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Powering the Future

Monumental Challenges & Disruptive Innovations in Power Electronics

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Advanced Mechatronic Systems Group
www.ams.ee.ethz.ch

May 12, 2025

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Monumental Challenges & Disruptive Innovations in Power Electronics

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Outline

- ▶ Introduction

- ▶ Net-Zero CO_2 by 2XXX
- ▶ Renewables & Storage
- ▶ Hard-to-Abate Sectors
- ▶ Raw Material Constraints
- ▶ The «Net Energy Cliff»
- ▶ Power Electronics 5.0

- ▶ Conclusions

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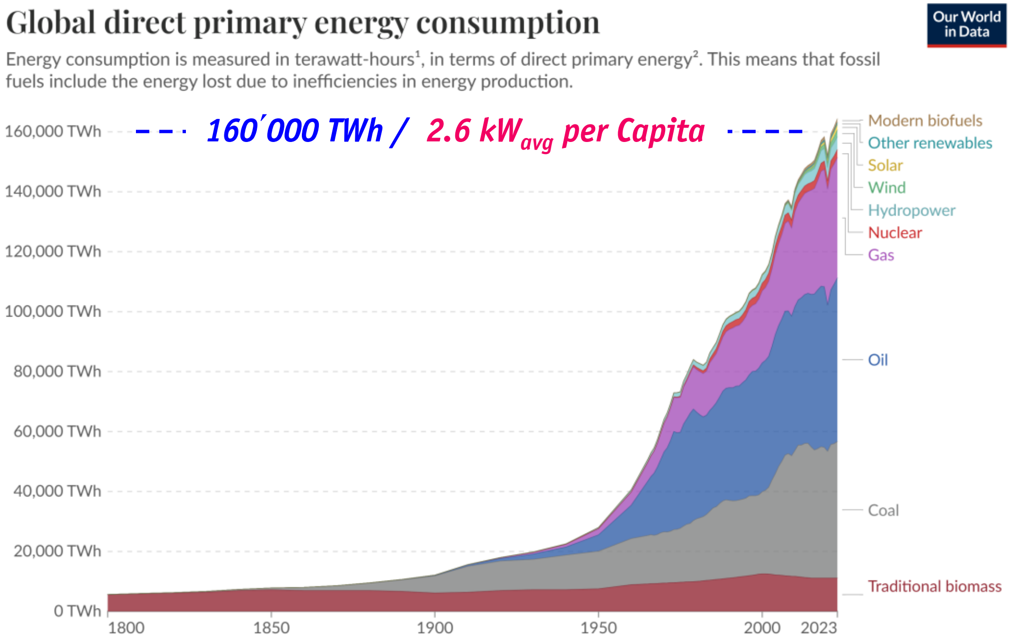
Power Electronic Conversion Technology Platform PECTA
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Swiss Federal Office of Energy SFOE
Acknowledgement
ECPE

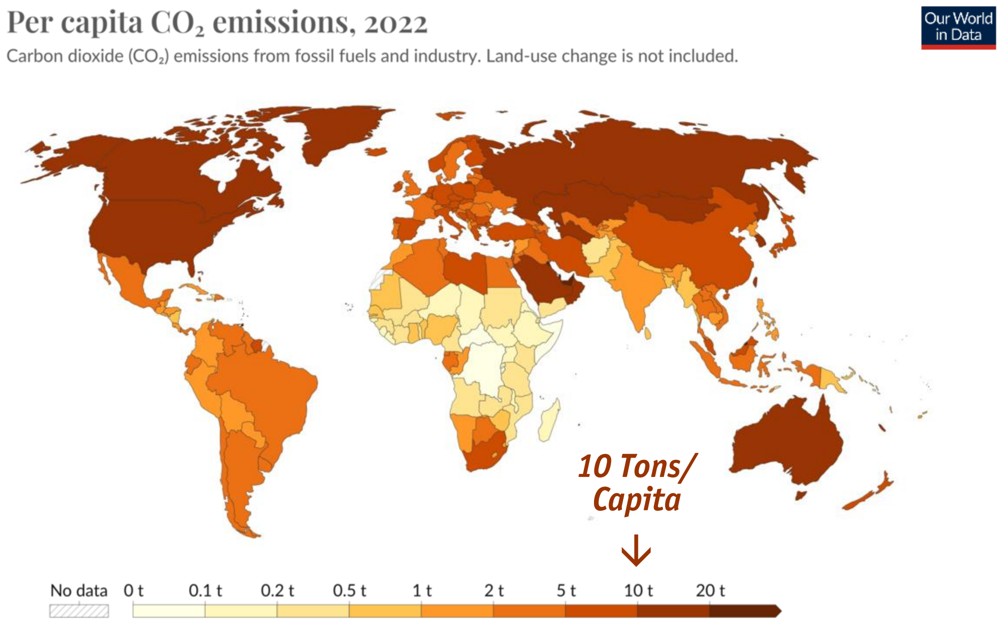
The Challenge

Net-Zero by 2XXX
Clean Energy Transition Costs

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*



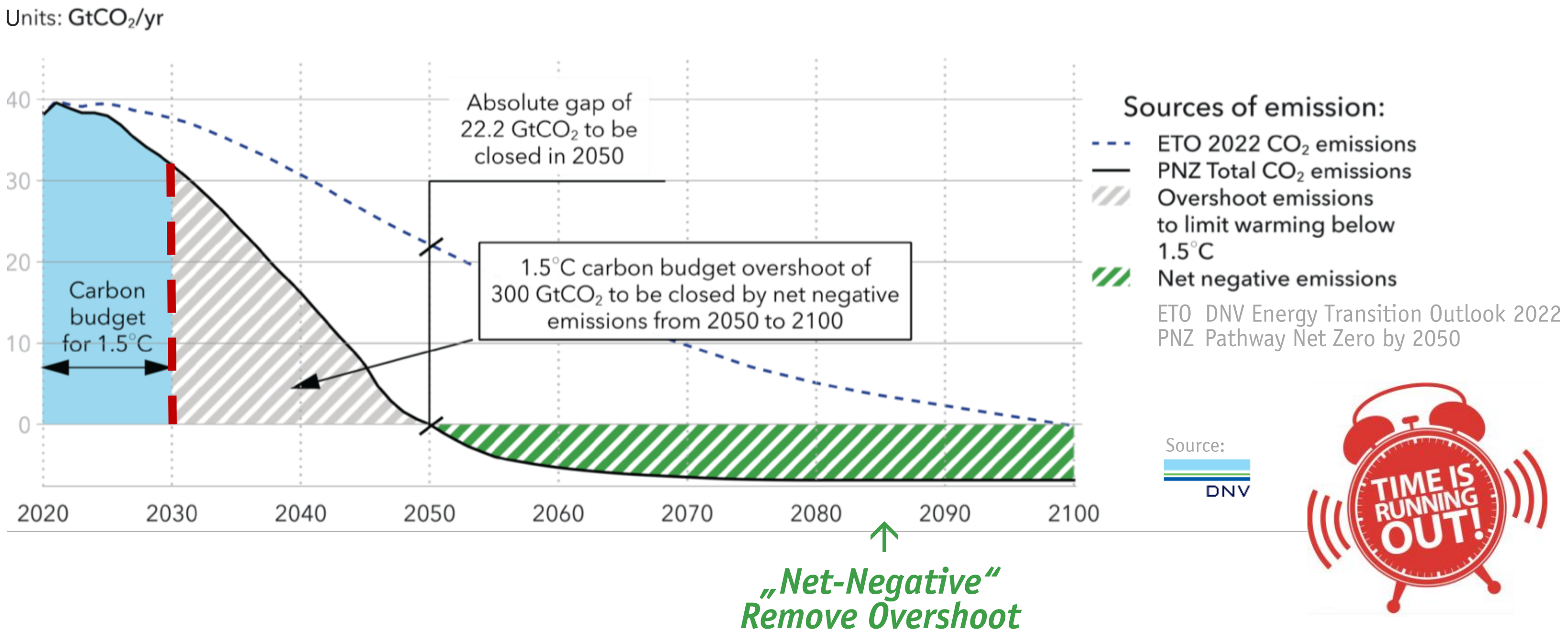


- *2024 % of Global CO_2 Emissions / % Global Population — China 32%/18% | USA 13%/4% | India 8%/18%*
- *Poorest Countries Contributed Least to Historic CO_2 Emissions/Climate Change BUT Are Most Vulnerable to Impacts*

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 $GtCO_2$ →



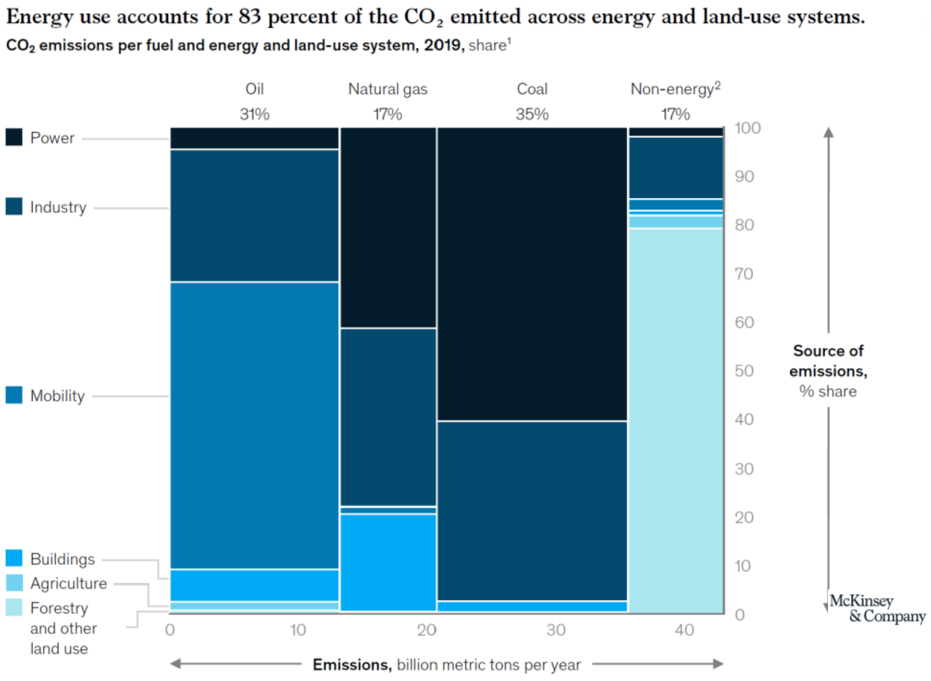
↑
„Net-Negative“
Remove Overshoot
of 300 $GtCO_2$

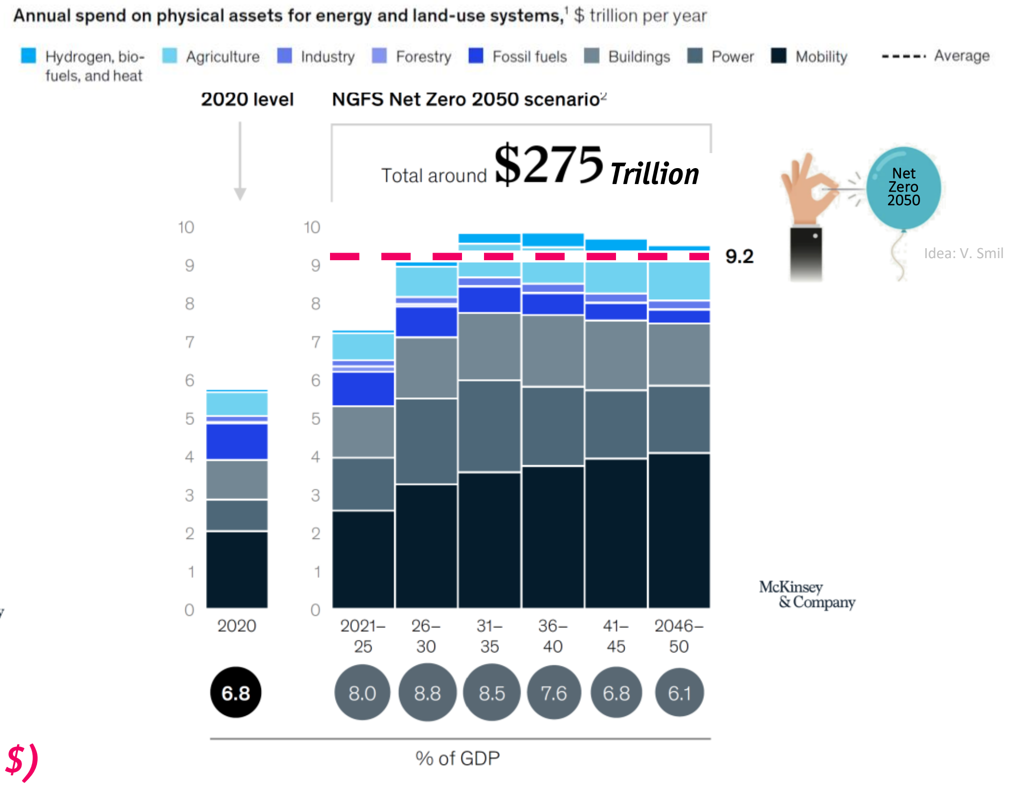
- *Challenge of Stepping Back from Oil & Gas*

