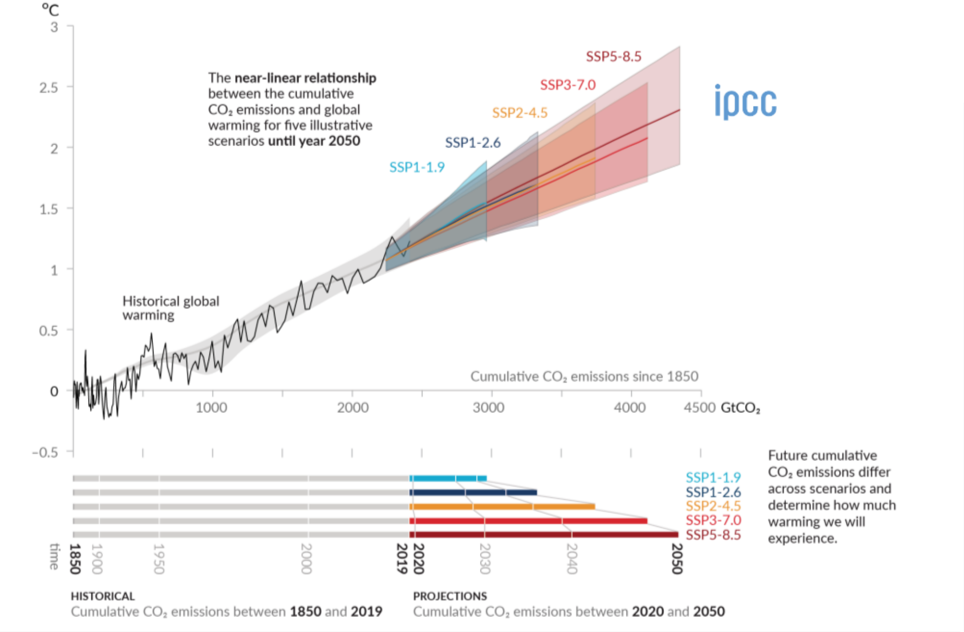
- Fossil fuels account for ≈ 80% of world's primary energy consumption

Consequences of Fossil Fuel Use

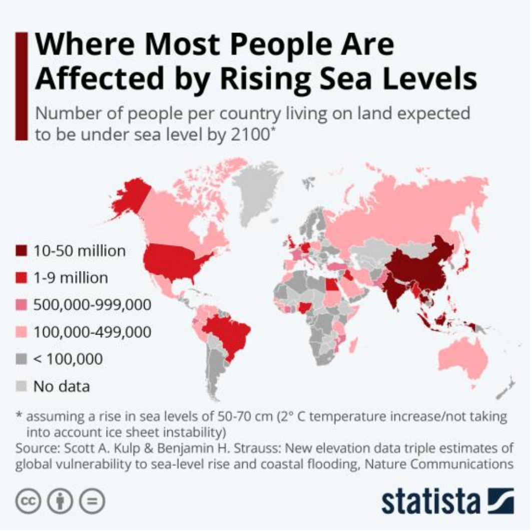
- **Air pollution — E.g., fine particulate matter (PM2.5) responsible for 8.7 mio. deaths p. a. globally**
- **Climate change — E.g., 200 mio. people will live below sea level line by 2100**



