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Uncharted Territories in Power Electronics

Johann W. Kolar et al.

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

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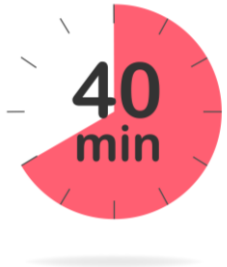


Outline

- *Introduction*
- *Mastering the Deep*
- *Taking Actions for a Healthy Planet*
- *Unlocking the High Frontier*
- *Conclusions*

Acknowledgment

Florian Krismer
David Menzi

Mastering the Deep

Deep-Sea E-HyDrones
Subsea Resident AUVs

Blue Economy

- *Economic Sectors Related to Exploitation / Preservation / Regeneration of Marine Environment*
- *Established Sectors — Maritime Transp. | Ship Buildg | Fishing | Off-Shore Oil & Gas | Coastal Tourism | etc.*

Source: EU Science Hub

- *Emerging Activities — Floating Off-Shore Wind & Solar Energy | Wave & Tidal Energy | Sub-Sea Robotics etc.*
- *Important Role in the EU´s Transition Towards a Carbon-Neutral / Circular / Biodiverse Economy*

Floating Off-Shore Wind Power Plants

- *80% of Off-Shore Wind Energy Available in Deep Waters*
- *Higher & More Consistent Wind Speeds / Lower Environmental Impact*

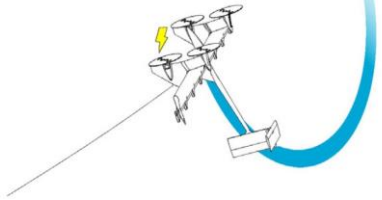
Source: Josh Bauer / NREL

- *Floating Support Structures for Seabed Depths > 60m — Seabed Connection Through Mooring Cables*
- *3 Basic Types — Tower-Like Spar Buoy | Semi-Submersible | Tension Leg (Mooring Cables Under Tension)*

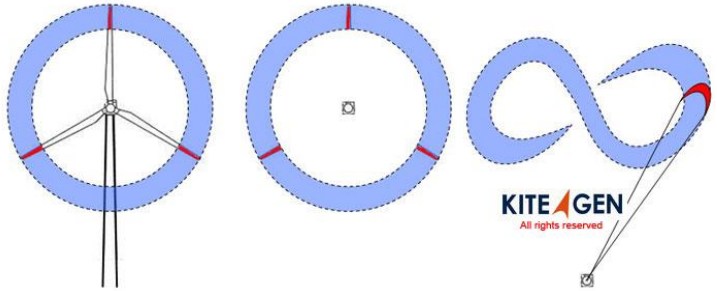
Remark Airborne Wind Turbines

- *"Pulling Power from the Sky" — Replace Conv. Windmills by Airborne Devices Suspended High Up in the Air*
- *Tether Cable Replaces Massive Steel Tower / Aerofoil Kite or Glider Replaces Long Rotating Turbine Blades*

Source: Ph. Bechtle, 2019



$$P_{\mathrm{T,i}} = c_{\mathrm{P,i}} \frac{1}{2} \rho A_{\mathrm{T}} v_{\mathrm{W}}^{3}$$



Source: MAKANI & AWEC 2019

- *High Crosswind Speed → Very Small Turbine Area / Higher & More Consistent Wind Speeds @ High Altitudes*
- *Floating Platform Anchored in Deep Water | On-Board Generators & Tether Conducting Electricity to Ground*

Floating Off-Shore Solar Plants

- *10x Growth of Solar Power to 5…10 TW Mandatory for Closing the Emission Gap*
- *Dense Population / Land Shortage → Utility-Scale Solar Projects on Inland Waters and in Oceans*
- *Potential Combination of Off-Shore Wind & Off-Shore Solar Infrastructures*

Source: www.rechargenews.com

- *Higher Sun Irradiance @ Sea & Lower Temperature → Higher Efficiency*
- *Destructive Wind & Wave Forces → Membrane-Type Flexible Circular Platforms w/ Buoyancy Rings*
- *Potentially Lower Cost of Off-Shore Solar Compared to Off-Shore Wind — 2x Higher GWh/km²*

Off-Shore Green-H_2 Production

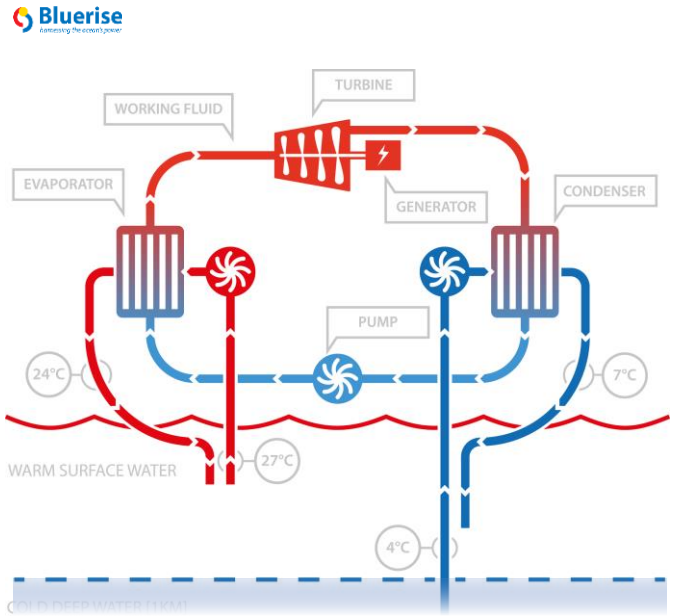
- *Energy Transport via Molecules / Hydrogen Avoids High $$$ of HVDC Cables / Systems*
- *Declining Oil & Gas Production → Repurposing of Offshore Assets / Platforms, Pipelines etc.*

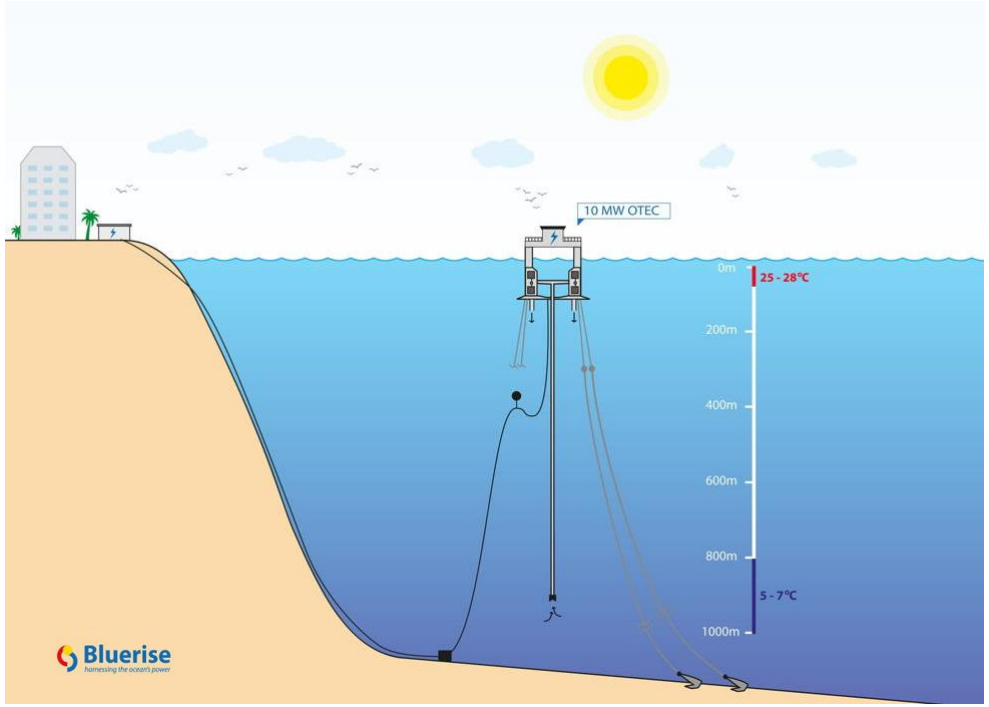
Source: https://tractebel-engie.com

- *P2G → Desalinated H_2O Electrolyzers on Off-Shore Platforms Converting Wind Energy to "Green Hydrogen"*
- *60-80% Conversion Efficiency / Multi-GW Scale / Interconnection of Neighboring Countries*

Ocean Thermal Energy Conversion

- *Temperature Difference in Oceans Utilized for 24/7 (!) Electricity Generation*
- *25°C Surface Water Vaporizes Low Boiling Point Ammonia – Expanding Vapor Drives Turbine*
- *Vapor @ Turbine Output Condensed by 5°C Seawater Pumped from -1000m*

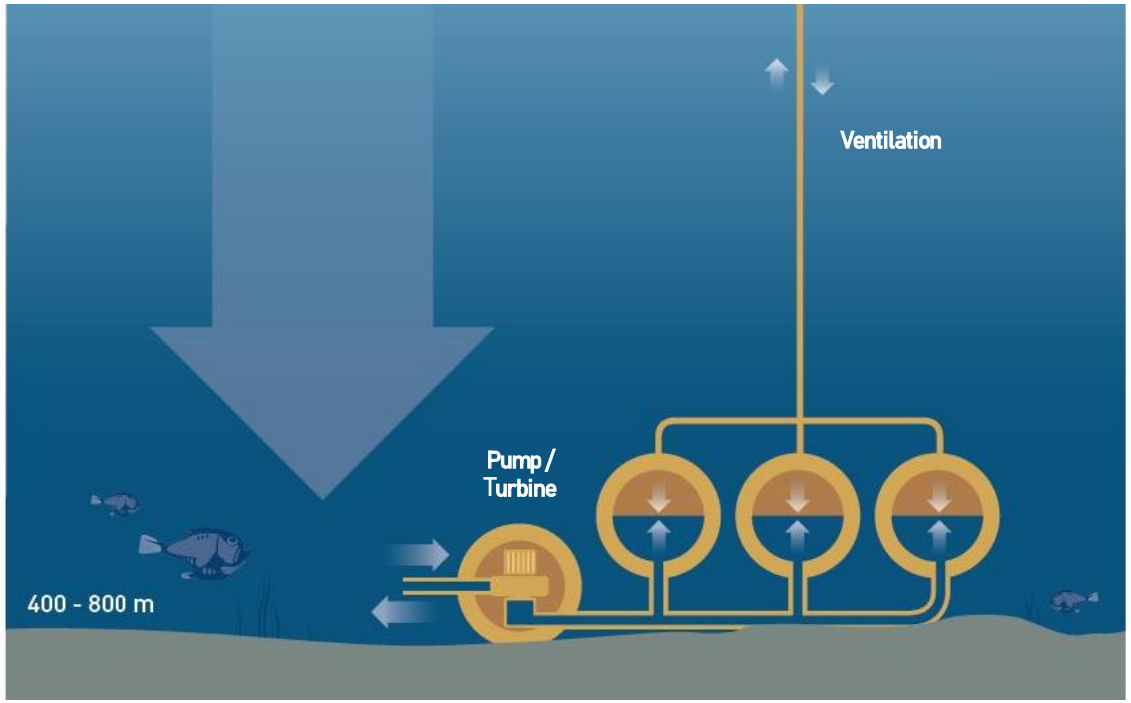




- *10MW OTEC Pilot Planned in Southern China by Lockheed Martin & Reignwood Group*
- *Potential of ≈ 7 TW Globally w/o Significant Effect on the Ocean Temperature Fields (30 TW Total Resource)*