Clean 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

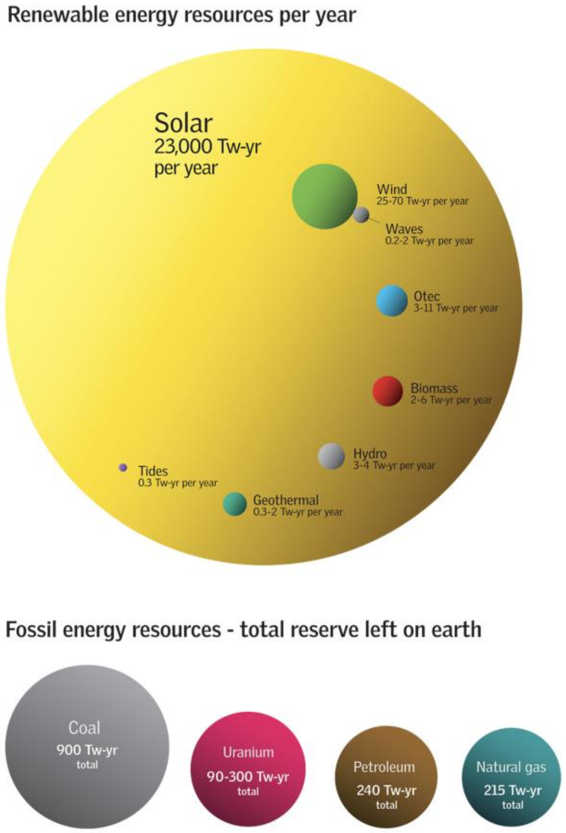
The Opportunity

(2009) 16 TW-yr

16 Tw-yr per year

27 TW-yr (2050)

100% Conv. Efficiency
Excl. Oceans

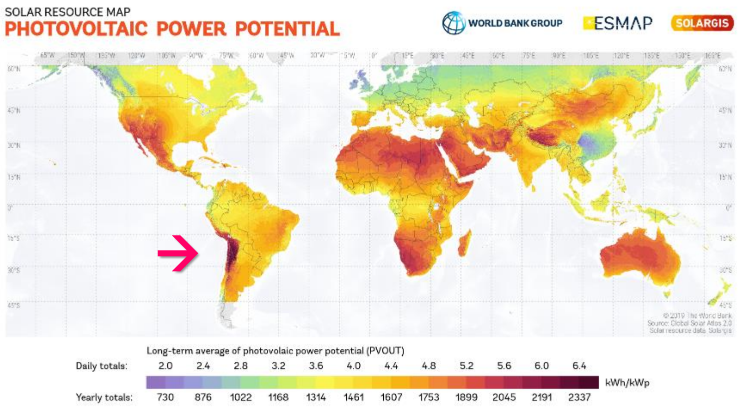


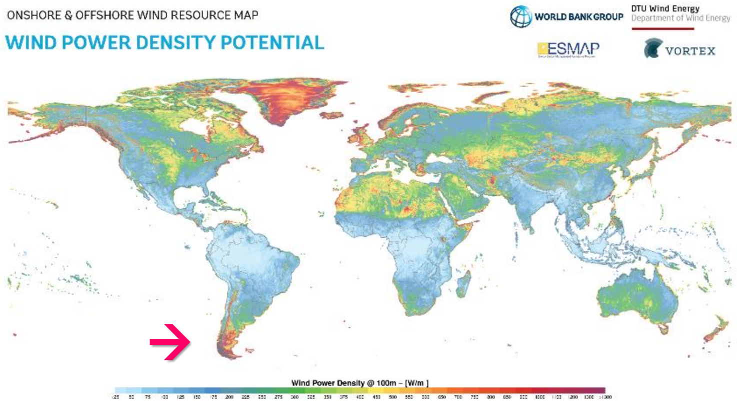
Note: Graphical Representation Assumes Spheres Not Circles

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*

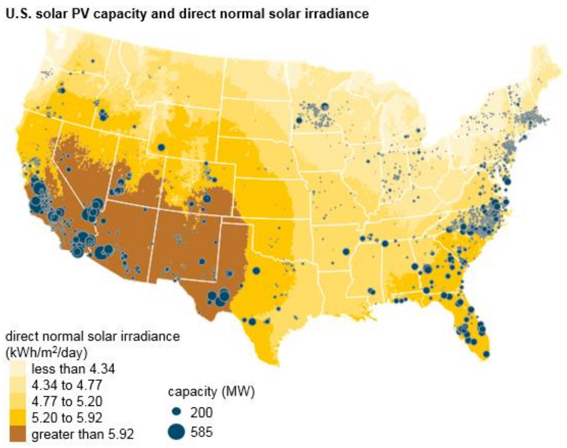


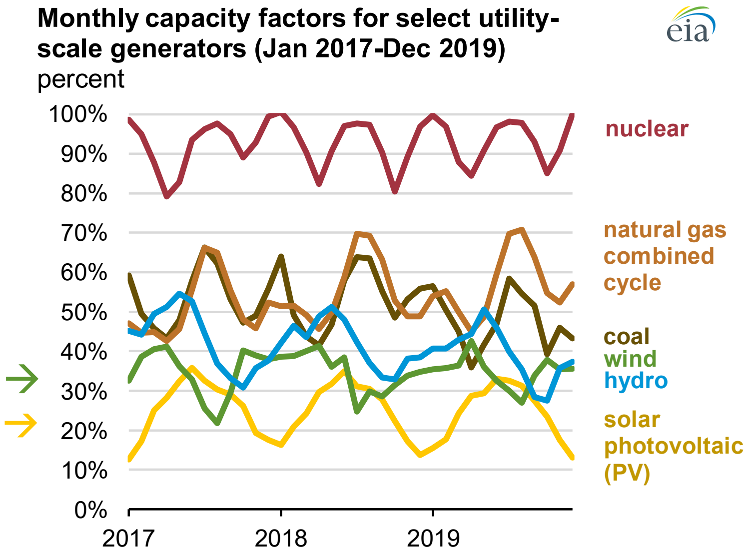


Challenge #1 – Low PV/Wind Capacity Factors

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

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



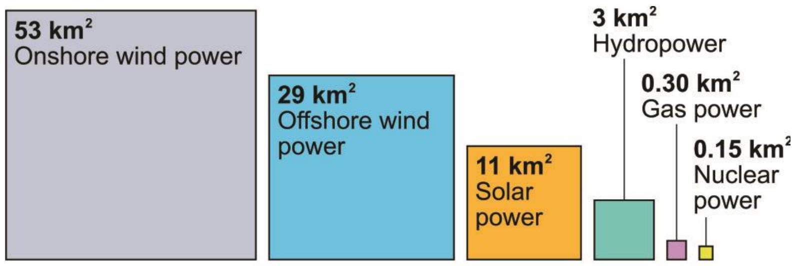


- *Capacity Factor of Renewables Dependent on Geogr. Location & Day/Night & Summer/Winter & Transm. Capacity*
- *PV & Wind Partly Complementary — Typ. Annual Avg. ≈30% for U.S. Wind | ≈20% for U.S. Solar (12% in Germany)*

Challenge #2 – Low PV/Wind Areal Energy Density

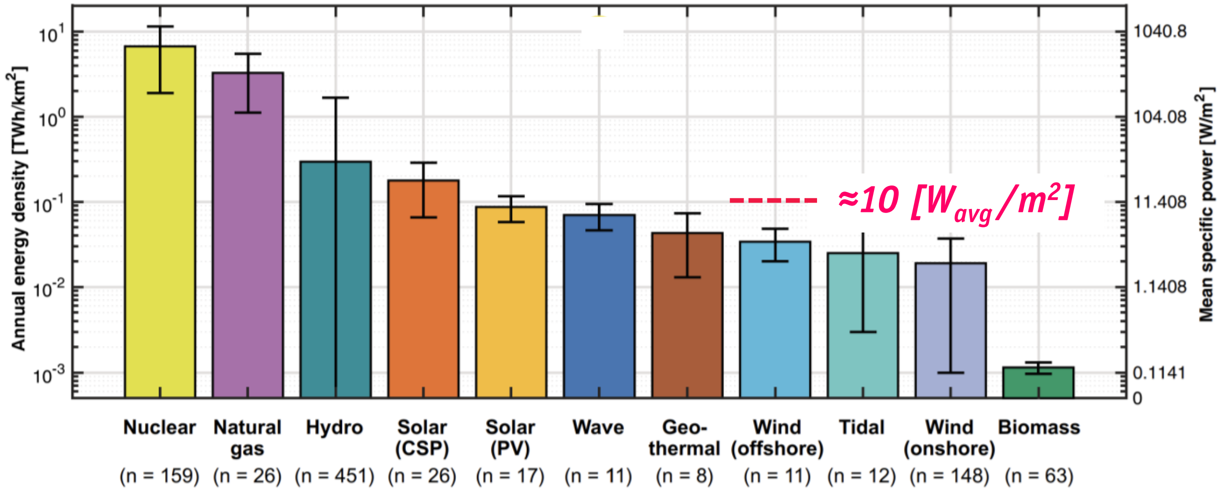
- *Energy Density — Determined by Power Density | Intermittency &/or Capacity Factor | Buffer Zones | Storage | etc.*
- *Land Footprint of Renewable Energy Sources Massively Larger Compared to Fossil Fuel / Nuclear Power Plants*

Annual Generation of 1 TWh (Smaller City)



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

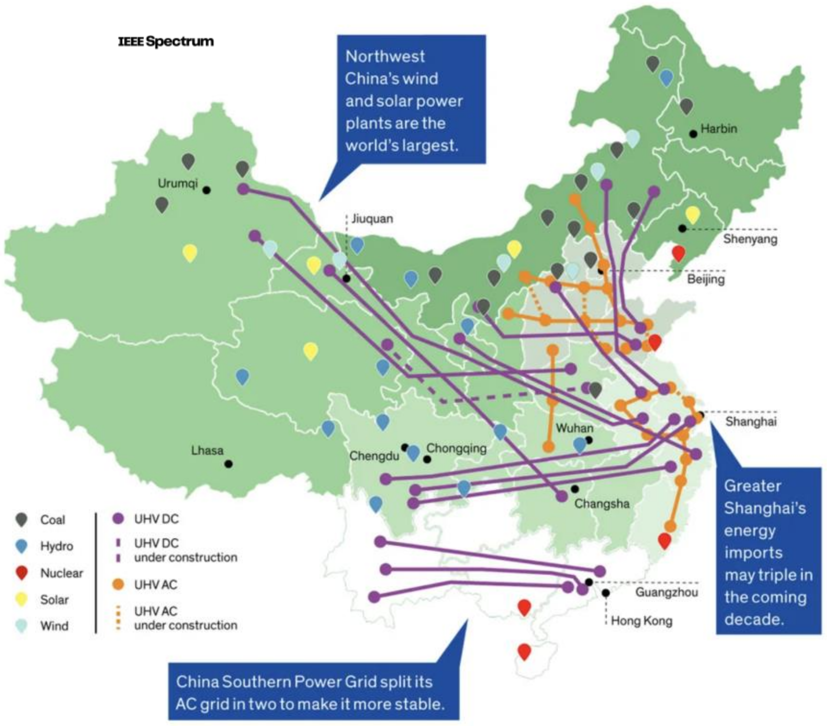
Source: nature, J.K. Nøland et al., 2022



- *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.*

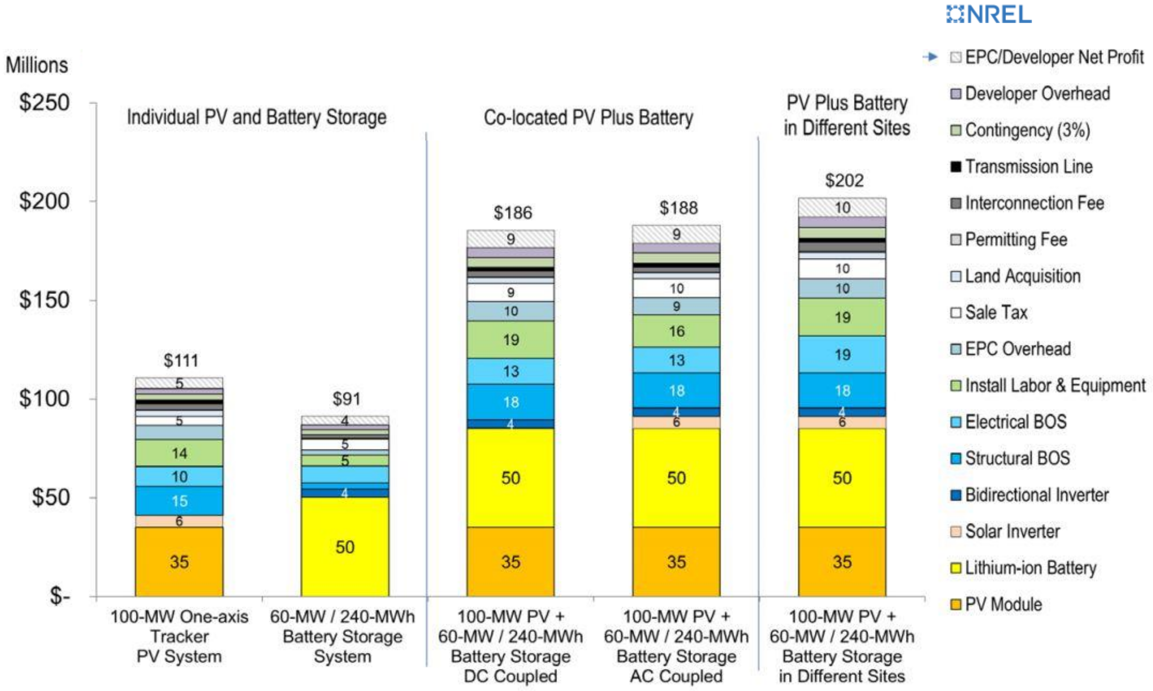


- *30´000 km U-HVDC Links Built Over Last Decade in China / Emerging Nationwide Super-Grid Interconn. Reg. Grids*