Global surface temp. increase vs. cum. CO_2 emissions



@ 2°C Temp. Increase

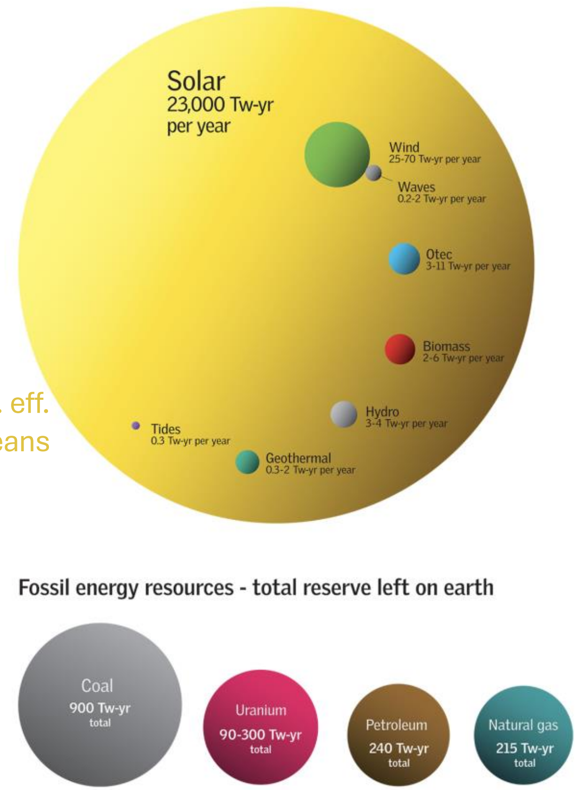


- **High import dependency of leading economies (e.g., Europe and Russian gas)**
- **As finite resources, fossil fuels are unable to sustain economic development in the long run (!)**

The Opportunity

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

Renewable energy resources per year



100% convers. eff.
Excl. oceans

Note: Graphical representation assumes spheres, not circles

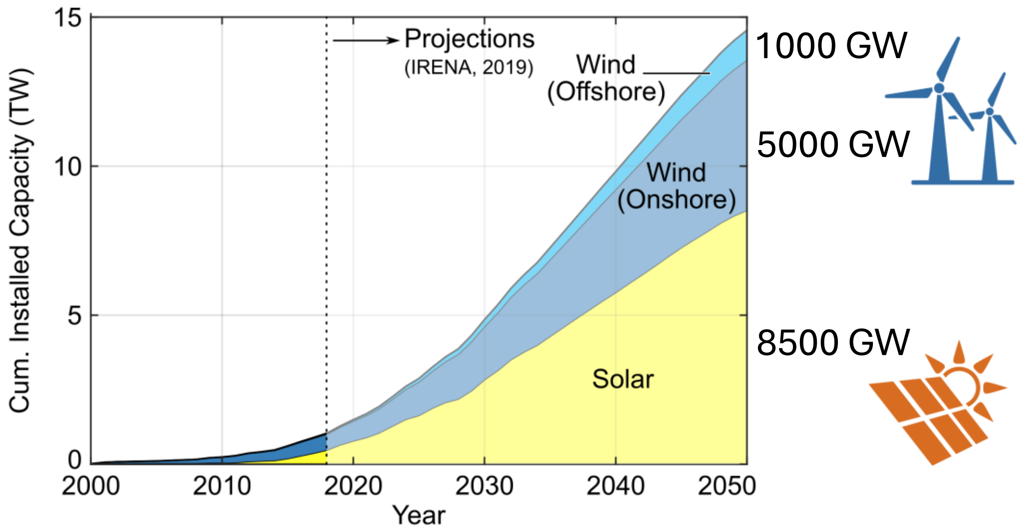
Primary consumption:
16 TWyr → 27 TWyr
Final consumption:
11 TWyr → 15 TWyr

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

Outlook of global cumulative install. until 2050

- In 2050 deployment of 370 GW/yr (PV) and 200 GW/yr (onshore wind) incl. replacements

Source: IRENA, Future of Wind / Future of Solar PV (2019)