Subsea Pumped Hydro Storage

- *GWh-Scale 10 MWh-Modular / Scalable Storage @ Seabed Exploiting the High Deep-Sea Pressure*
- *Off-Shore Installation Near Wind Farms / Floating Solar Farms / Tidal & Wave Energy Systems etc.*

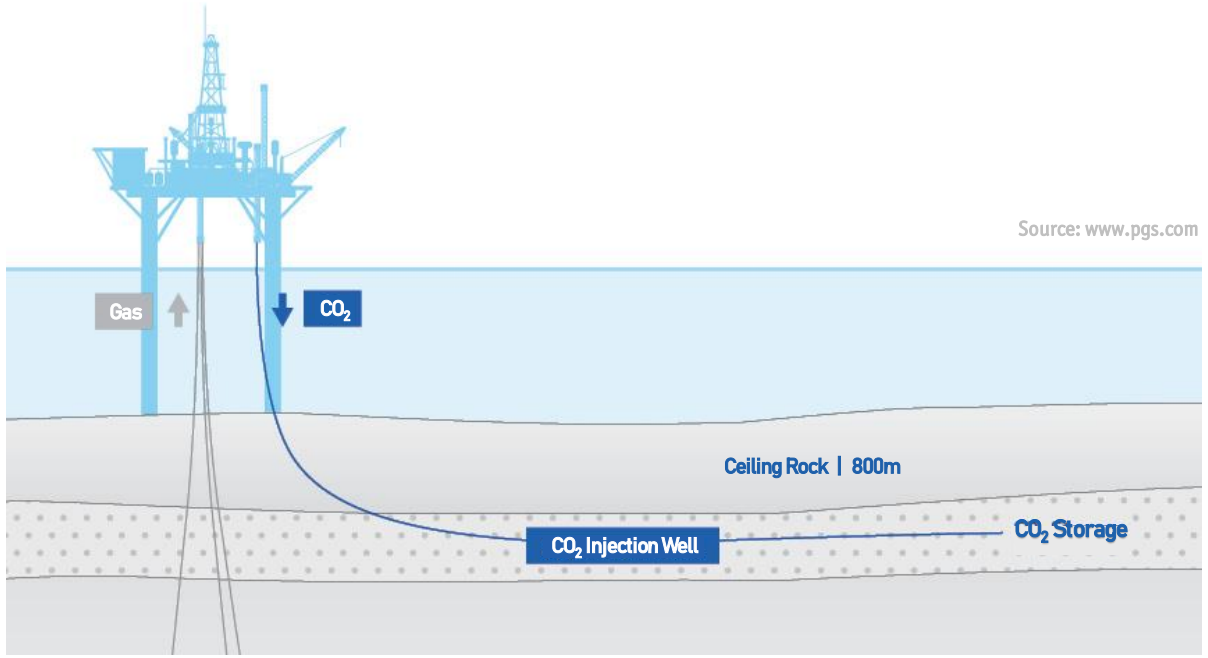


Source: SINTEF

- *Charging → Pumping Water from Low-Pressure Rigid Reservoir into High Pressure Environment*
- *Discharging → High Pressure Environment Pushes Water Into Reservoir / Drives Turbine*

Off-Shore CO_2 Storage

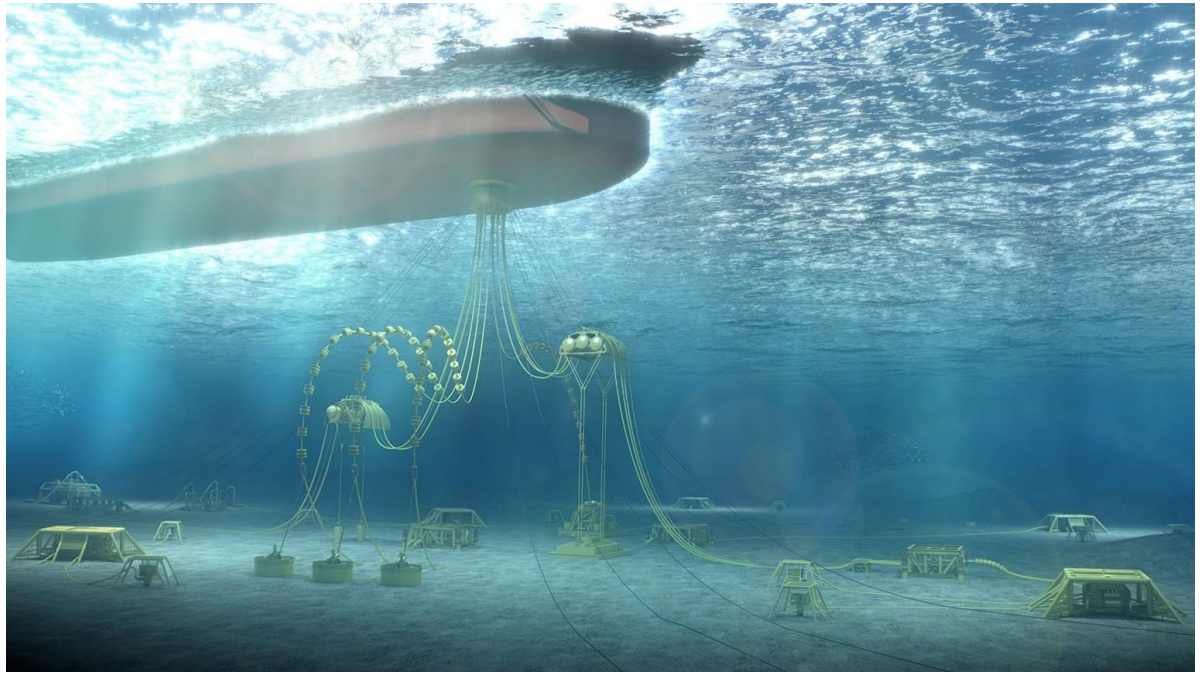
- *CO_2 Capture & Storage (CCS) → Main Element of the Energy Transition to a Low Carbon Future*
- *Future Industrial CCS Value Chain → CO_2 Transported by Ships & Stored in Off-Shore Formations*



- *World´s 1st Off-Shore CCS Plant in Operation since 1996 in Sleipner Natural Gas Field (Equinor = Statoil)*
- *Norwegian CO_2 Tax Introduced 1991 → CO_2 Contained in Natural Gas Re-Injected Into Porous Sandstone*

Subsea Industry / Autonomous Factories

- *Deep-Sea Oil & Gas Extraction / Processing — No Platforms / Lower $$$ | Deep-Sea Mining*
- *Lower Environmental Impact of Natural Gas Compared to Coal → "Golden Age of Gas"*

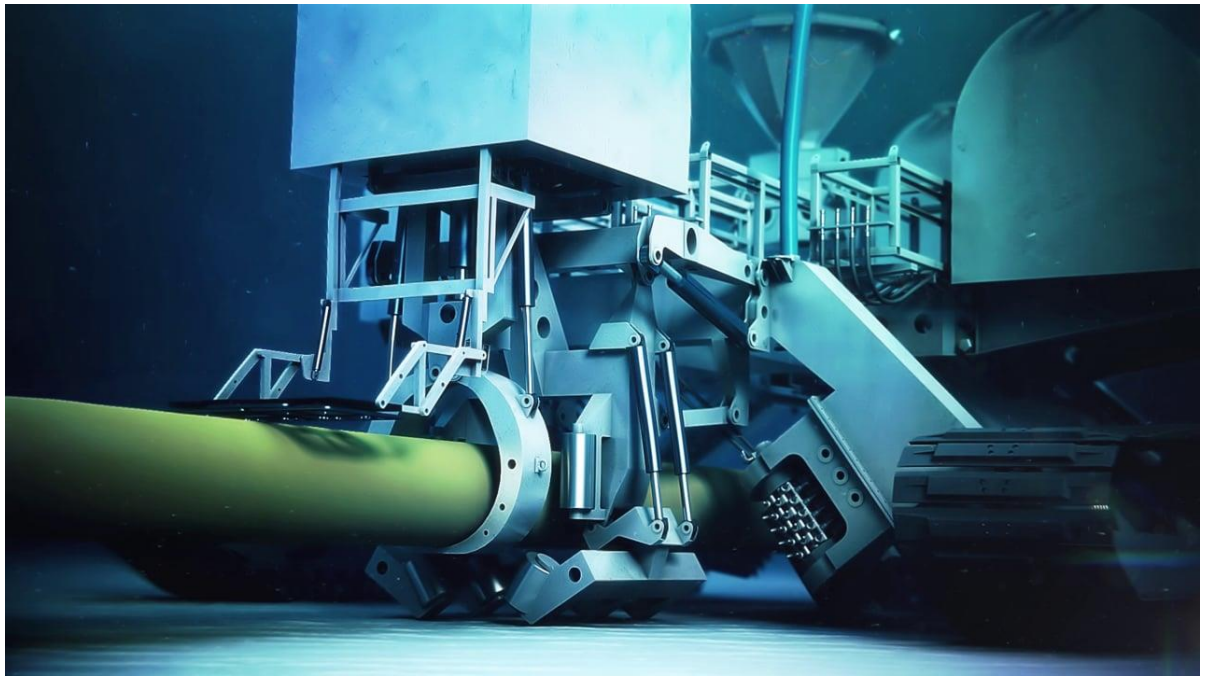


Source: www.ocean-5.com

- *Hydraulic Wells → High Eff. All-Electric Wells → No High Pressure Equipm. / No Pipe Leaking / Lower $$$*
- *Long Distance DC Power Transmission (600km, 100MW, 3000m) → Pumps etc. Located @ Seabed*