Challenge #4 – Storage Requirements

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

Source: TESLA

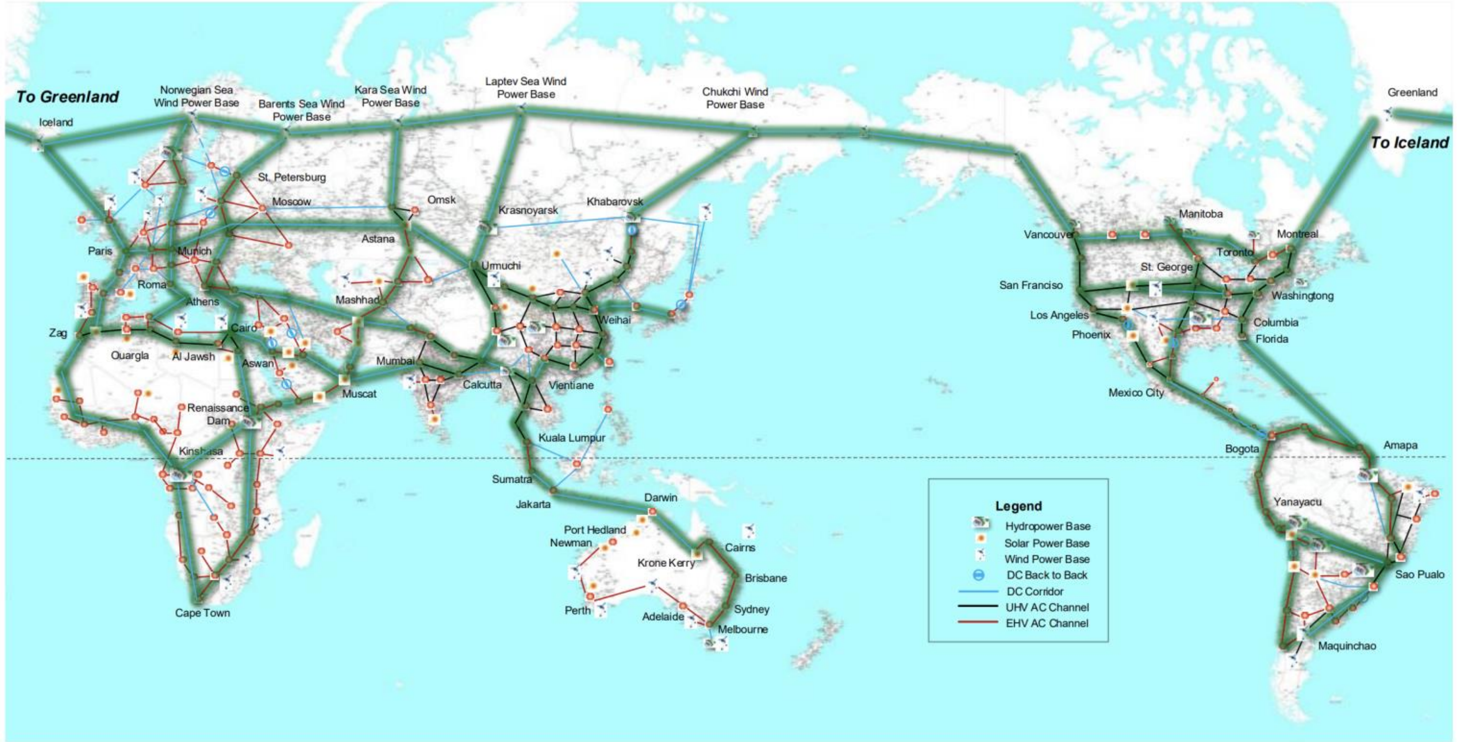


- *Comparison of PV & Fossil Fuel Power Gen. Must be Based on "LCOE" (Panels/Inverter/Cap. Factor/Transmission/Storage etc.)*

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*

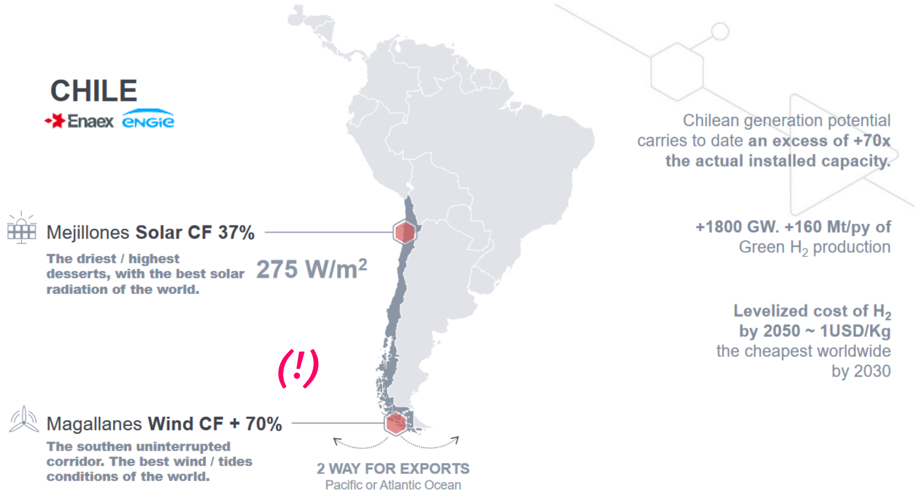
Source: GEIDCO 2018

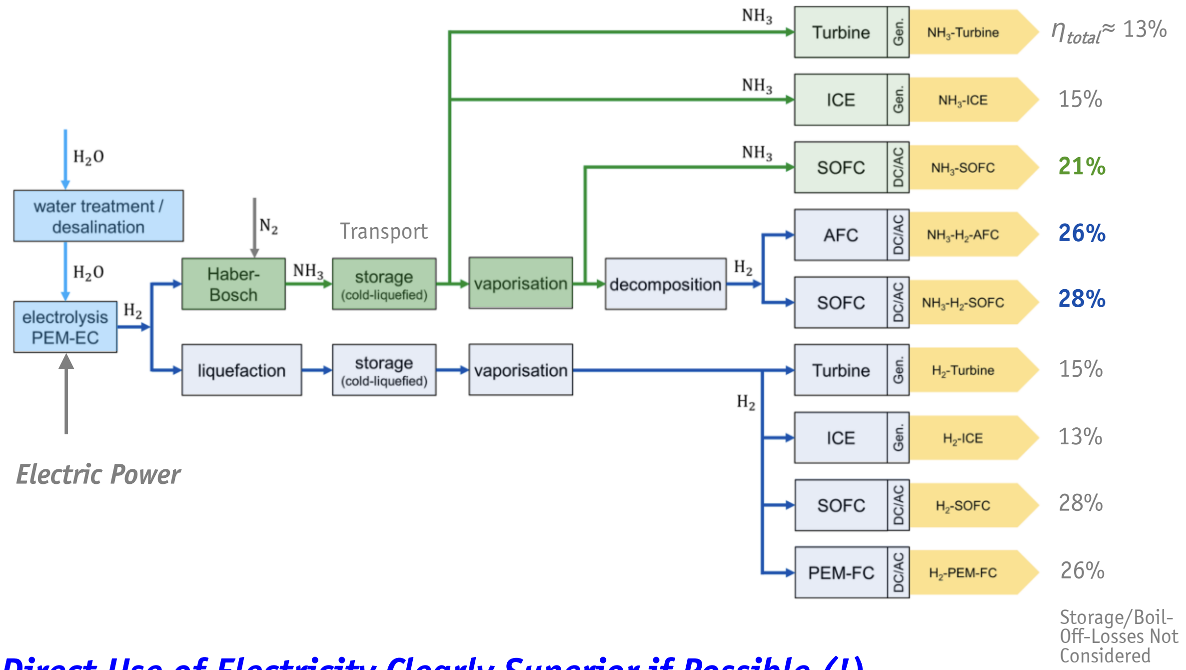


- *Example of the "Global Energy Interconnection Backbone Grid" (GEIDCO) Proposed by China in 2015*

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*





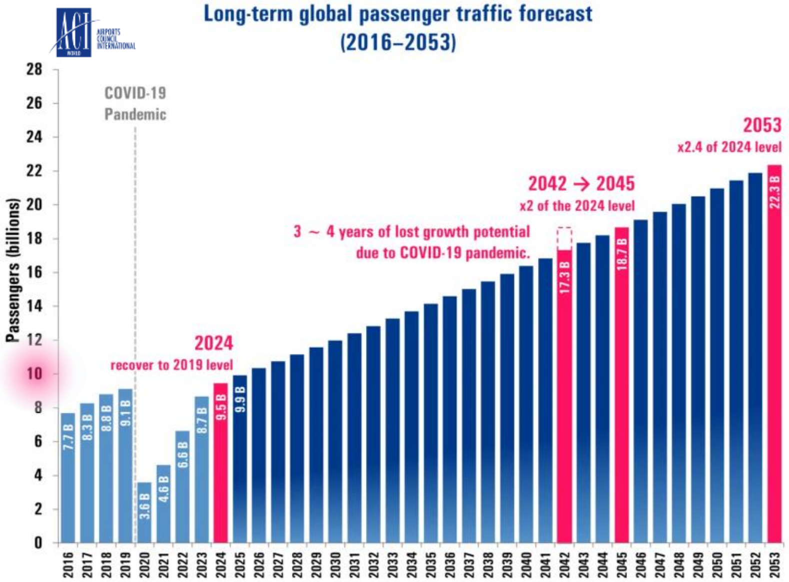
- *Hydrogen Hype — A Story of Energy Loss (?) / Direct Use of Electricity Clearly Superior if Possible (!)*
- *Low-Efficiency Processes — 60% Electrolysis / 70% Liquefying Hydrogen / 60% Fuel Cells / etc.*

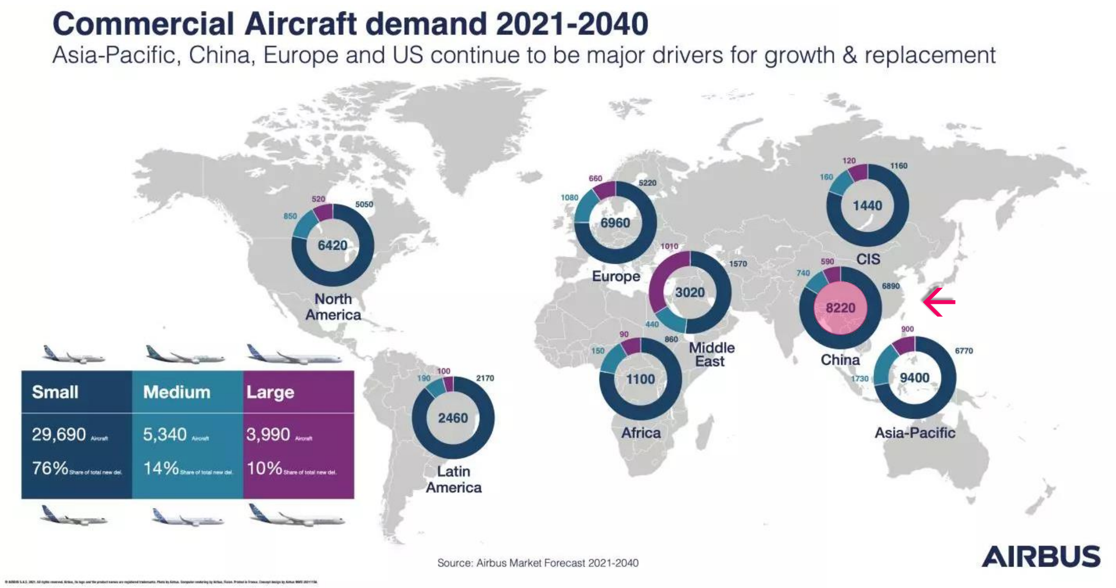
Multi-Carrier Energy System

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)*

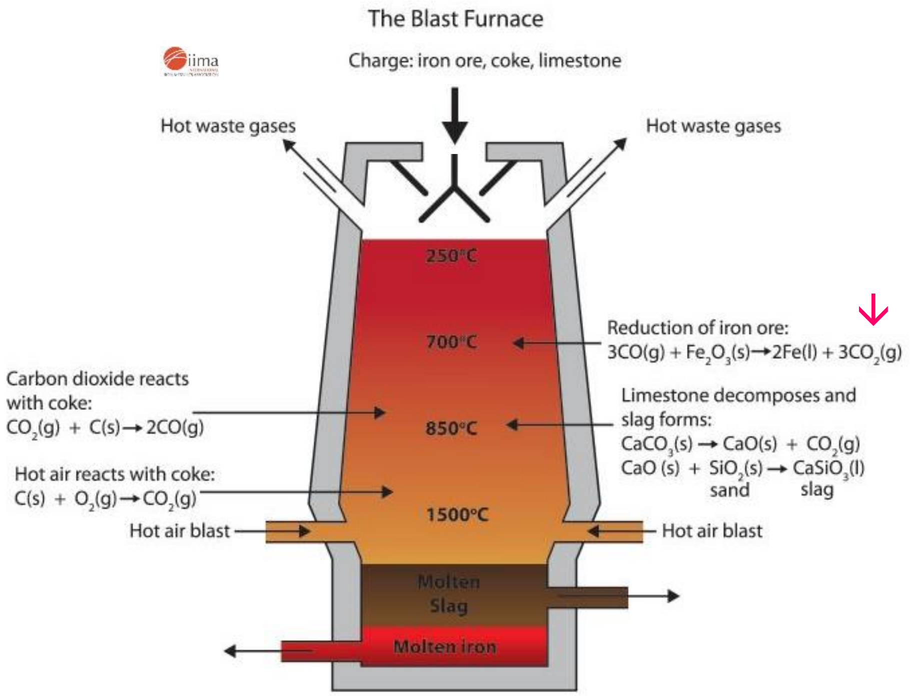
Source: https://www.ship-technology.com/