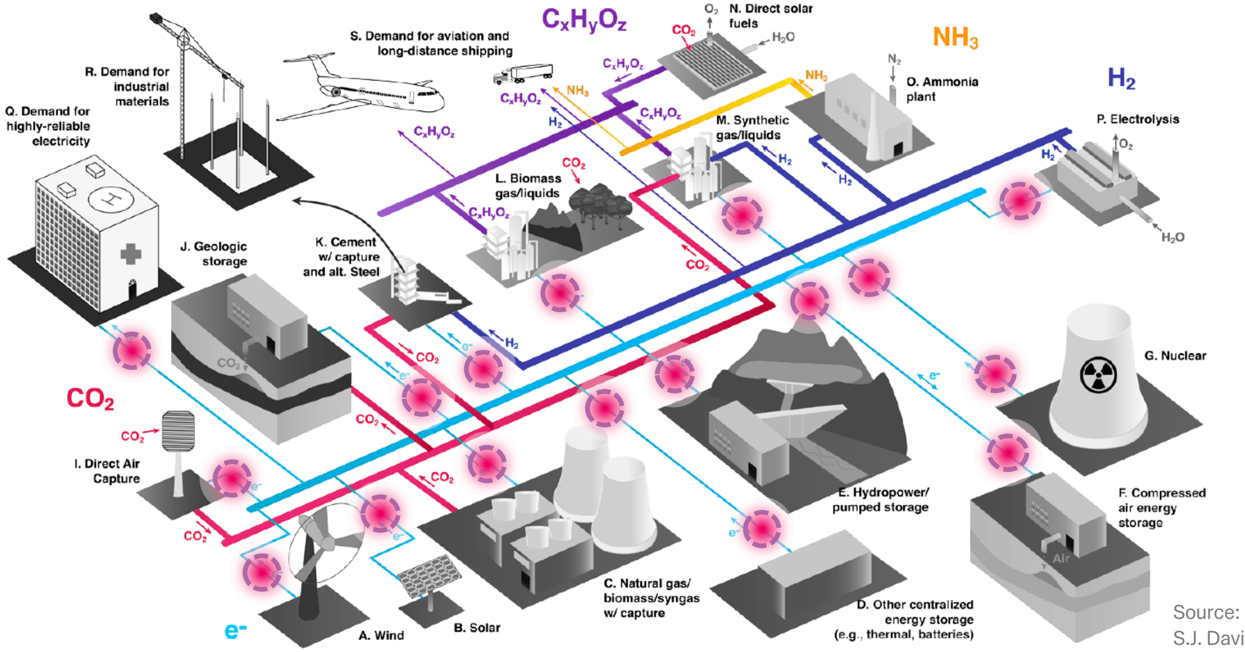


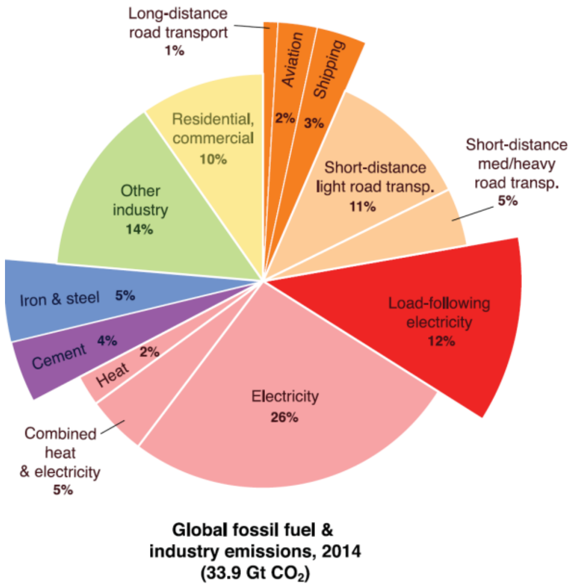
Challenges

- Energy storage (short-term, seasonal)
- Long-distance electricity transmission
- Sector coupling / Power-to-X

Net-Zero Multi-Carrier Energy Systems

- CO_2-free electricity / electrification / efficiency gains — Reducing emissions & costs (long term)
- *Not* all-electric — Iron & steel, cement, transportation, heating → Power-to-X and E-fuels w. low efficiency





Source:
S.J. Davis et al., *Science* (2018)

- Renew. gen. & cross-sector convers. — Heat pumps / electrolyzers / fuel cells / … → All dep. on power electron.
- Power electronics is a key enabling technology!