Seabed Interventions – 1/2

- *Burial of Subsea Pipelines and Cables*
- *Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000m Operation Depth*



Source: DEEPOCEAN

- *World´s Most Powerful Trencher (T3200 / 2.4MW / DeepOcean)*

Seabed Interventions – 2/2

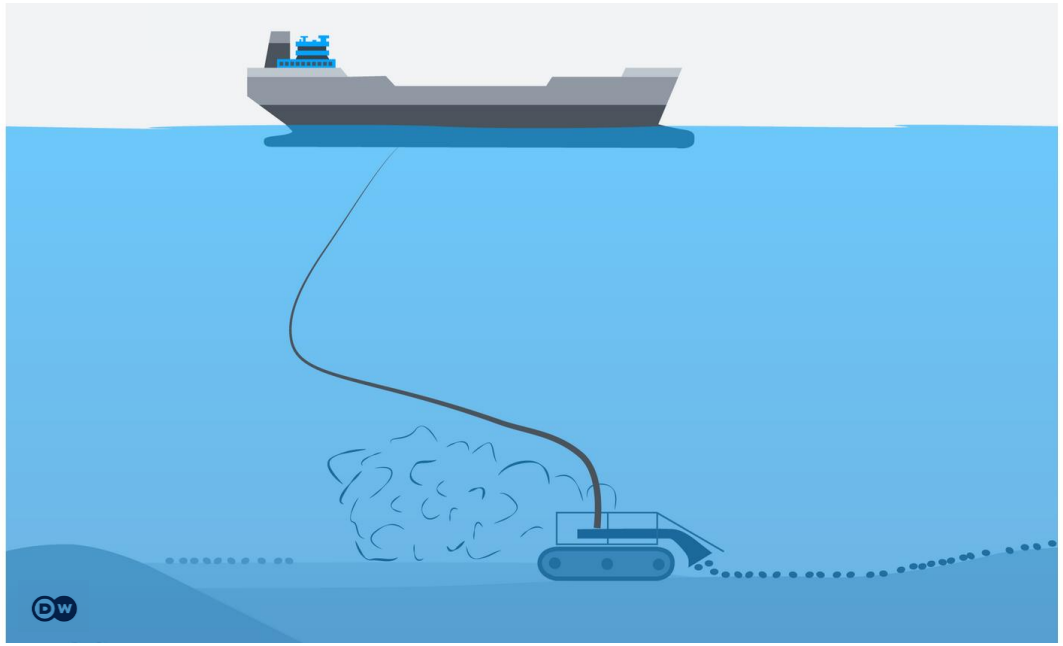
- *Burial of Subsea Pipelines and Cables*
- *Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000m Operation Depth*

Source: DEEPOCEAN

- *World´s Most Powerful Trencher (T3200 / 2.4MW / DeepOcean)*

Deep-Sea Mining Vehicles – 1/2

- *Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000...6000m)*
- *Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel*



Source: www.hydrographica.org

- *Potential Serious Threat to Global Oceans (!)*

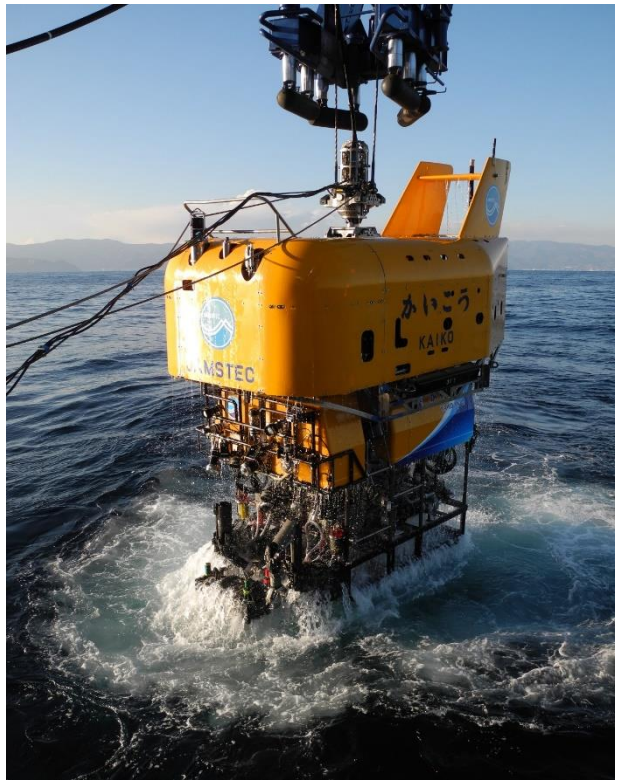
Deep-Sea Mining Vehicles – 2/2

- *Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000…6000m)*
- *Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel*

Source: GSR

- *Patania II 25t Robot "Nodule Collector" (Tested @ 4500 m)*

Scientific Exploration of Ocean Depths



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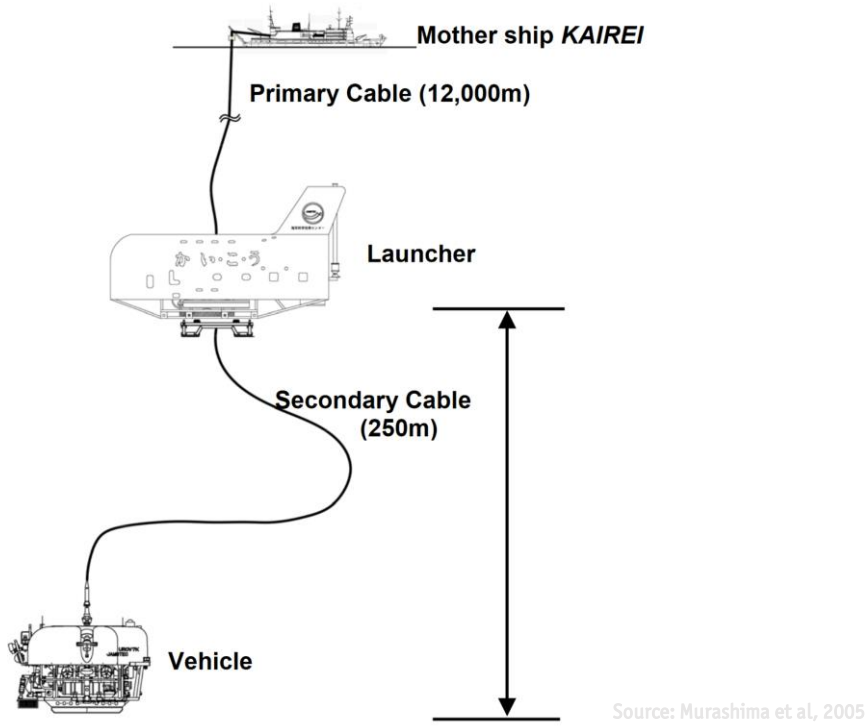


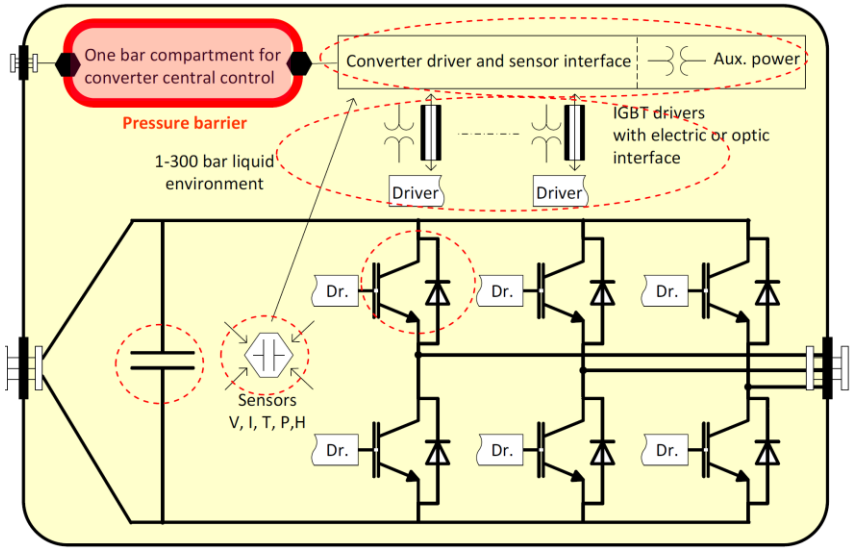
Source: Murashima et al, 2005

- *Full Ocean Depth ROV Kaiko / JAMSTEC (Launcher & Vehicle) → 10´911m / Lost During a Typhoon*
- *New 11´000m-Class ROV (ABISMO — Automatic Bottom Inspection and Sampling Mobile)*

Remark Electronics Pressure Housings

- *Air or Gas Filled Components → Would Implode in Large Depths (e.g. 6000m → 600bar)*
- *One-Atmosphere Housings → Maintain Constant Inside Pressure / Cylindrical or Spherical Shape*
- *Pressure Balanced Housings → Int. ≈ Ext. Pressure / Oil Filled – No Voids / Not Shape (Cooling) Restricted !*