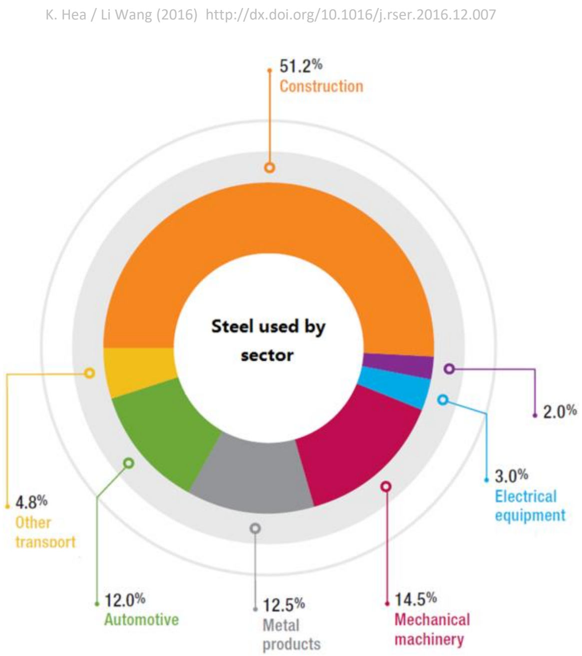

https://www.shipsnostalgia.com/

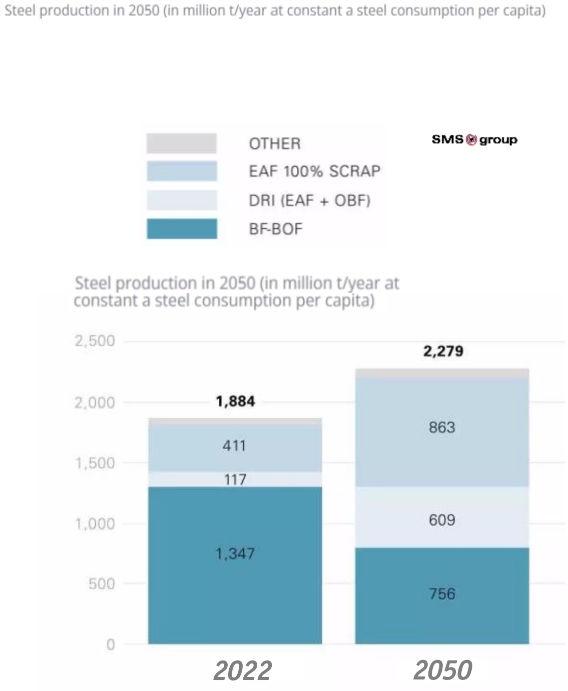
- *Ultra-Large Container Vessels (ULCVs) — 20´000 Twenty Foot Containers / 15´000 Liters of Heavy Fuel Oil per Hour*
- *80 MW @120 rpm / 2´300 Tons Largest Diesel Engine Used in ULCVs*

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*



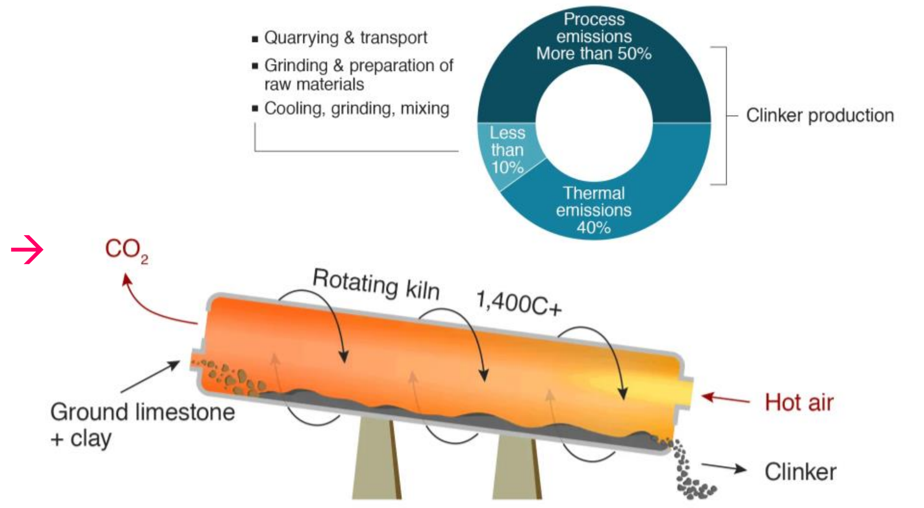




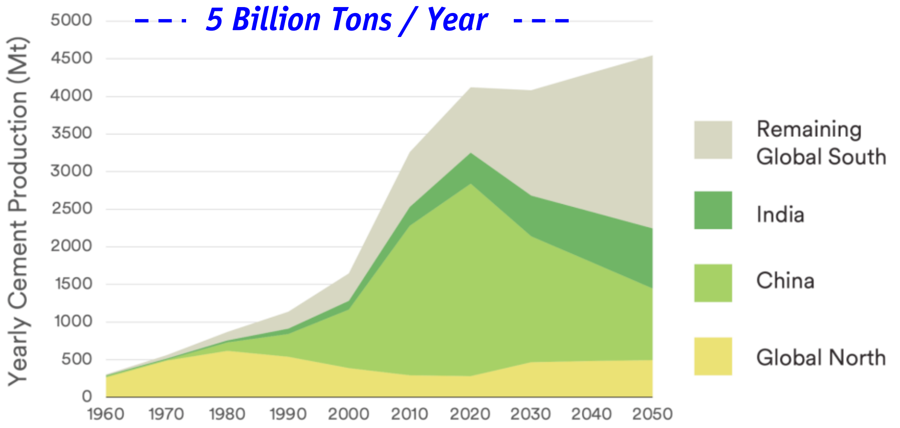
- *Steel Production Responsible for ≈8% of All Global Direct Emissions From Fossil Fuels*
- *Global Steel Demand Expected to Increase from ≈1.9 Billion Tons/a in 2021 to Over ≈2.3 Billion Tons/a by 2050*

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.*



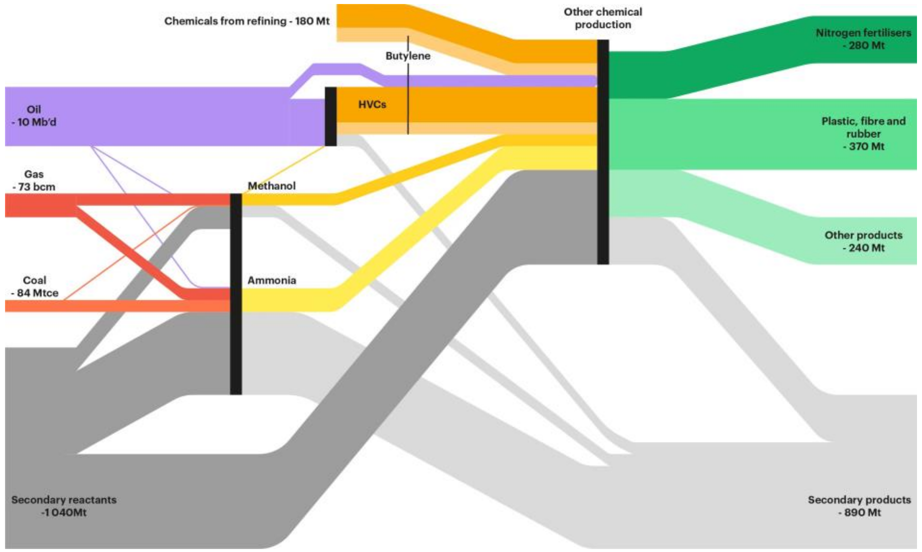
Source: Carbon Brief, Chatham House

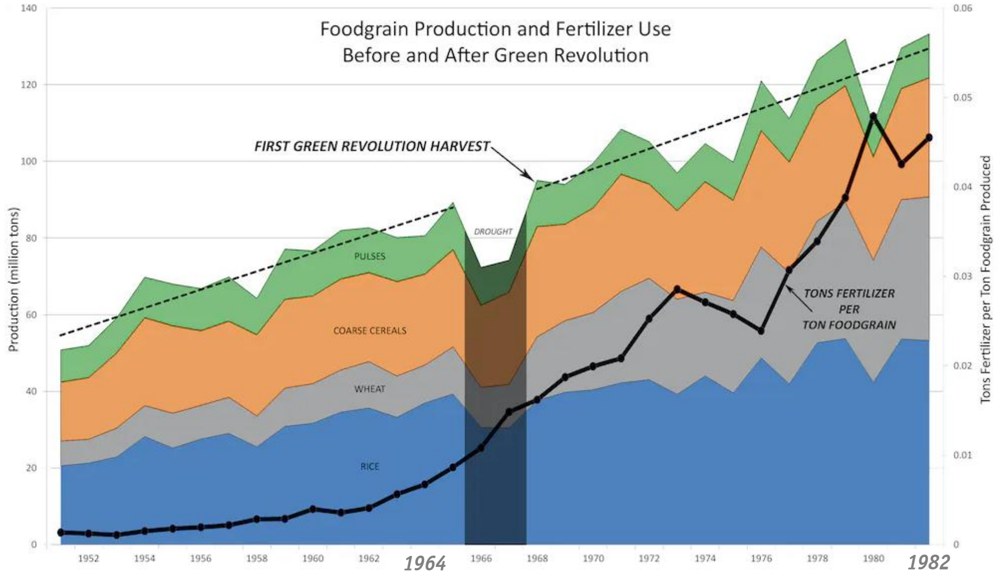


- *China & India Account for Around 50% of Global Cement Production*
- *Intensity of Cement Use Declines After Initially Rising w/ Increasing GDP/ Capita*