Critical Minerals/Metals

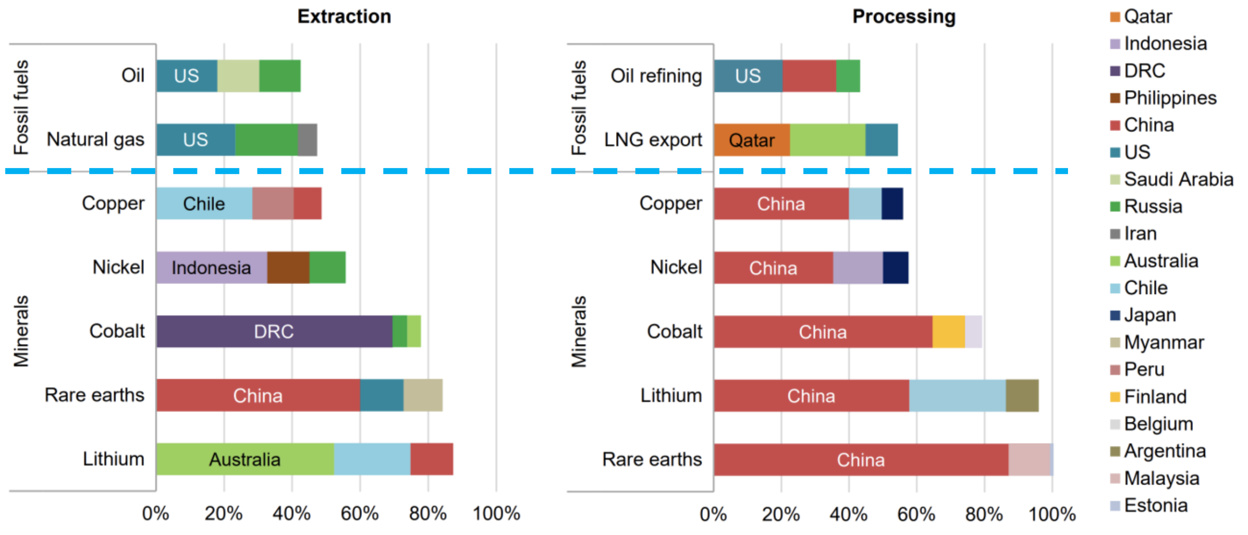
- **Minerals/metals supply shortages due to massive expansion of clean energy system**
- **Extraction & processing more geographically concentrated than for oil & gas (!)**

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.

BloombergNEF



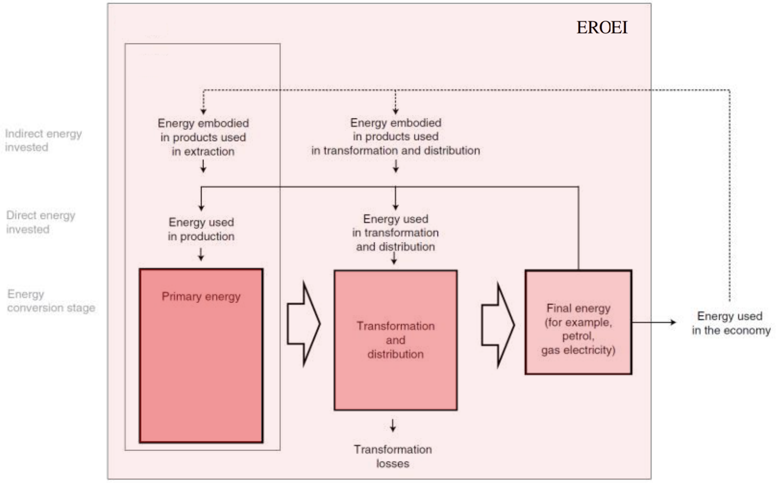
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