Source: M. Hernes SINTEF



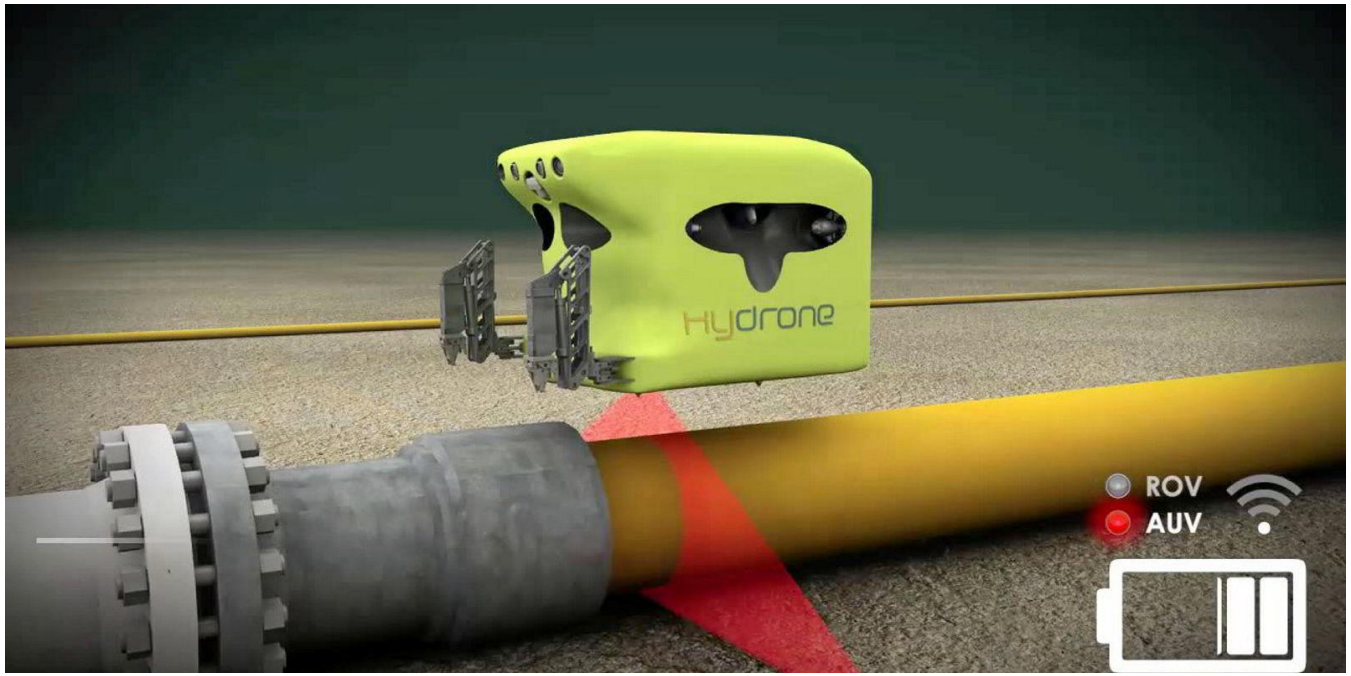
Source: SAAB

Electronics Compartment of Seaeye Jaguar

- *Research on Pressure-Tolerant Power Electronic Components (300bar) @ SINTEF*
- *IGBTs → Sw. Behavior Unaffected / Chip Interface Needs to be Protected from Surrounding Liquid*
- *Pressure Affects BH-Curve of Magnetic Cores & Impairs Self-Healing of PP Film Cap. → Voltage Derating*

Autonomous Underwater Vehicles — AUV

- *Self-Powered & Self-Guided → No Tether or Line to Crewed or Uncrewed Surface Ship / Lower Mission $$$ etc.*
- *Mission Range & Duration Limited by Onboard Battery Capacity*

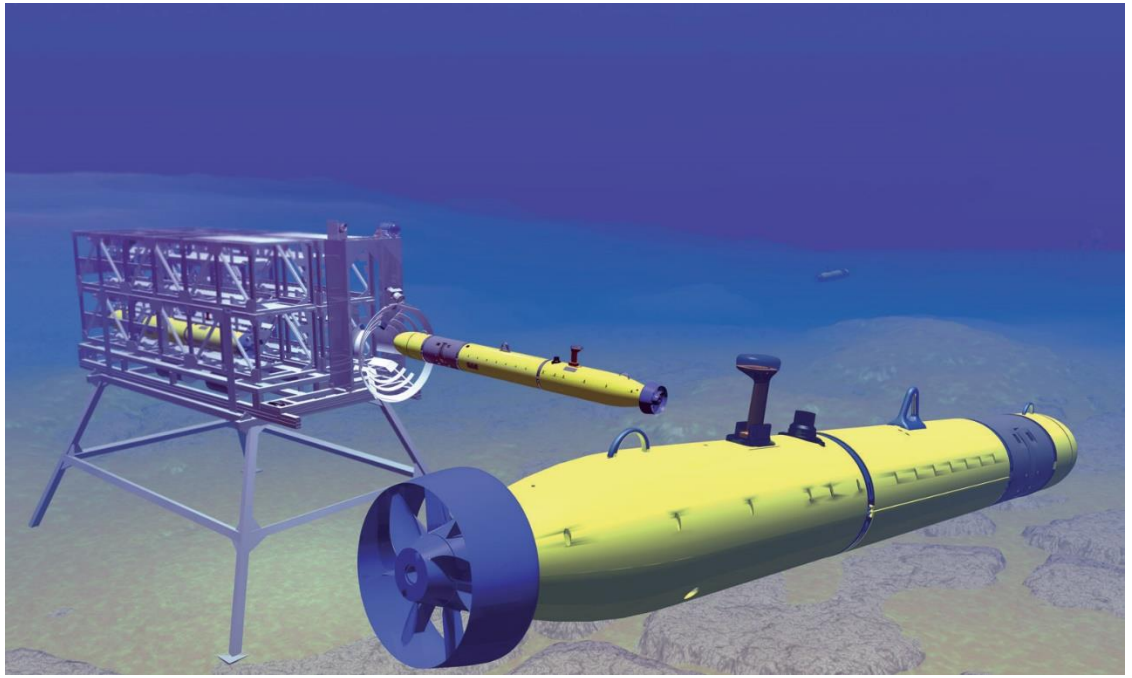


Source: SAIPEM

- *Seabed Docking Station for Battery Recharge / Mission Download & Data Offload → Enables Subsea Residency*
- *Local Power Generation & Surface Communication | Unmanned Surface Vehicle for Launch & Recovery*

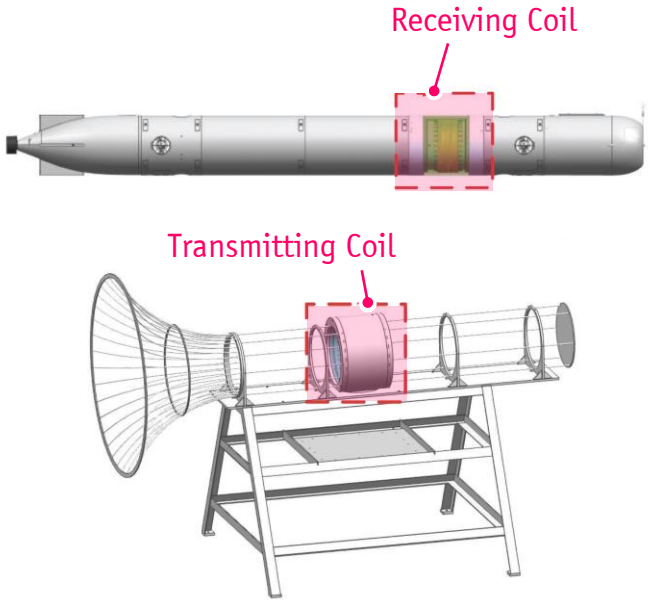
Wireless AUV Charging — Resonant IPT

- *Co-Axial Arrangement of High-Q Coils Operating in Resonance / Relatively Large Misalignment Tolerance*
- *Funnel-Shaped Recovery Cage — Entry Cone & Docking Tube*



Source: www.oedigital.com

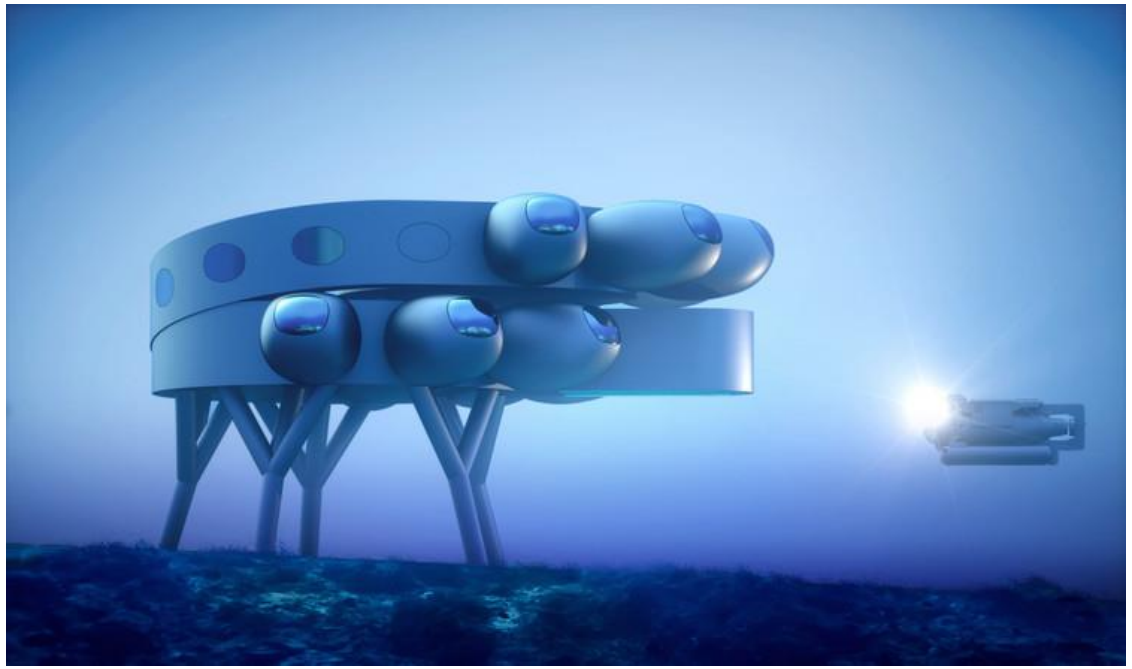
Source: Peizhou Liu et al., 2022



- *Ferrite Elements for Magn. Flux Shaping → Red. Field/EMI Inside the AUV & Red. Eddy Curr. in AUV Metal Hull*
- *Coil Geometry Adapted to Physical AUV Structure → Limited Interoperability*