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)*

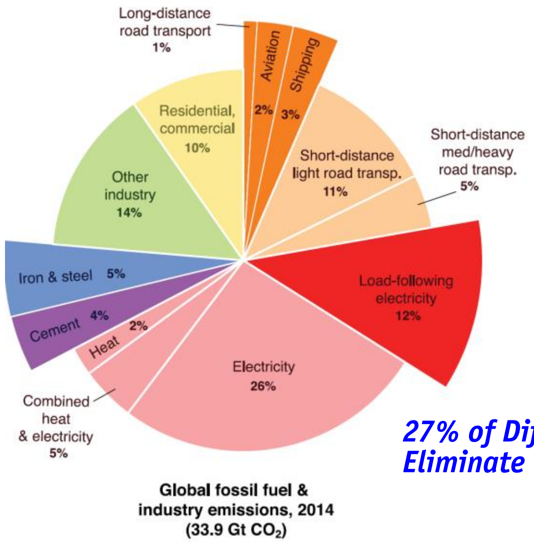




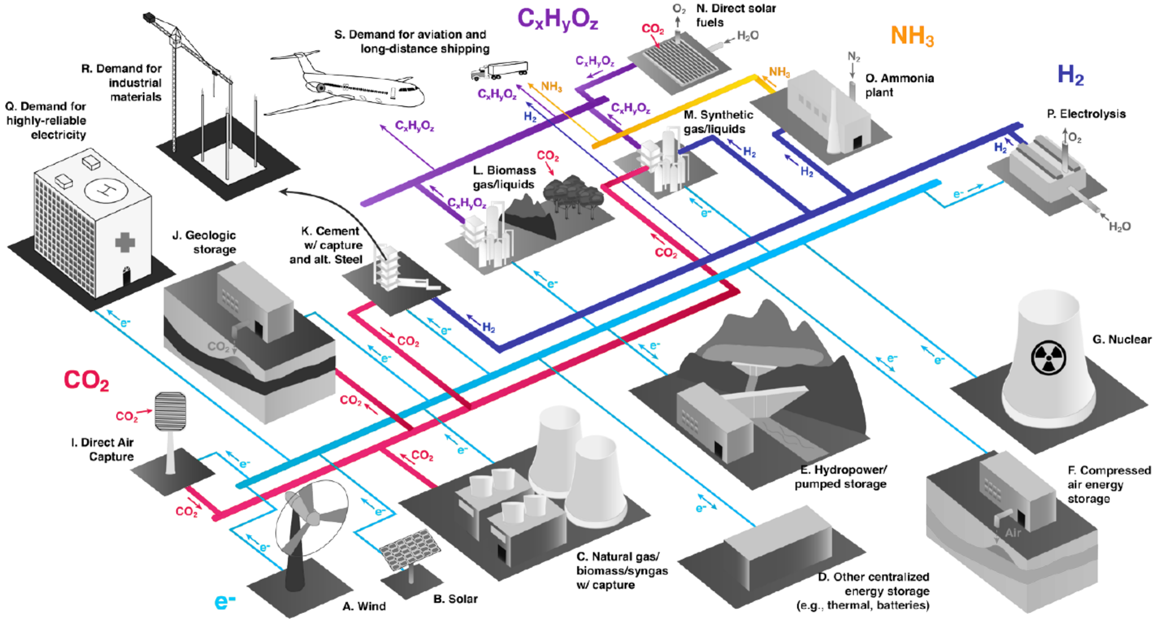
- *"Green Revolution" in Mid-20th Century — Higher Yield Due to Use of Fertilizers & Pesticides & Mechanization*
- *Chemical Sector — Largest Industrial Energy Consumer / 3rd Largest CO_2 Emissions after Steels & Cement*

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



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

- 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

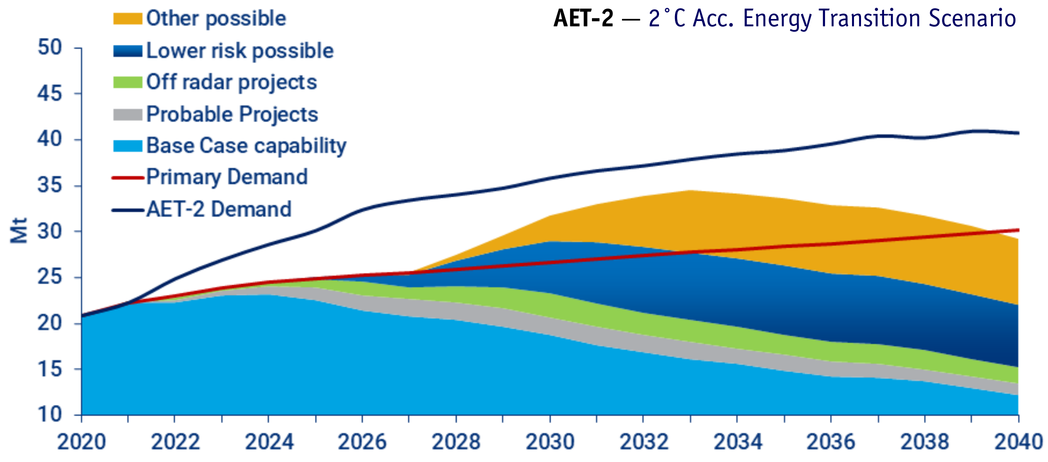
Figure 1: Market balances for energy transition metals under BNEF's Economic Transition Scenario and Net Zero Scenario – expected supply surplus and supply deficits

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

Primary copper demand scenarios versus mine supply potential

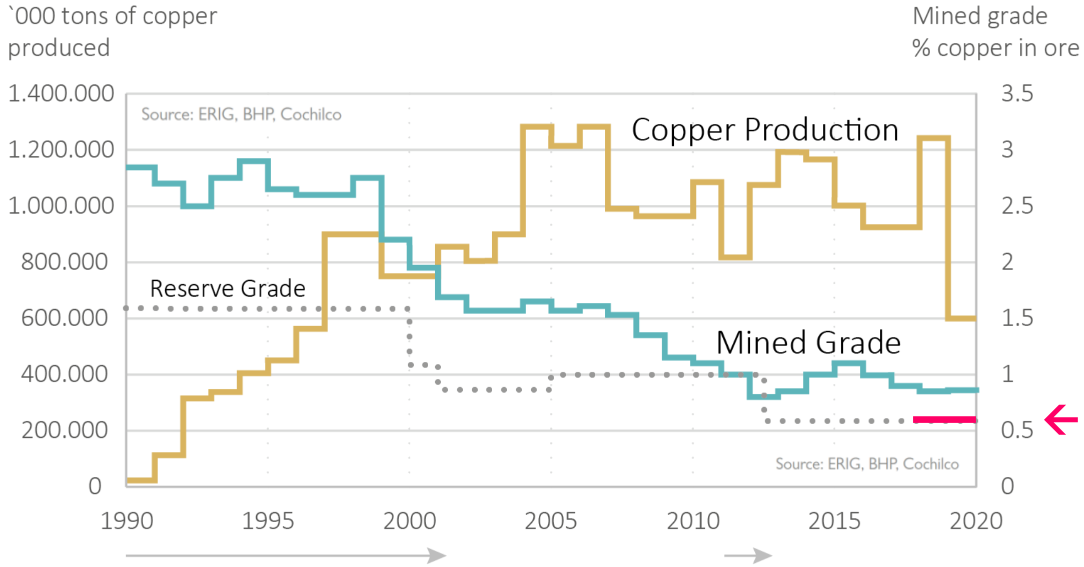


Source: Wood Mackenzie

- *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"*

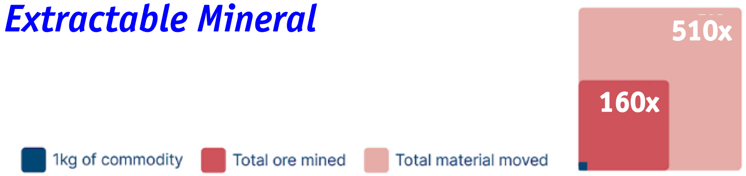
„Peak Minerals/Metals“ of Net-Zero Scenario 2/2

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



-Phase I to phase IV
Expansion, USD 2.5B
-220.000 tons per day

-New concentrator
-Desalination plant, USD 7.5B
-375.000 tons per day through mill

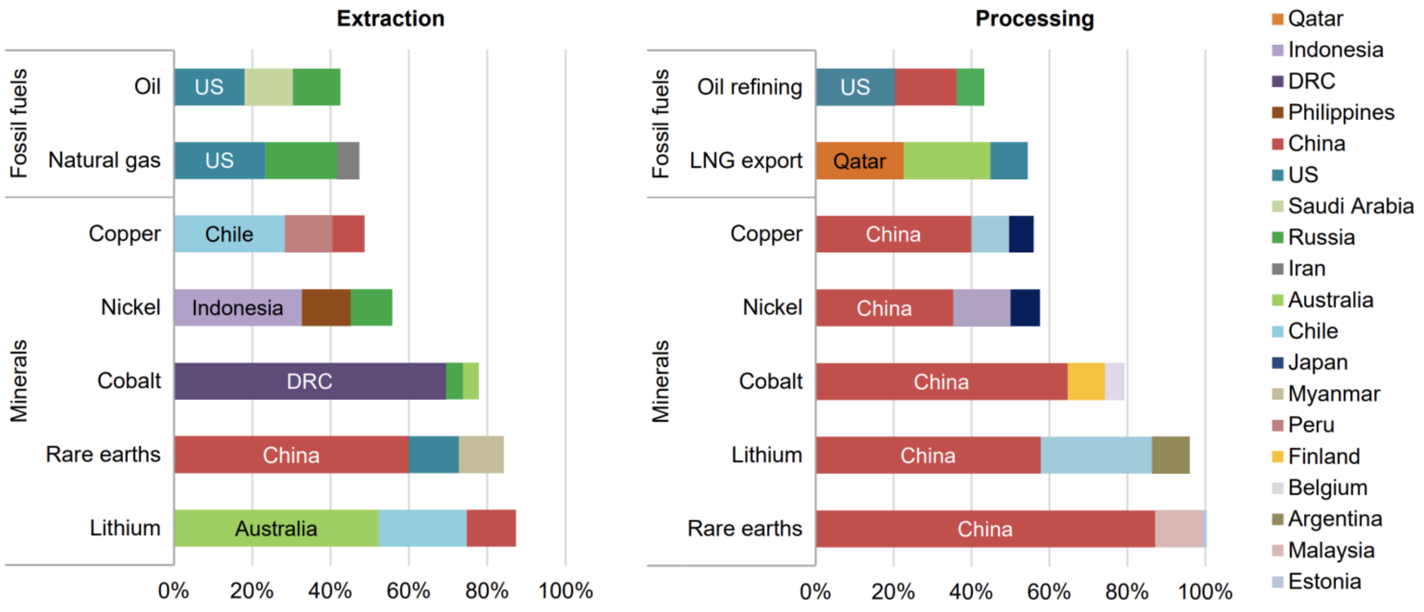


Caterpillar 797F — 350 tons payload / 3 MW

- *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 (!)*

Advanced Mechatronic Systems Group

The “Net Energy Cliff”

Energy Return of Energy Invested
Fossil Fuels vs. Renewables

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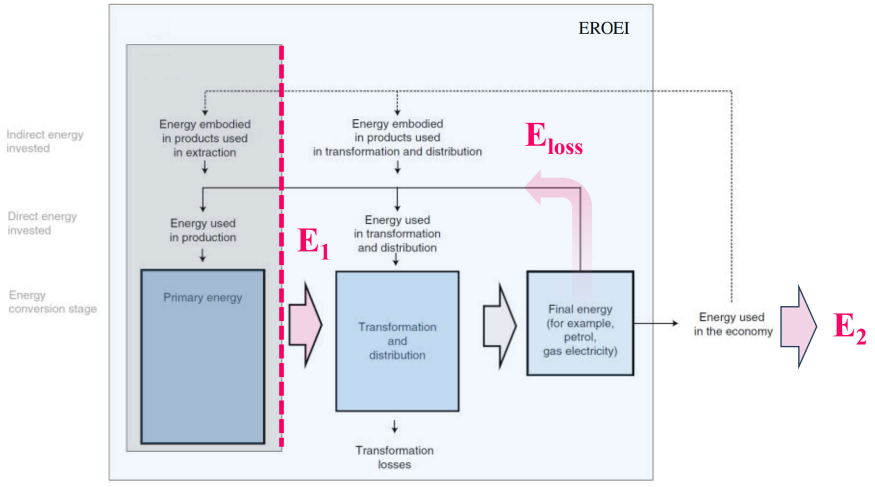
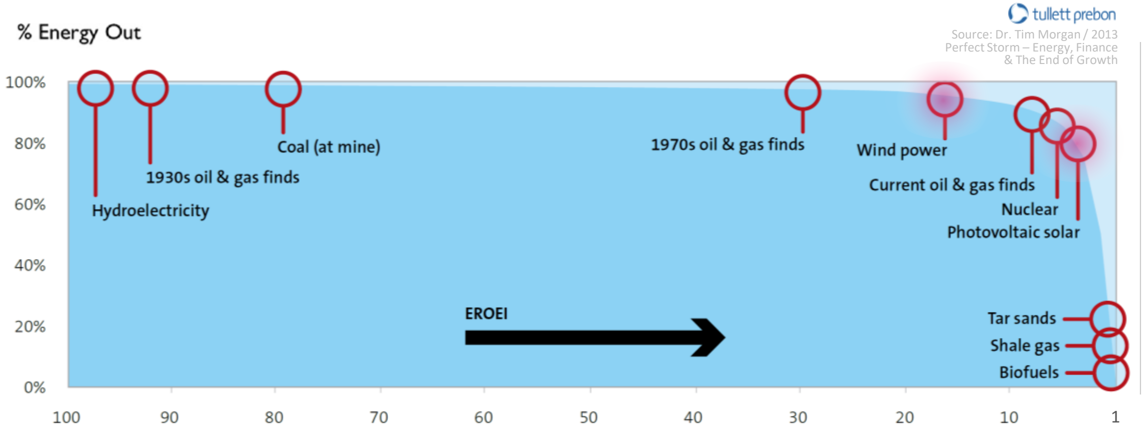
Energy Return on Energy Invested (EROEI)