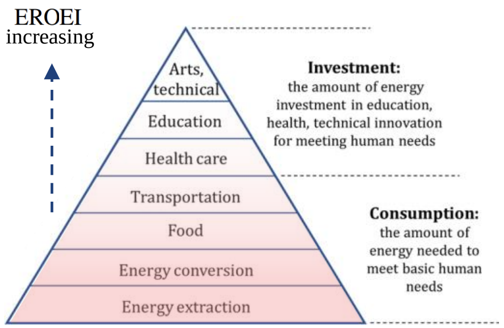
- **50 new lithium / 60 nickel / 17 cobalt mines required to meet 2030 EV battery demand**
- **EU Critical Raw Material (CRM) Act 2024 → Sustainability & circularity of CRMs on the EU Market**

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)**

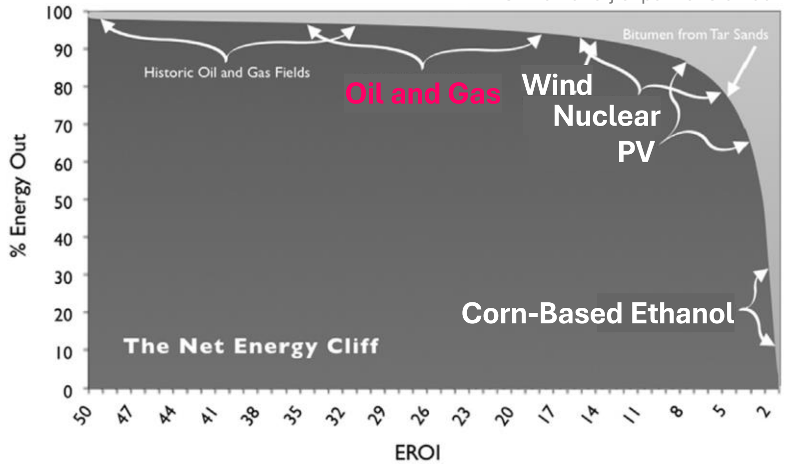
$$\text{EROI} = \frac{\text{Energy Obtained}}{\text{Energy required to obtain that energy}} \rightarrow \text{Net Energy} = \text{Energy Obtained} \cdot \left(1 - \frac{1}{\text{EROEI}}\right)$$