Future Underwater Habitats

- *Underwater Version of the International Space Station*
- *Discovery of New Species of Marine Life / Aquacultures / Understanding Climate Change Effects*

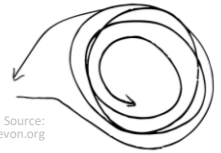


Source: ArchDaily / Protheus

- *PROTEUS — First in a Network of Future Underwater Habitats*

Taking Actions for a Healthy Planet

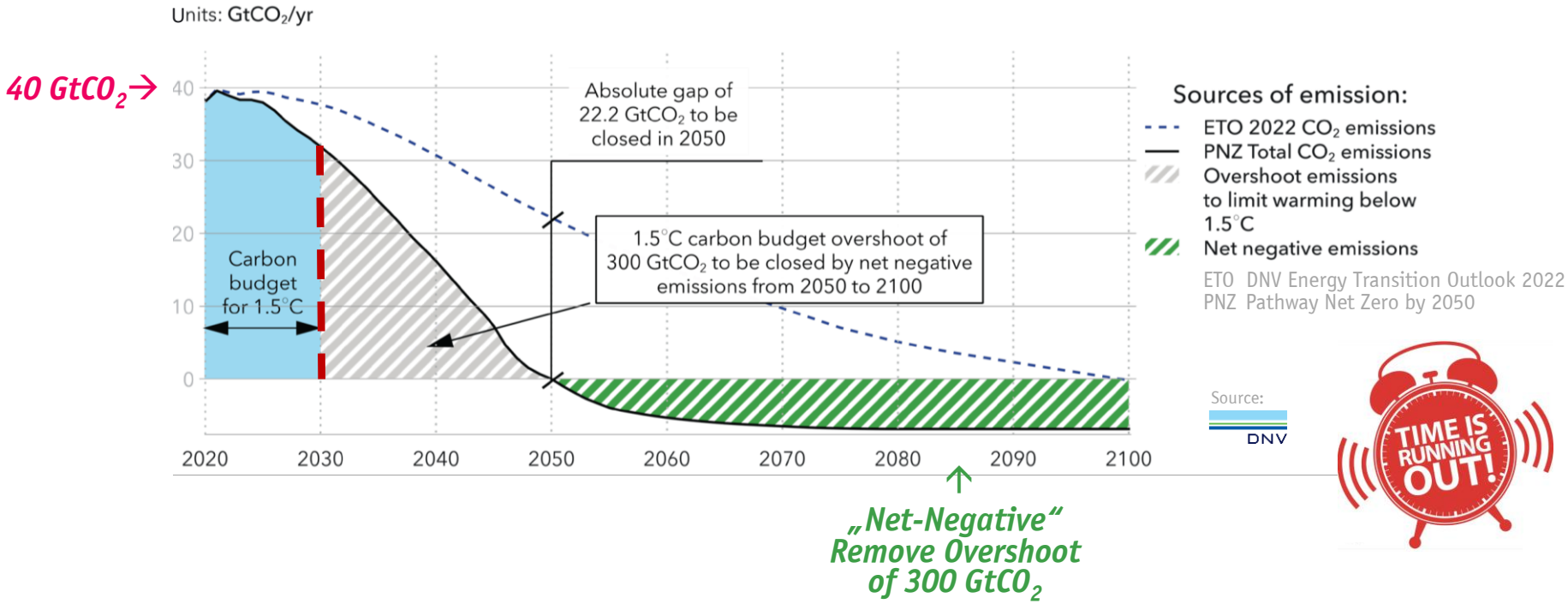
Decarbonization
Circular Economy



Source:
zone.recycledevon.org

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*

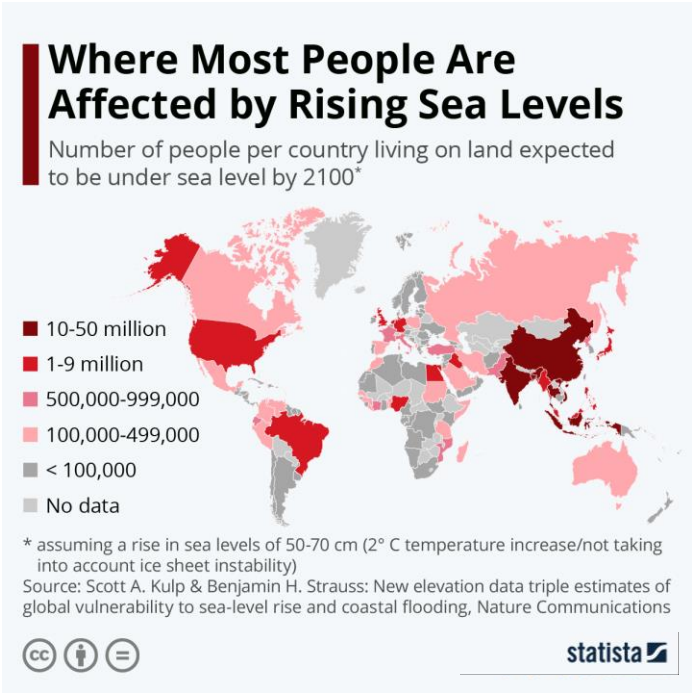


- *Challenge of Stepping Back from Oil & Gas*
- *Human History — Transition from Lower to Higher Energy Density Fuel — Wood → Coal → Oil & Gas*

Remark Global Sea Levels by 2100

- *Rising Sea Levels Due to Global Warming*

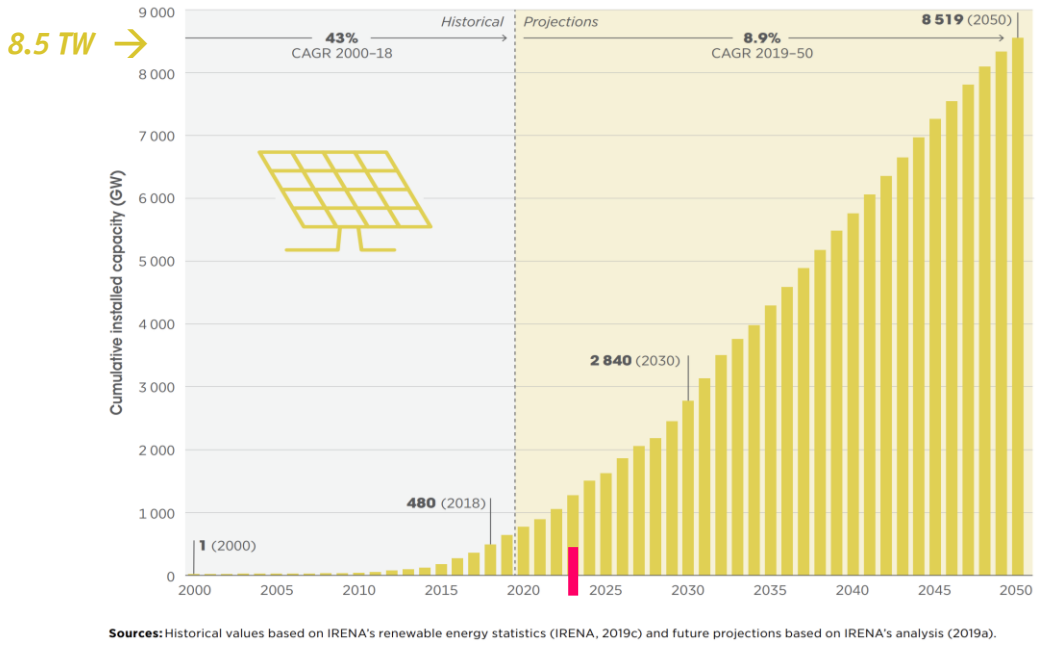
@ 2°C Temp. Increase



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

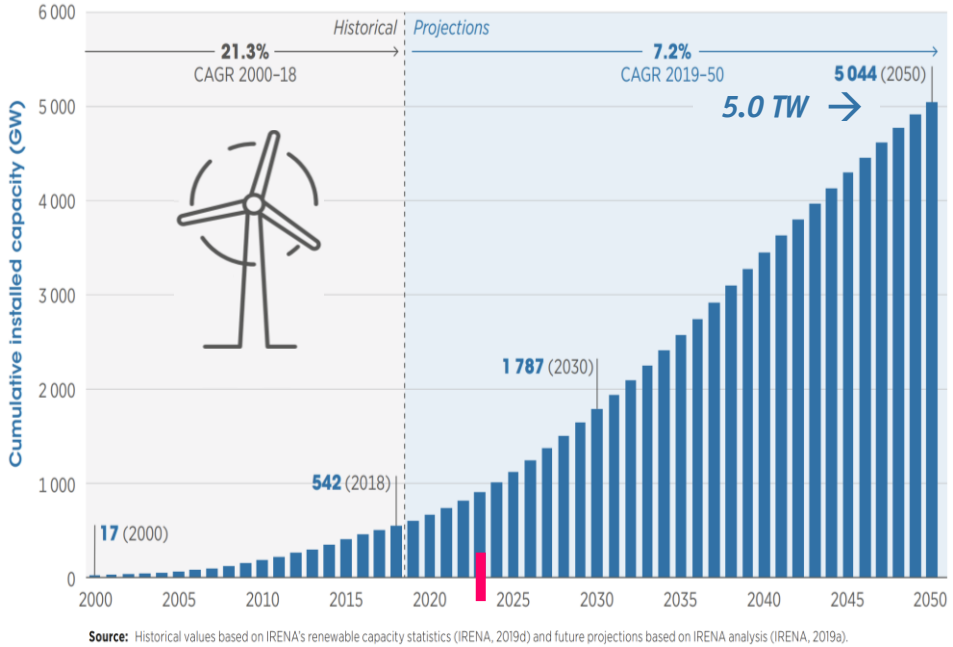
The Solution

- *Outlook of Global Cumulative Installations Until 2050 / Add. 1000 GW Off-Shore Wind Power*
- *In 2050 Deployment of 370 GW/Year (PV) & 200 GW/Year (On-Shore Wind) incl. Replacements*



Sources: Historical values based on IRENA's renewable energy statistics (IRENA, 2019c) and future projections based on IRENA's analysis (2019a).