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

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



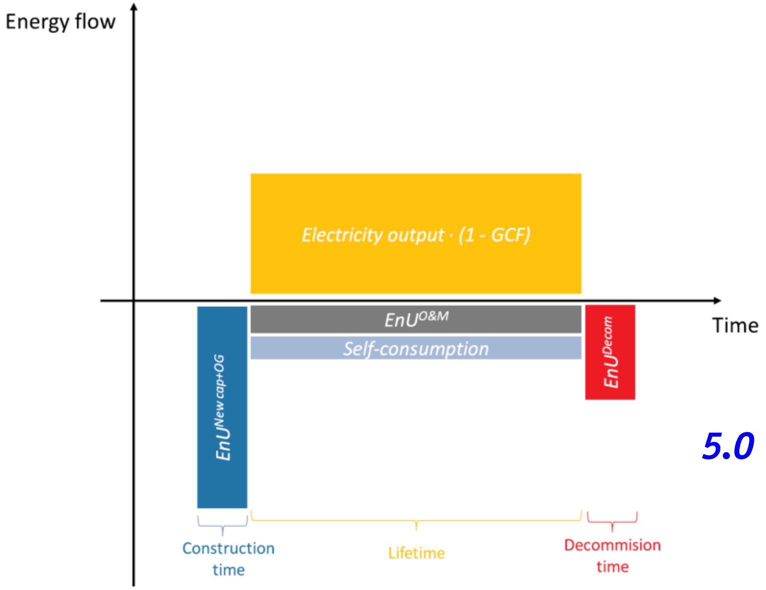
Source: K. Zhao et al. / 2021
doi.org/10.1007/s41247-021-00094-7



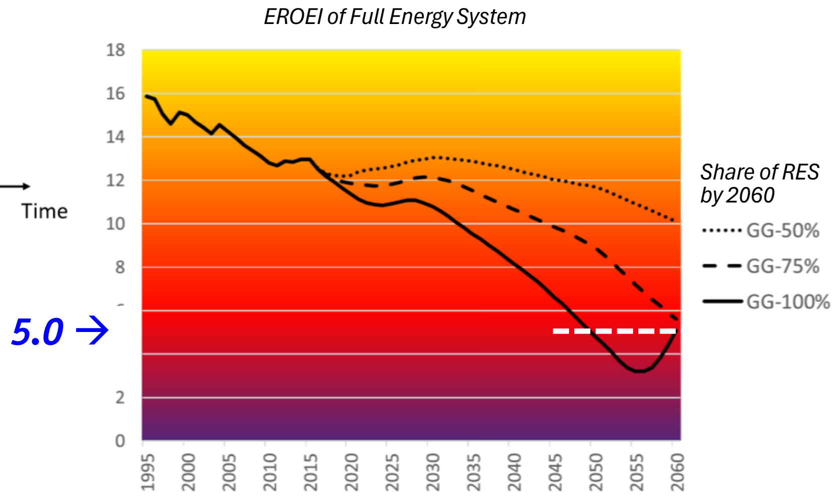
- *"Pyramids of Energy Needs" — Higher EROEI Values Enable Medical Care/Education/Technology Innovation/Art etc.*
- *The "Net Energy Cliff" Indicates the Minimum EROEI = 5…10 Required to Maintain a Complex Industrial Society*

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*

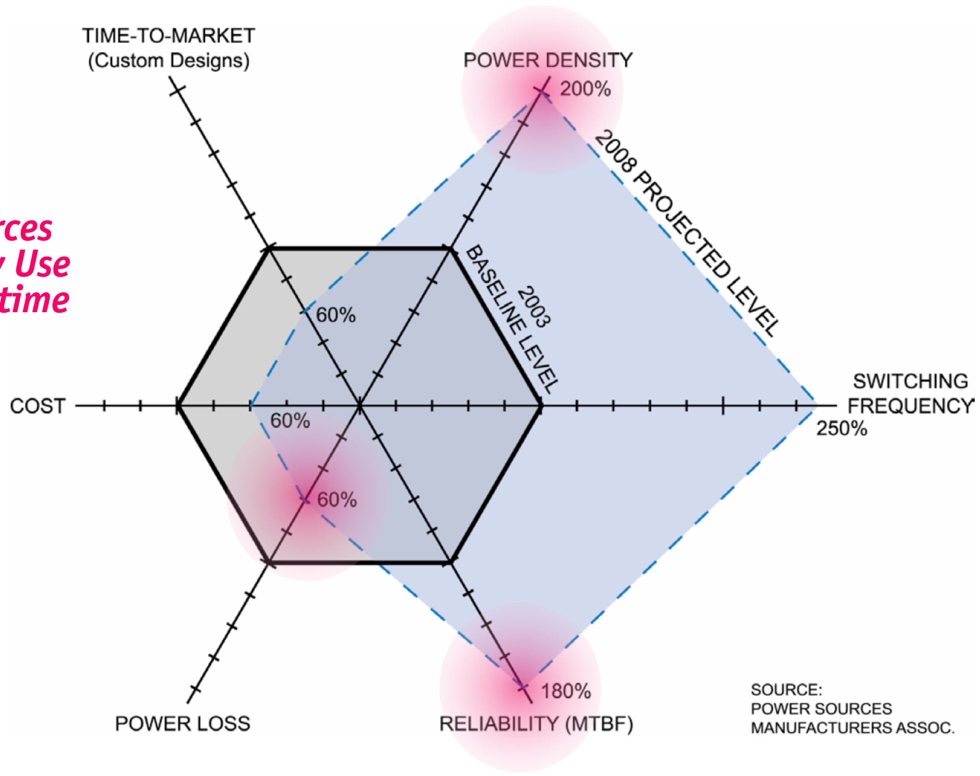
Power Electronics 4.0

"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

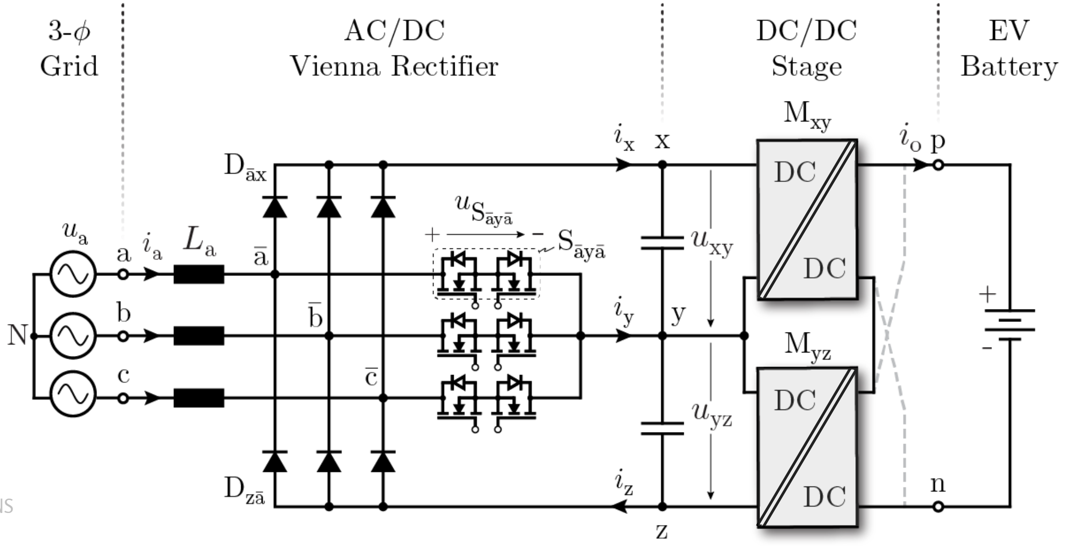
EPSMA

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

Example of 3-Φ EV-Charging

- *Isolated Controlled Output Voltage*
- *Buck-Boost Functionality & Sinusoidal Input Current*
- *Applicability of 600V GaN Semiconductor Technology*
- *High Power Density / Low Costs*

Source: SIEMENS

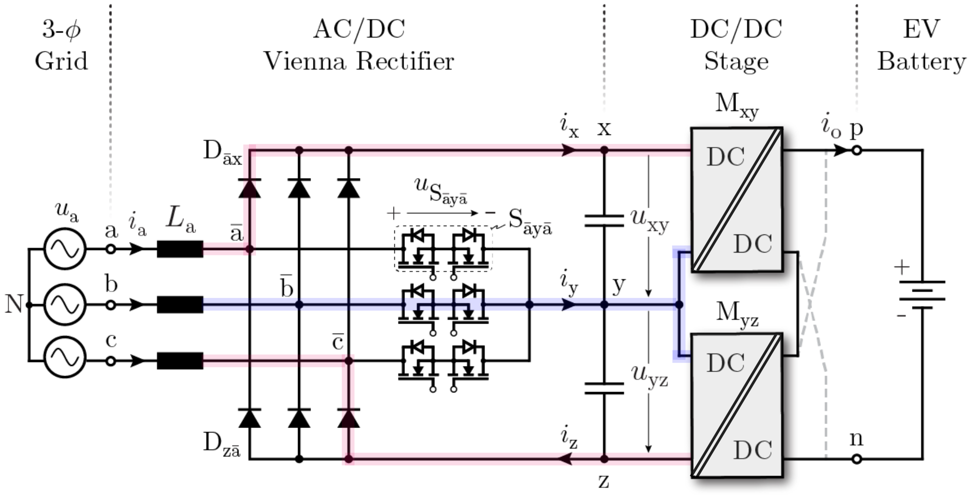


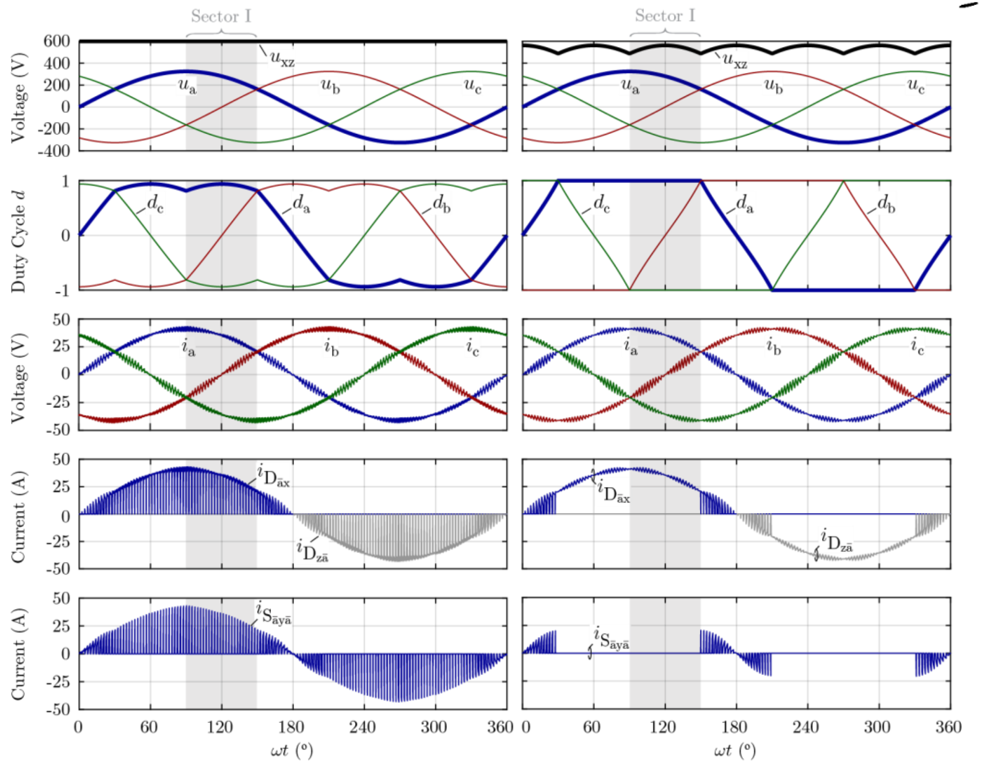
- *Conventional / Independent OR "Synergetic Control" of Input & Output Stage*

Two-Stage Isolated 3-Φ AC/DC Conversion 1/2

- *Synergetic Association of PFC Rectifier & DC/DC Converter Stage*
- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*