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

Source: J. G. Lambert et al. / 2024
DOI: 10.1016/j.enpol.2013.07.001

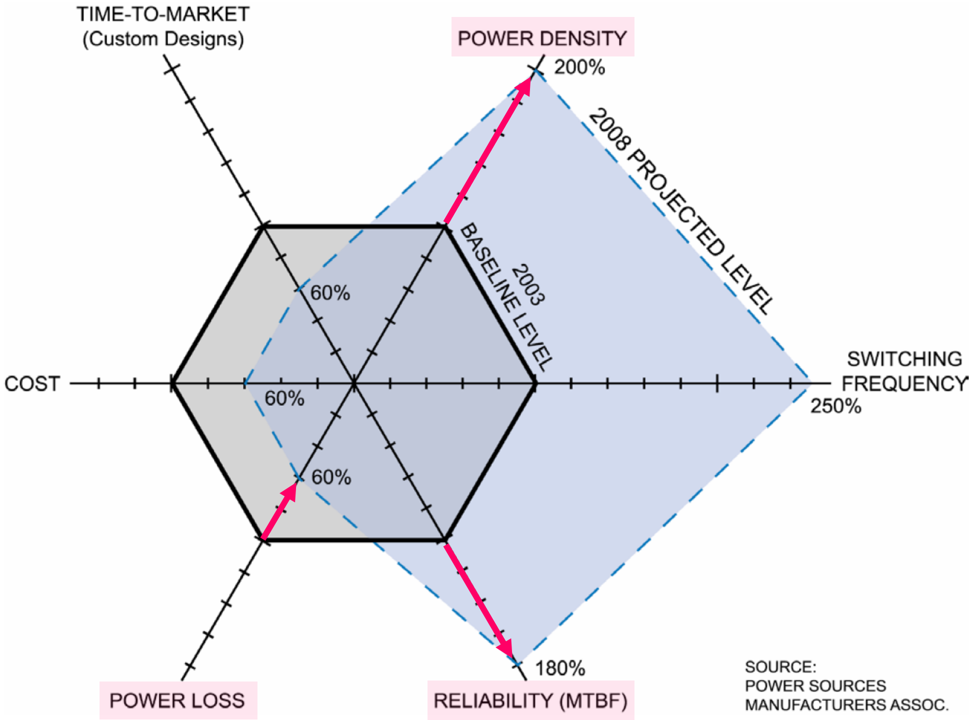


- **“Pyramids of Energy Needs” — Higher EROEI values enable medical care/education/technology innovation/art, etc.**
- **“Net Energy Cliff” — Minimum EROEI = 5…10 required to maintain a complex industrial society**

Power Electronics 4.0: “Do More with Less”

■ **Today’s power electronics innovation basically contributes to lower environmental impact**

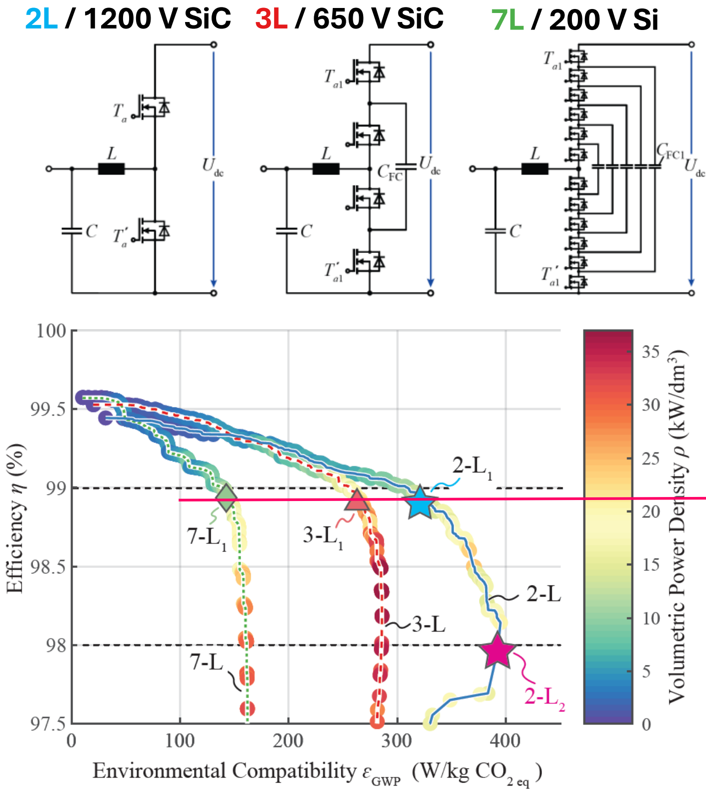
- Power Density → Red. of resources
- Efficiency → Red. of energy use
- Robustness → Increased lifetime