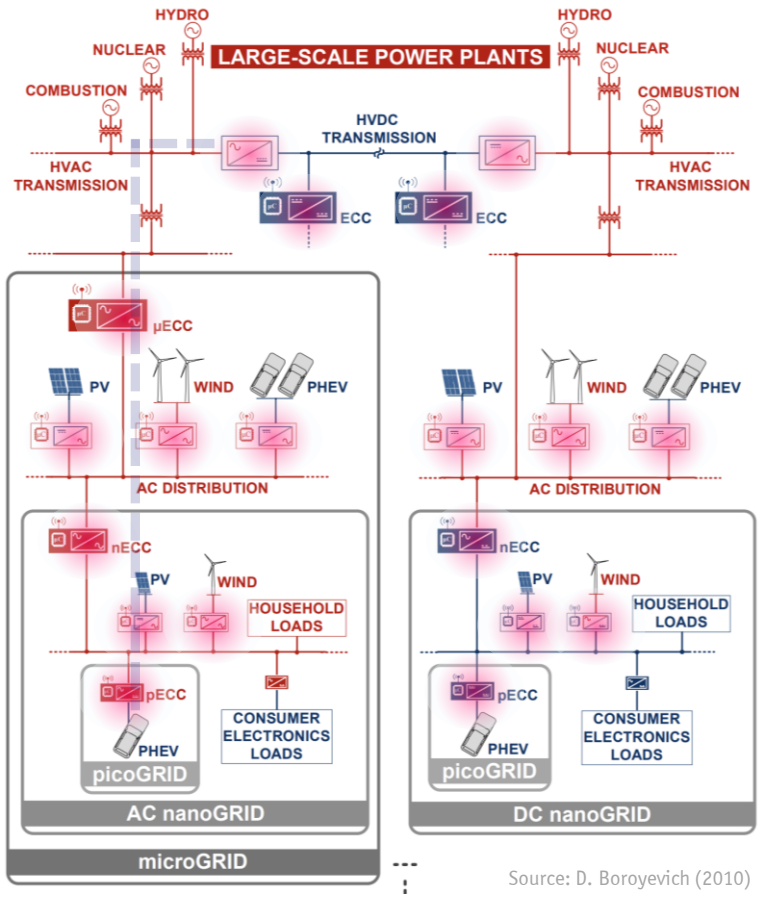
- *CAGR of ≈9% up to 2050 → 8500 GW*



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

- *CAGR of ≈7% up to 2050 → 5000 GW*

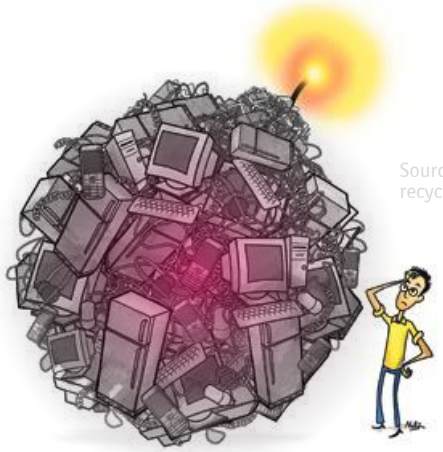
The in the Room



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*

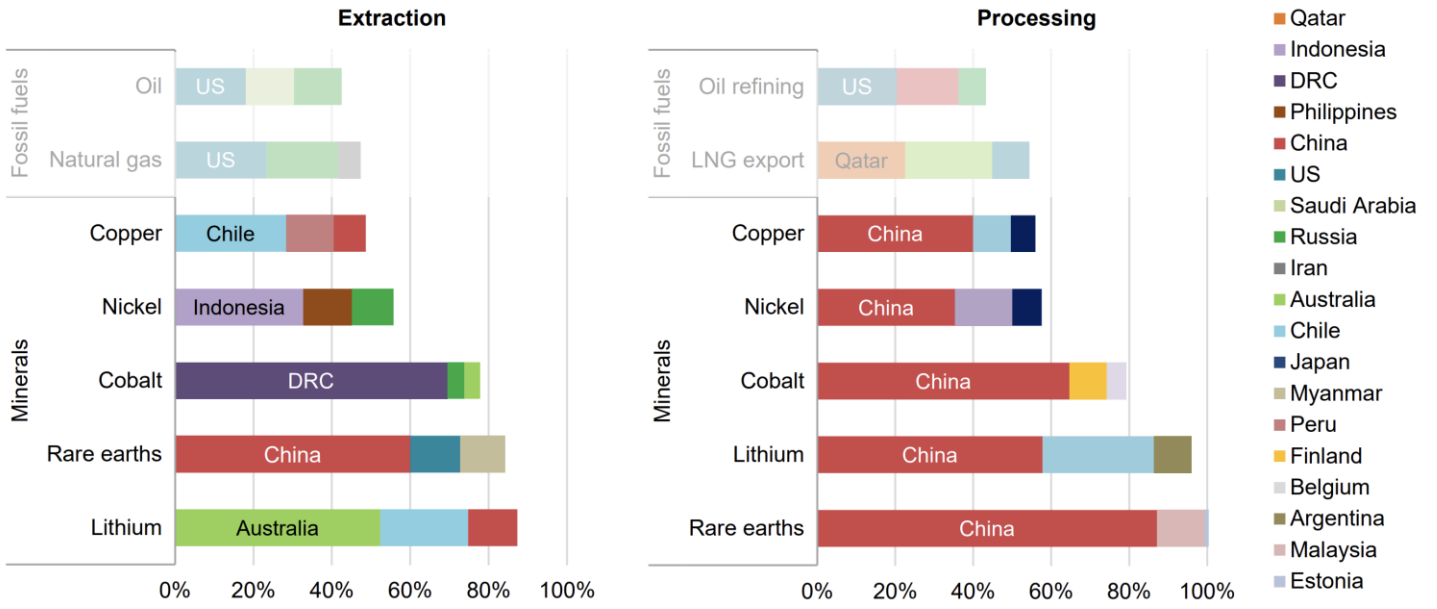


Source: www.e-waste-recyclers.co.in

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

Critical Minerals

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



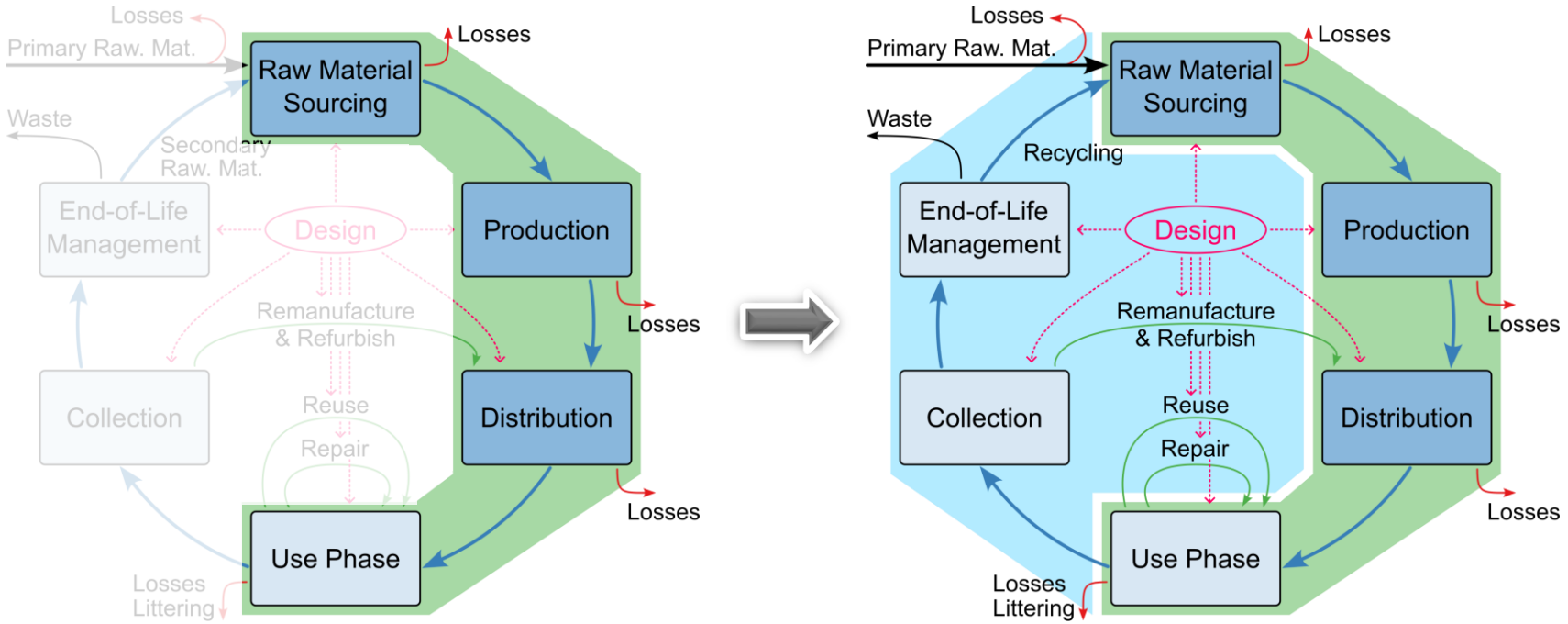
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

Shares of top three producing countries, 2019

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

"Closing the Loop"