- *Conduction Losses of the Switches ≈ -80%*
- *Switching Losses ≈ -70%*



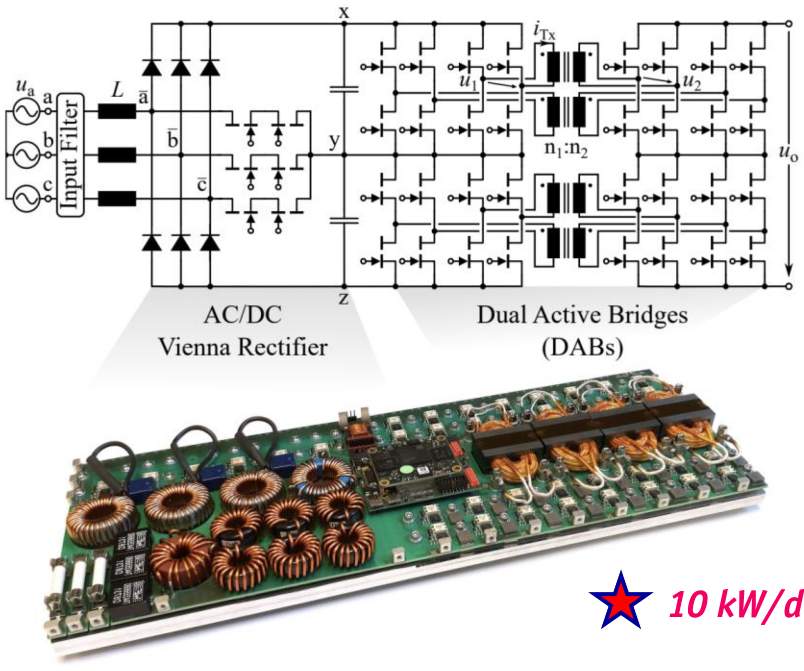


- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

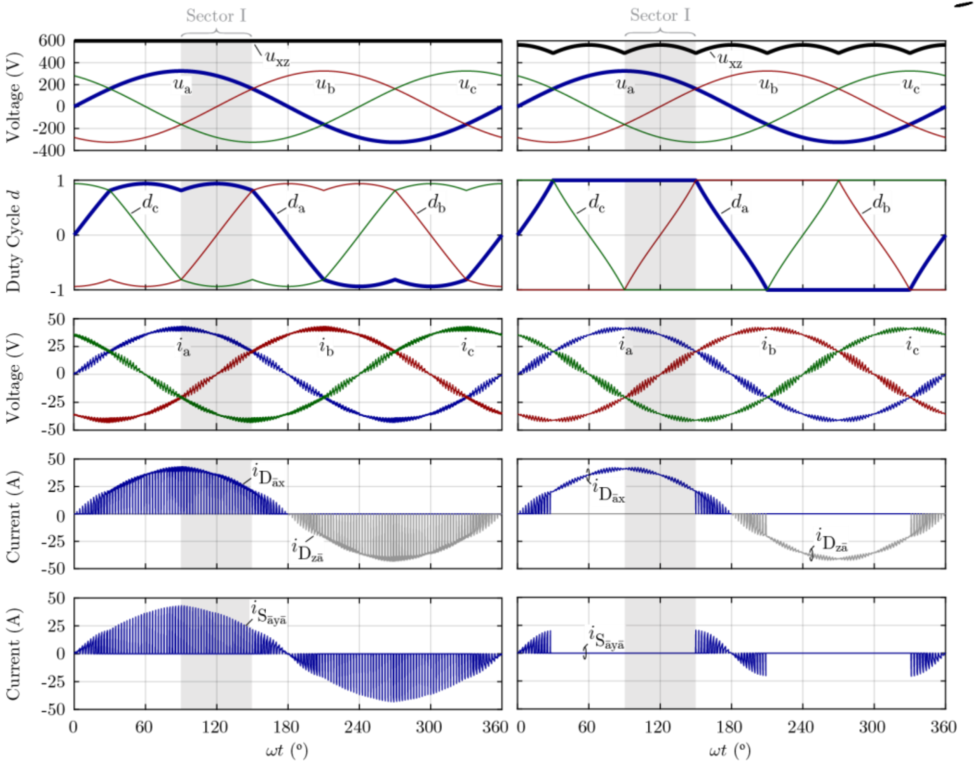
Two-Stage Isolated 3-Φ AC/DC Conversion 2/2

- *Synergetic Association of PFC Rectifier & DC/DC Converter Stage*
- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*

- *Conduction Losses of the Switches ≈ -80%*
- *Switching Losses ≈ -70%*



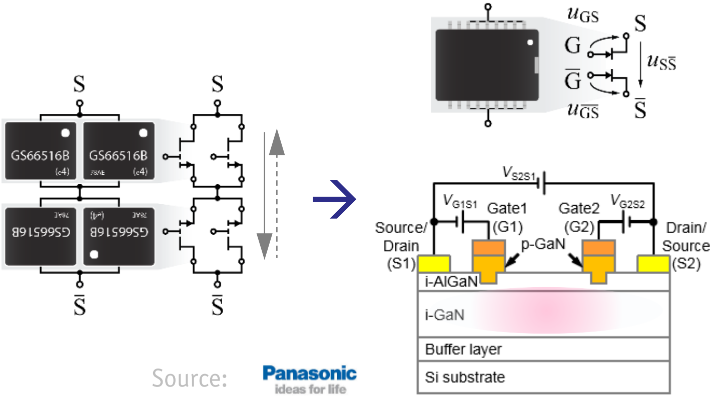
★ *10 kW/dm³*



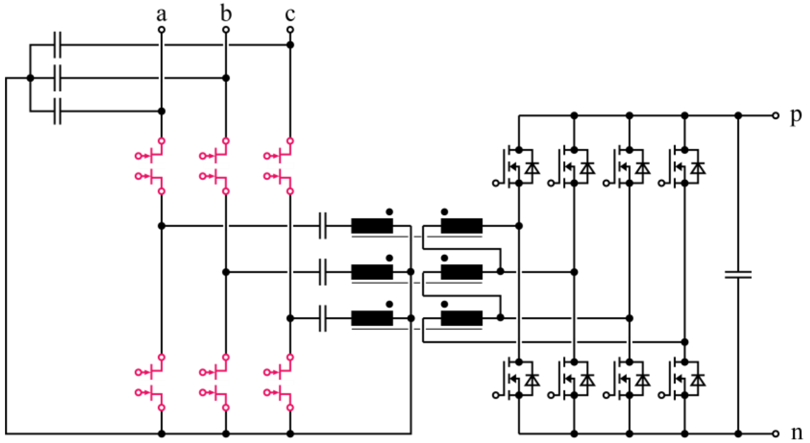
- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

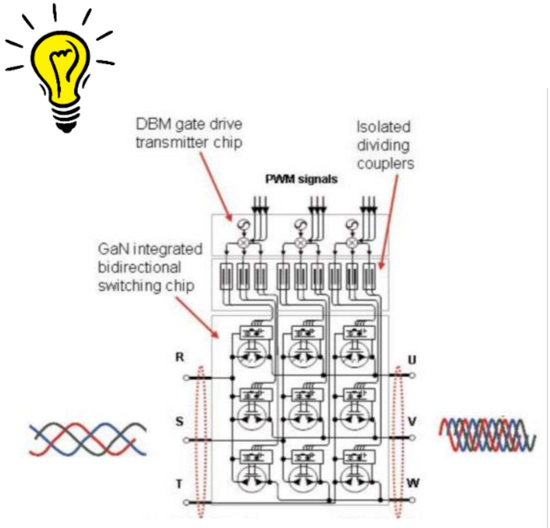
Single-Stage Isolated 3-Φ AC/DC Conversion 1/2

- *3-Φ Matrix-Type AC/DC Converter w/ Three-Phase Transformer — i3X-Rectifier*
- *Advantageous for Future 20…50kW AC/DC Power Supply Modules*



Source: Panasonic

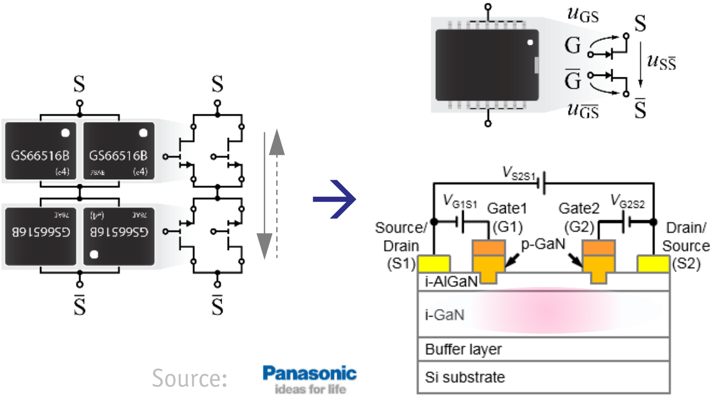




- *Use of MBDS GaN Power Transistors — Eliminates Factor of 4 Chip Area Penalty (!)*
- *Lateral GaN Device Technology — Facilitates Monolithic Integr. of Matrix-Type Switching Stage & Gate Drives*

Single-Stage Isolated 3-Φ AC/DC Conversion 2/2

- *3-Φ Matrix-Type AC/DC Converter w/ Three-Phase Transformer — i3X-Rectifier*
- *Advantageous for Future 20...50kW AC/DC Power Supply Modules*



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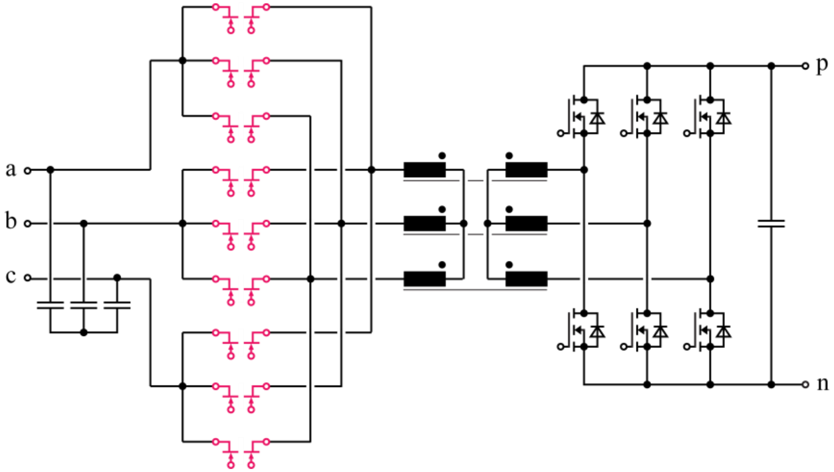

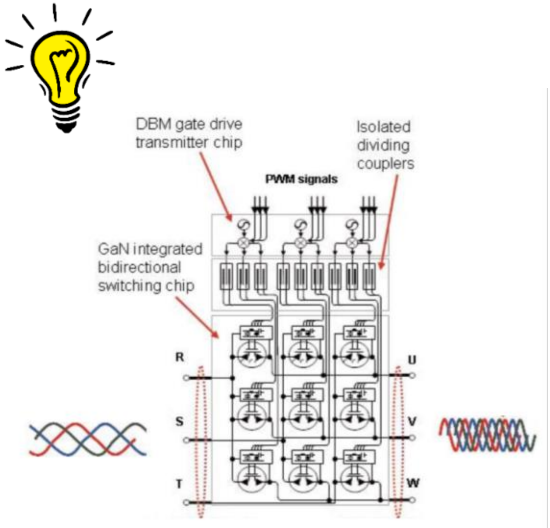

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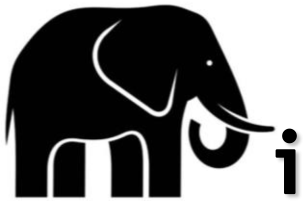
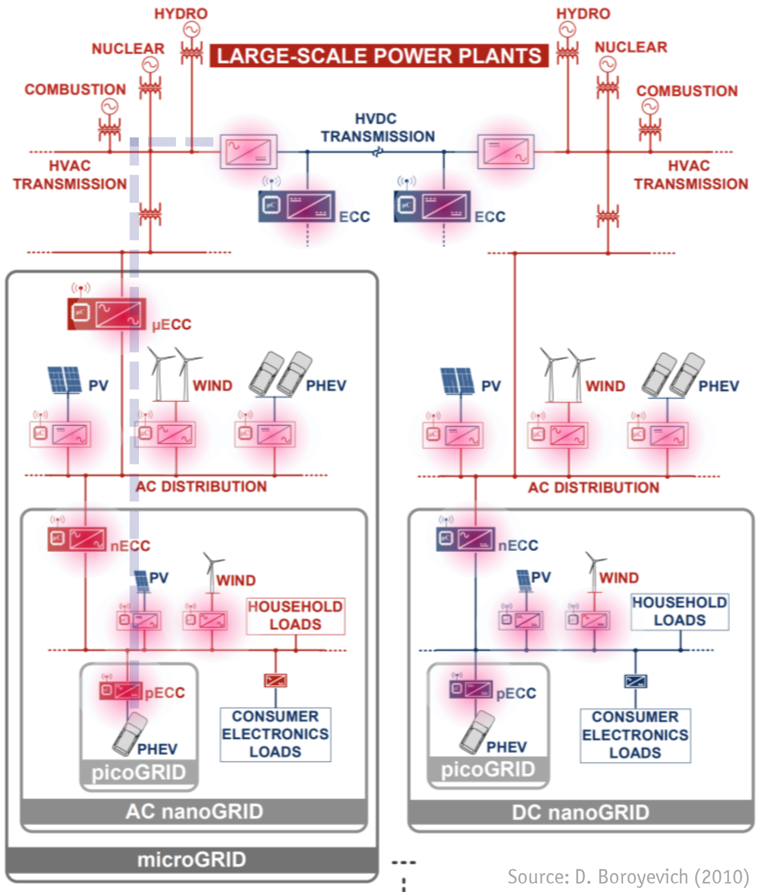
Advanced Mechatronic Systems Group