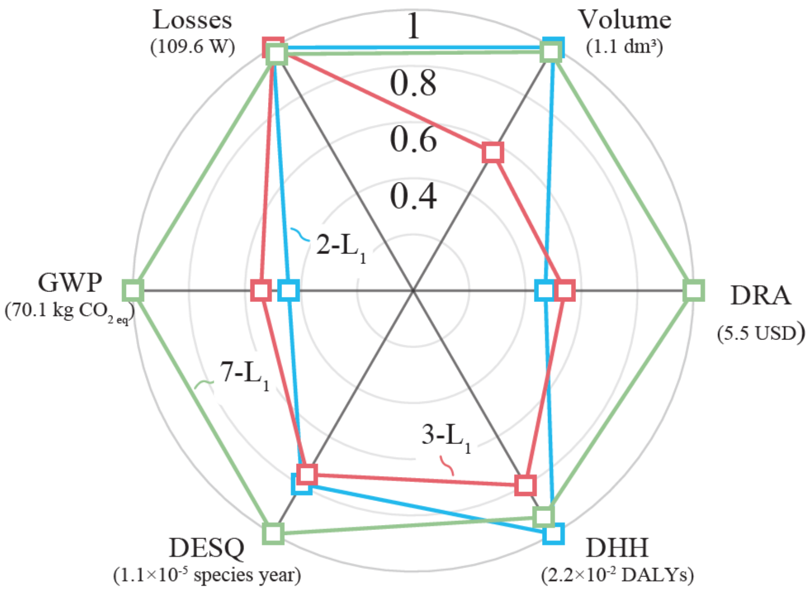
■ **New set of KPIs mandatory to meet future environmental protection objectives**

Multi-Objective Opt. with Environmental Impact KPIs

- Three-phase ac-dc PEBB with LC input filter, 800 V dc, 10 kW — Different bridge-leg realizations



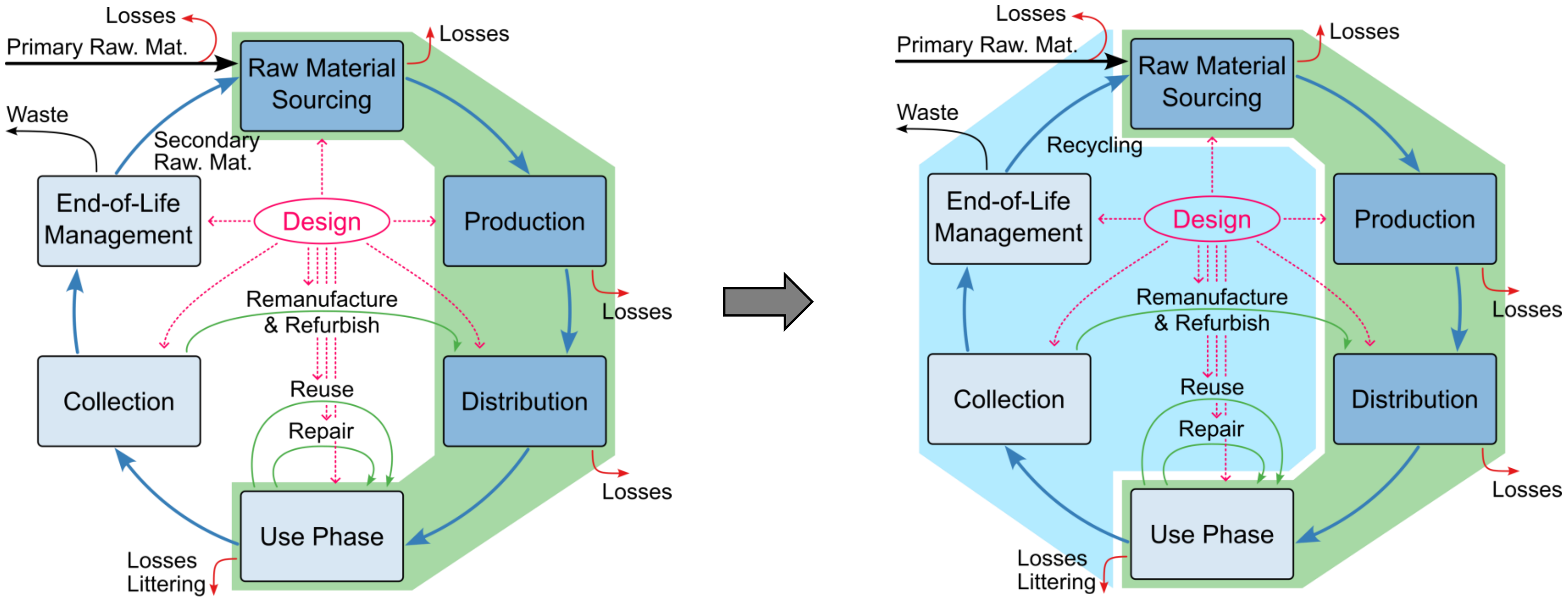
GWP: Global warming potential ("carbon footprint")
(!) DESQ: Damage to ecosystems
DHH: Damage to human health
DRA: Damage to resource availability
ReCiPe 2016