- *"4R" Included Into the Design Process — Repair | Reuse | Refurbish | Recycle*

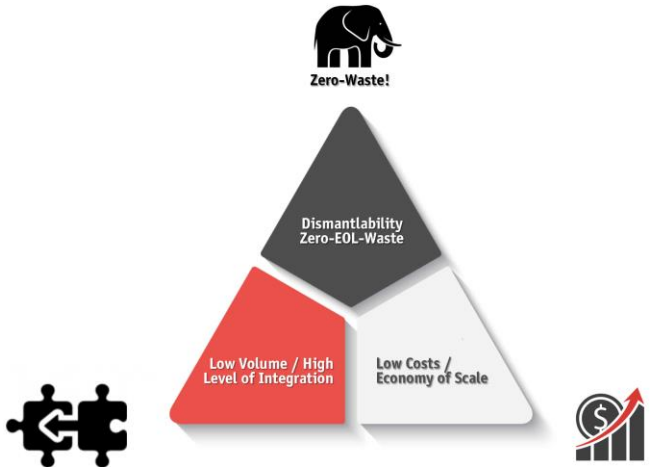


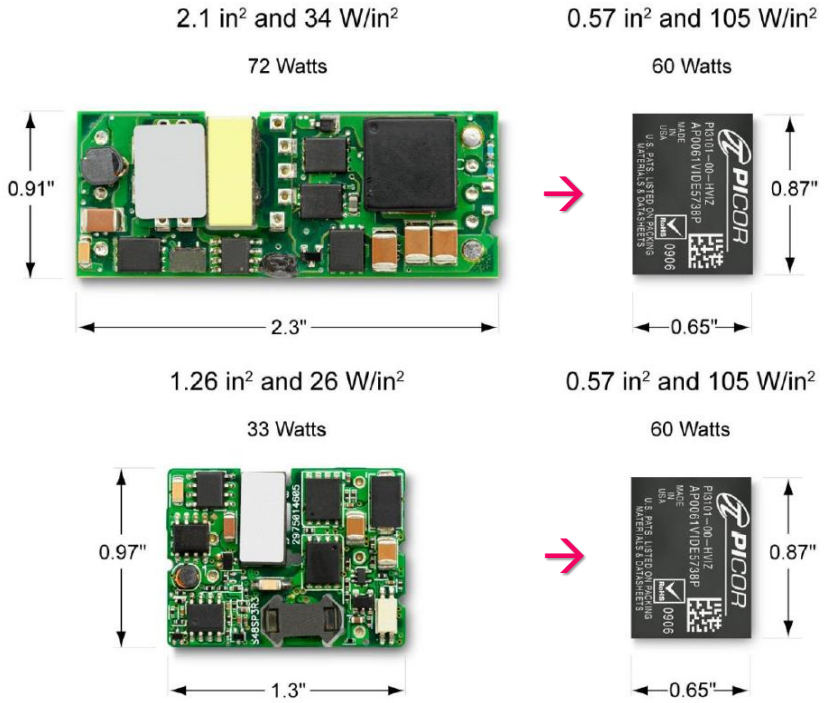
- *Life-Cycle Cost Perspective Potentially Advantageous for Suppliers & Customers*
- *Quantification of Repairability / Reusability / etc. Still to be Clarified*

Remark "Integration" vs. Circular Economy

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

Source: VICOR

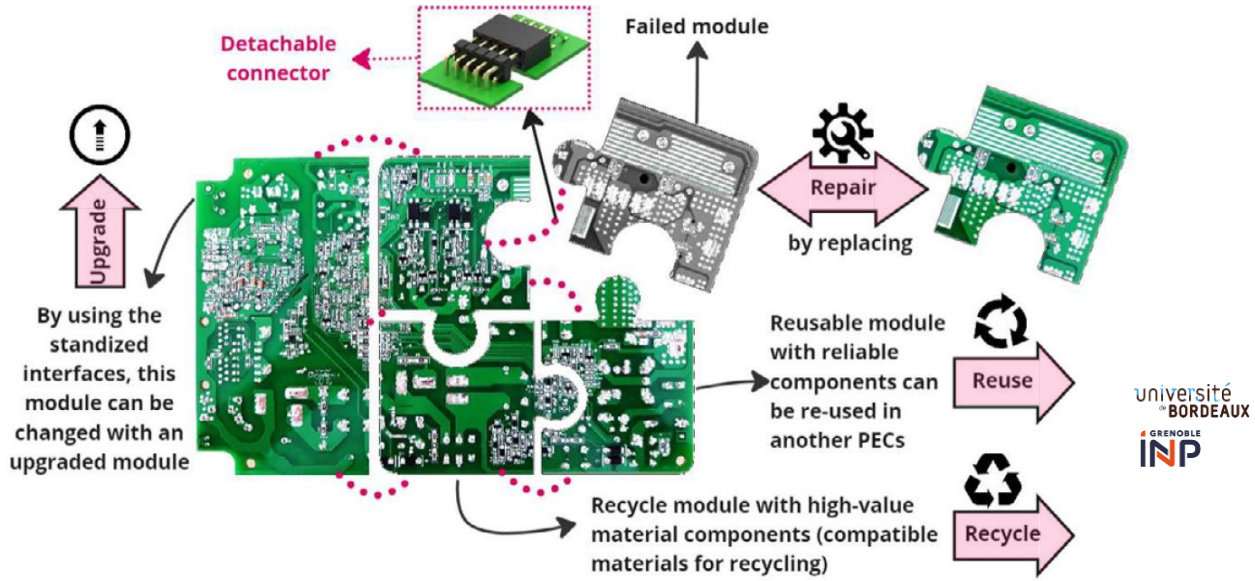




- *Extreme Power Density / Dismantlability (?)*
- *Specific Functionality / Economy of Scale (?)*

Modularity — Facilitating Upgrade | Reuse | Repair

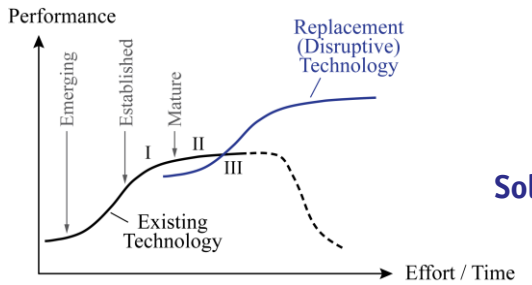
- *Modular Design Considering Ease of Disassembly | Maintainability | Upgradability | Reusability | etc.*
- *Grouping of Components Determined by Reliability Level & Expected Lifetime / Level of Reusability or Recyclability*

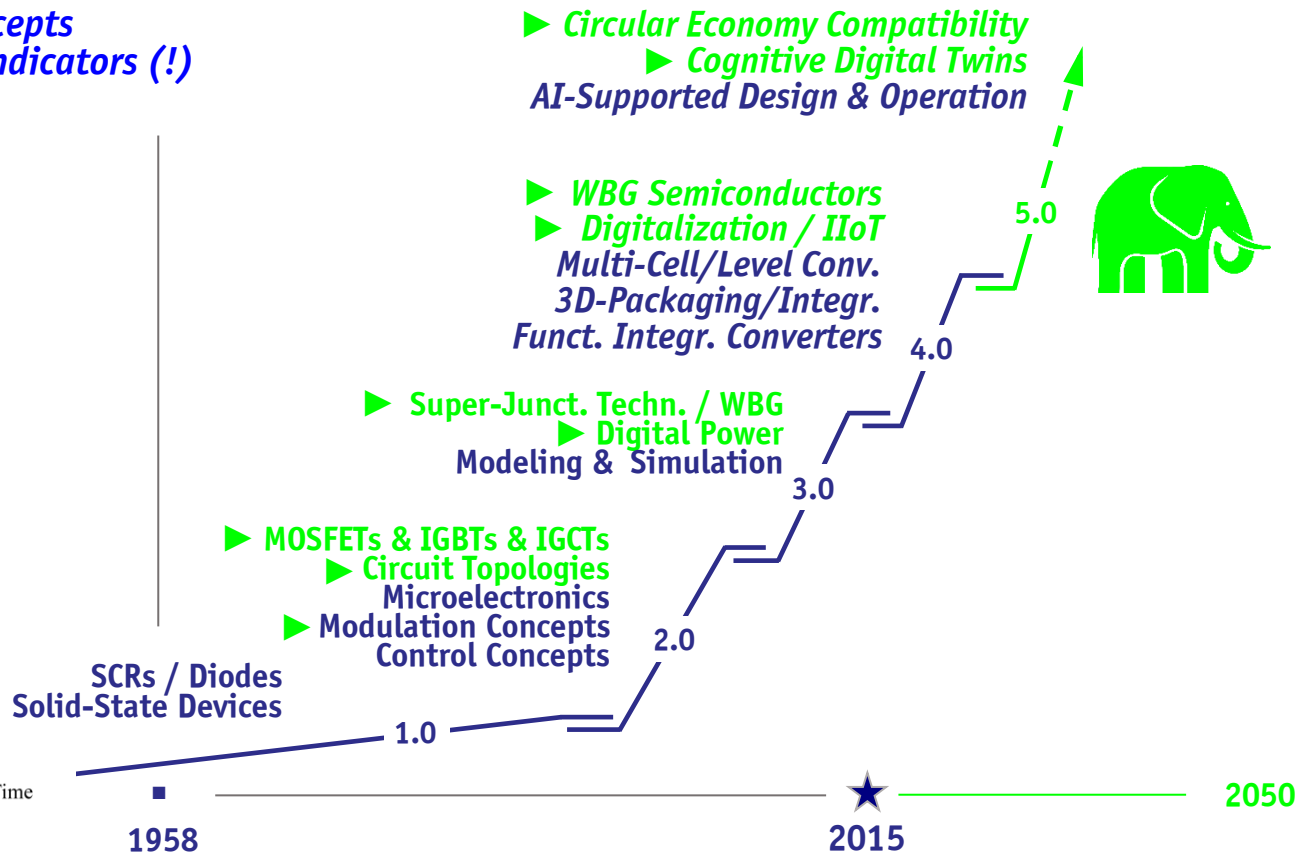


- **FAIRPHONE** — *Modular | Manually Replaceable Parts | 100% Recycl. of Sold Products | Fairtrade Materials*
- *Standardized Interfaces / Mechanically Separable Connections*
- *Leveraging Economies of Scale to Compensate Interface Costs*