Power Electronics 5.0

"Zero-Waste" Paradigm

ETH zürich

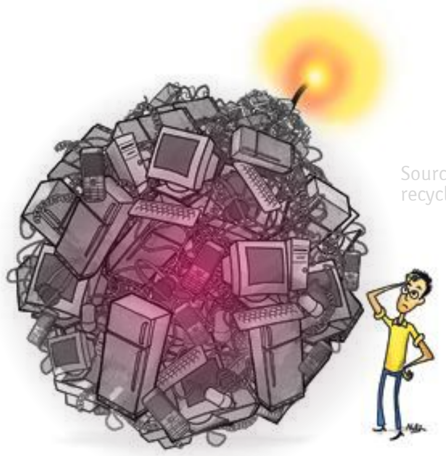
The  in the Room



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*

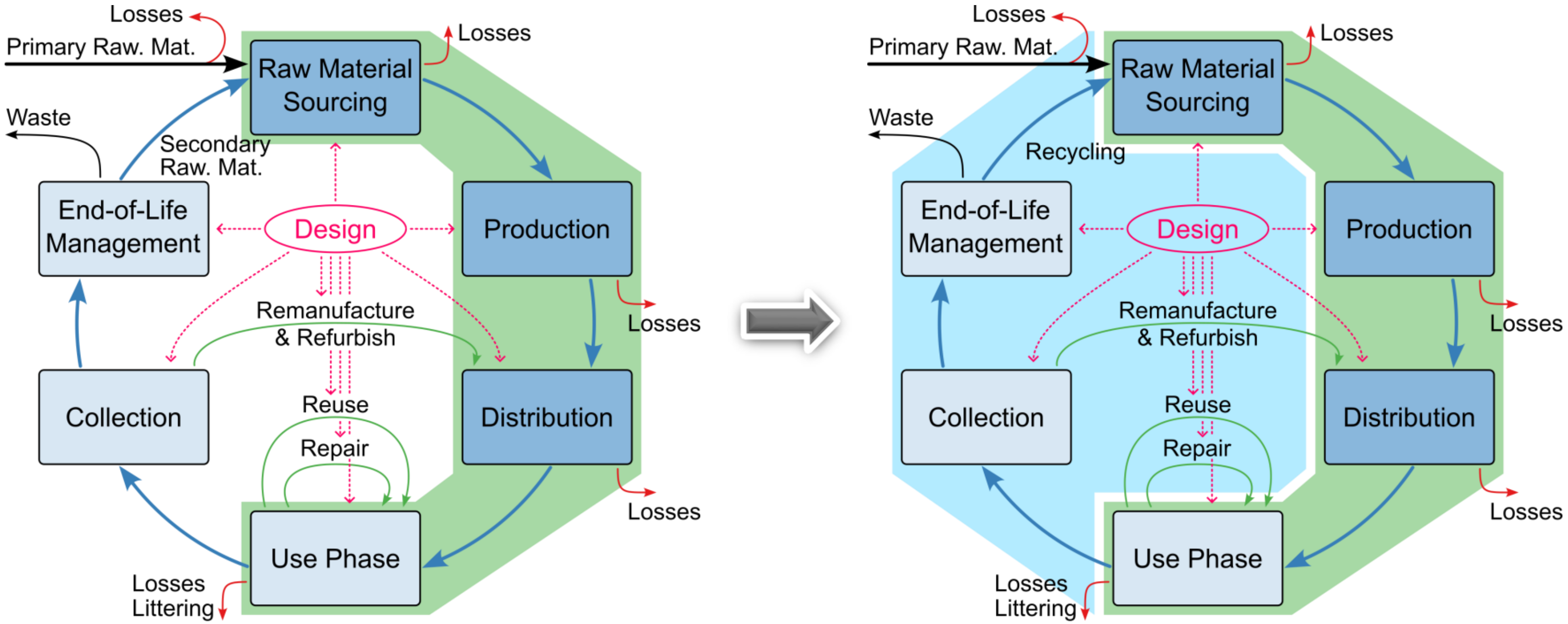


Source: www.e-waste-recyclers.co.in

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

Power Electronics 5.0 — "Closing the Loop"

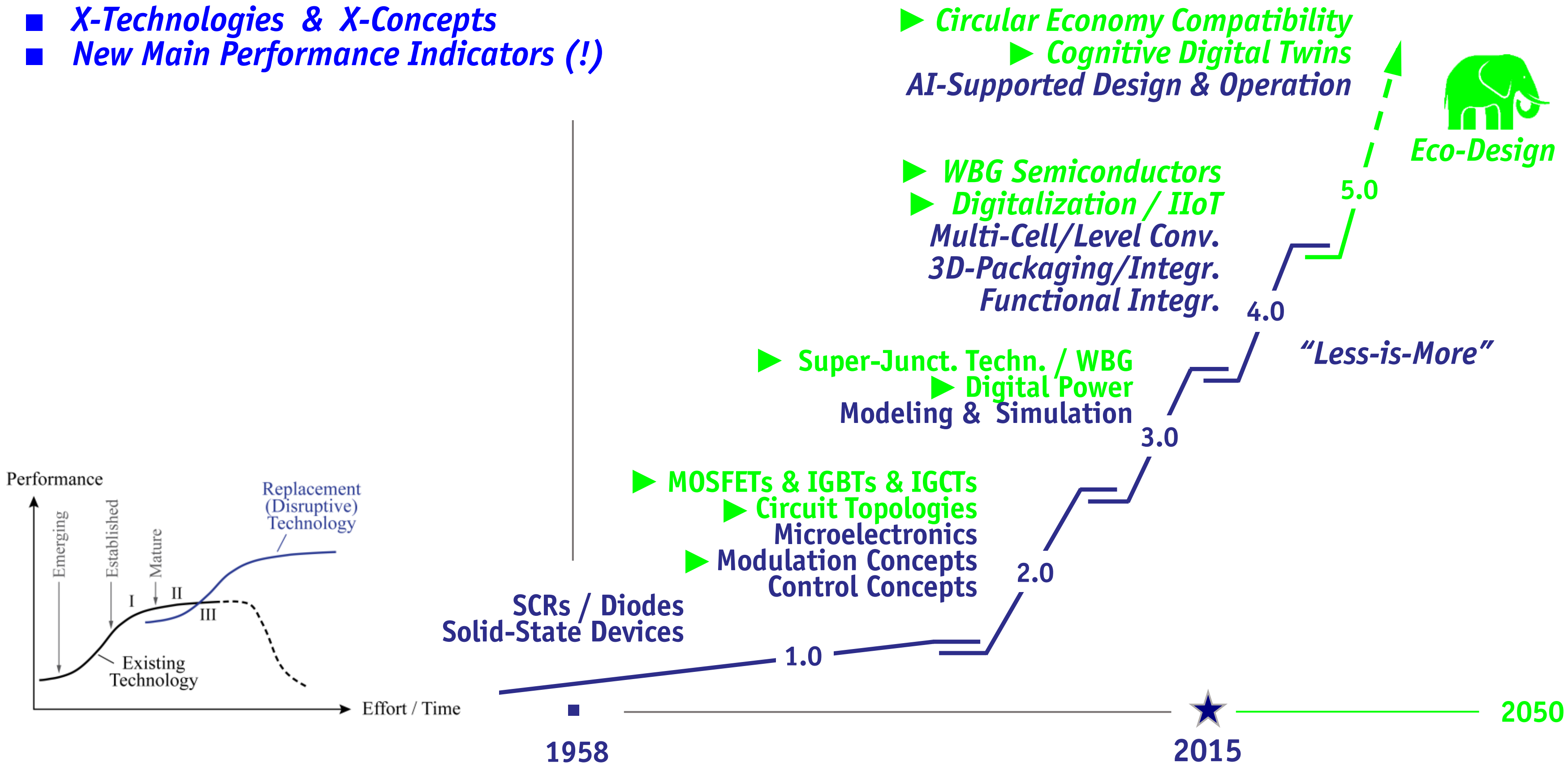
- *Infinite Consumption form a Finite Resource Base is Impossible (!)*
- *80% of Environmental Impact of Products Locked-In @ Design Stage*



- *"4R" Included Into the Design Process — Repair | Reuse | Refurbish | Recycle*
- *"Life-Cycle Cost Perspective" — Potentially Advantageous for Suppliers & Customers*

Power Electronics 5.0

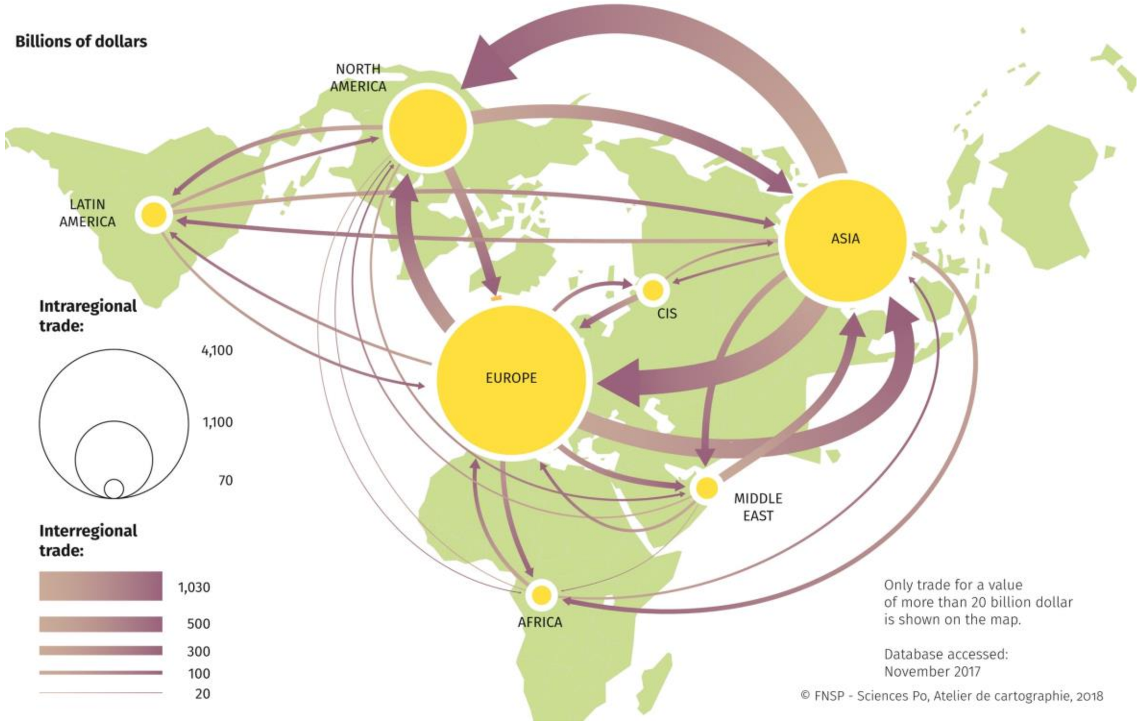
- *Power Electronics 1.0 → Power Electronics 5.0*
- *X-Technologies & X-Concepts*
- *New Main Performance Indicators (!)*



Conclusion

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*

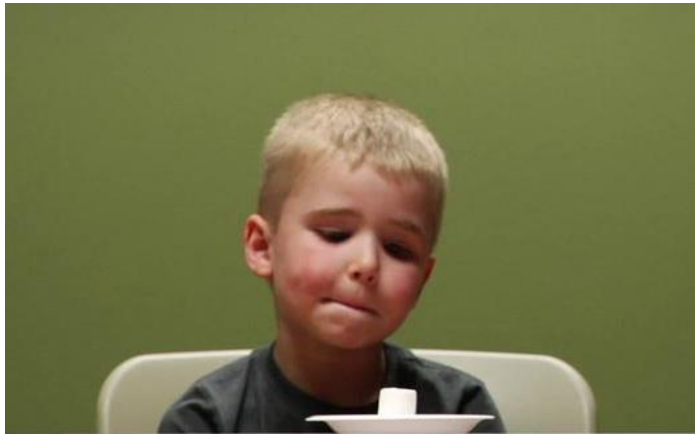


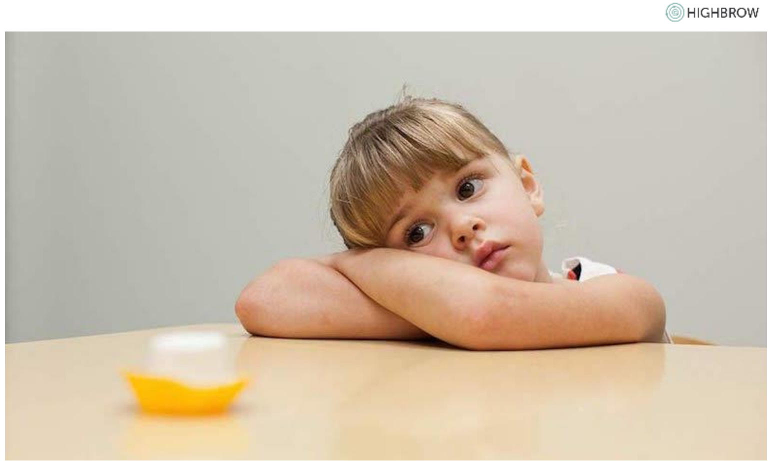
- *Environmental Impact Aggregates Over Time — No Serious $$$-Consequences / "Tragedy of Commons"*
- *"Prisoner´s Dilemma" — Why Take Action If You Can´t Be Sure Other Countries Will Act As Well?*

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/





- *"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, … , 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"*

Thank you!

Source:
www.terencemauri.com