- 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!

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



- How to quantify repairability / reusability / ...?
- Value proposition through life-cycle cost perspective (suppliers *and* customers)?

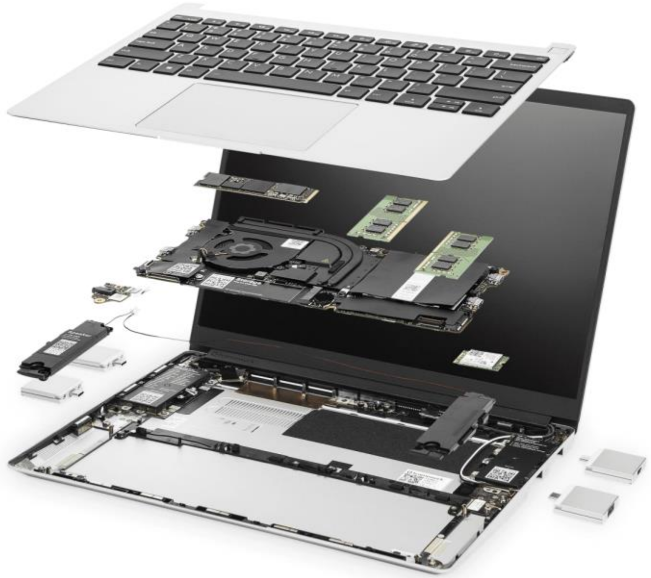
Design for Repairability & Circularity

- **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/



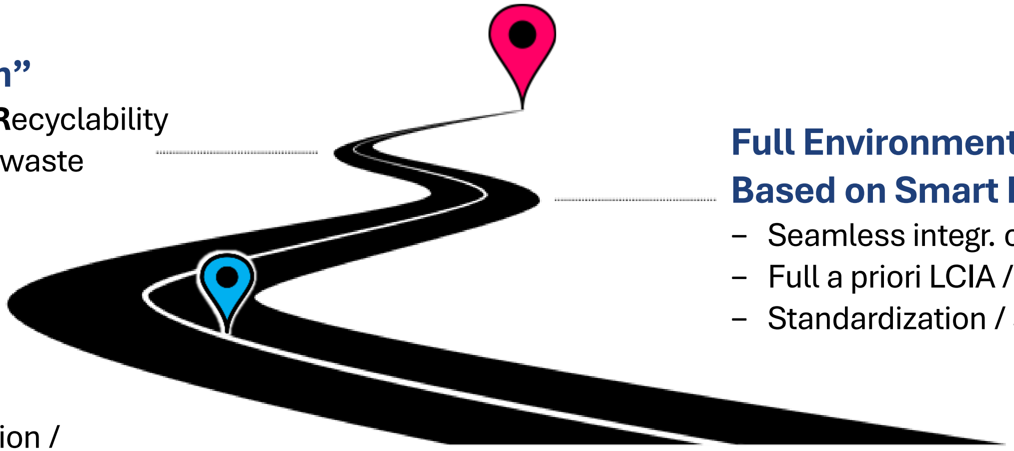
Source: Life Cycle Assessment of the Framework Laptop 2022, Fraunhofer IZM

- **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.

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
- Max. lifetime/reliability

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 *ηρ*-Pareto Optimization / Design
- Manual a posteriori LCA of complete converters

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

Thank You!