Power Electronics 5.0

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





Unlocking the High Frontier

Launch Systems
Space Colonies

Space — An "Unexplored Ocean" to be Navigated

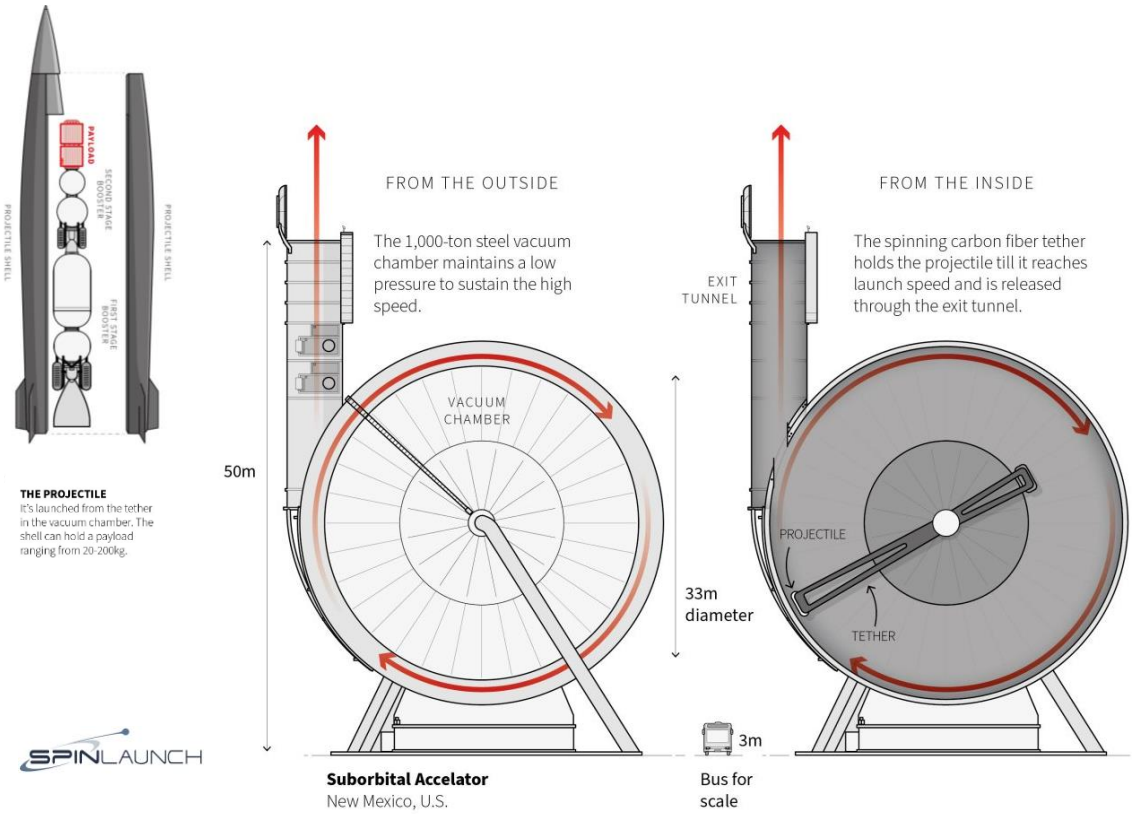
- *Global Space Race — Demonstration of Technology Leadership | Military Interests | Resources*
- *Mining the Moon — Helium-3 | Rare Earth Elements | Platinum | etc. & Ice (Life Support & Propellant)*
- *Satellite Network — Communication | Navigation | Military Operations*

Source: NASA

- *NASA — Artemis Program — Land Humans @ Lunar South Pole by 2026*
- *ESA — Planning to Send a Lunar Lander to the Moon´s South Pole / Construct "Lunarville"*
- *CNSA — China | Crewed Moon Landing by 2030*

Launching Satellites w/o Rockets

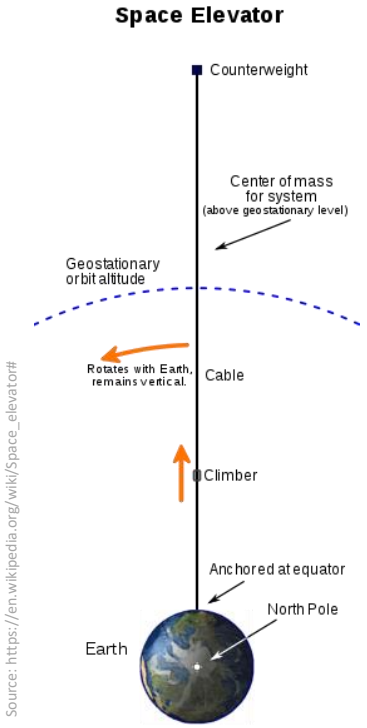
- *Traditional Fuel-Based Rocket Launching — Up to $ 100´000/Pound ($ 2000/Pound w/ SpaceX)*
- *SpinLaunch Uses Electrical Slingshot to Catapult a Spacecraft into Orbit*



- *Payload (up to 200kg) in Reusable Launch Vehicle | 1.5h Acceleration in Vacuum Centrifuge up to 8000km/h*
- *Released Through Hypersonic Header | 10´000g Take-Off | Ignition of Small Rocket Engine in 60km Altitude*

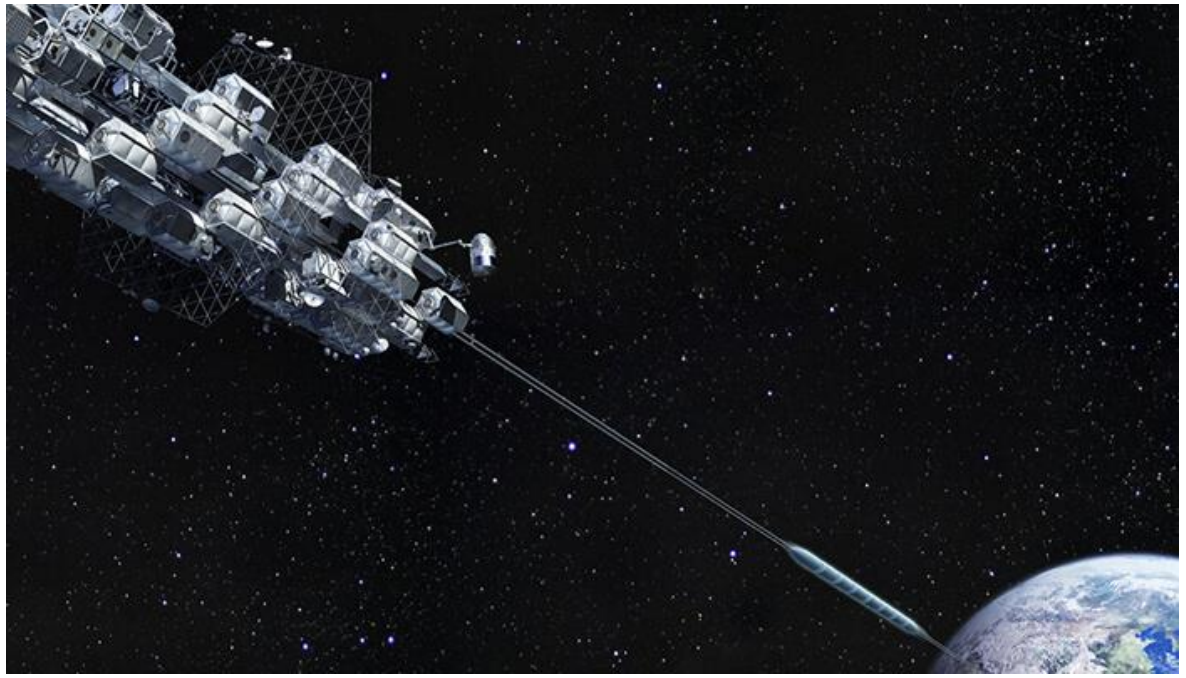
Space Elevator

- *"Cosmic Railway"/ Space Elevator Envisioned by to Y. Artsutanov as Alternative to Rockets in 1960*
- *By 2050 — 100t Electric Climber | 96´000km Carbon Nanotube Tether | 400m Diameter Floating Earth Port*



Source: https://en.wikipedia.org/wiki/Space_elevator#

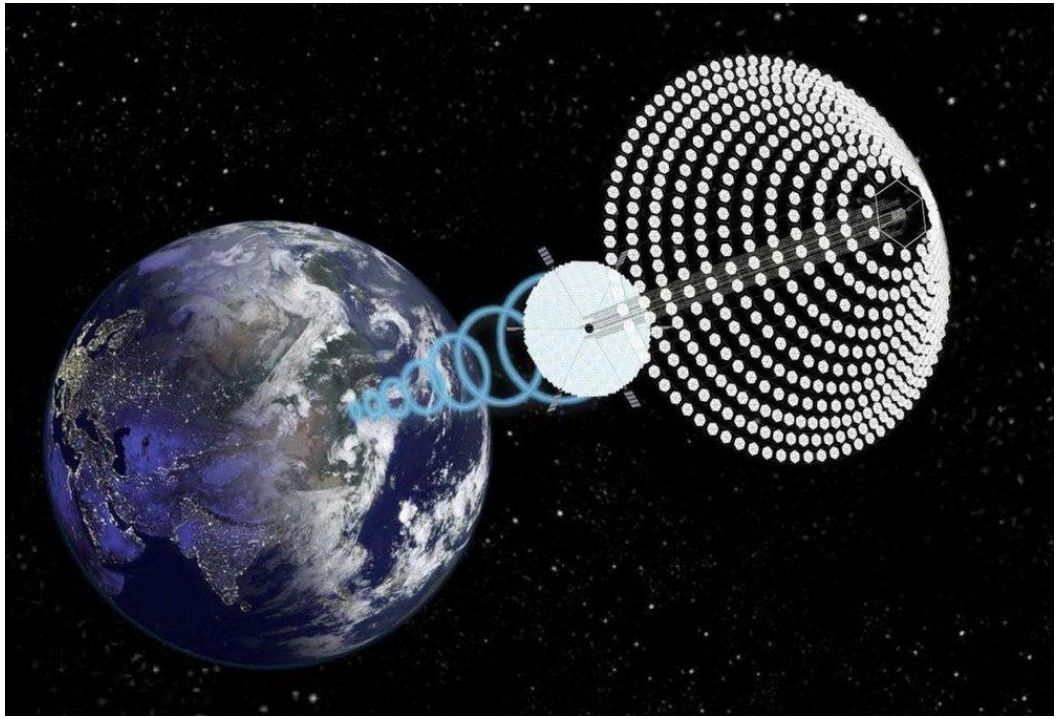
Source: Obayashi Corporation



- *Upward Centrifugal Force on 12´500t Counter-Weight & Gravity Acting on Lower End Keep Tether Under Tension*
- *Balanced Forces at Geostationary Equatorial Orbit (GEO) — Orbit Station @ Height of 36´000km*

Beaming Solar Power from Space

- *Solar Power Harvested in Space | Converted to Microwaves | Sent to Earth-Based Receiving Stations*
- *Advantage of Permanent Availability of Energy Regardless of Weather or Time of Day – No Storage (!)*

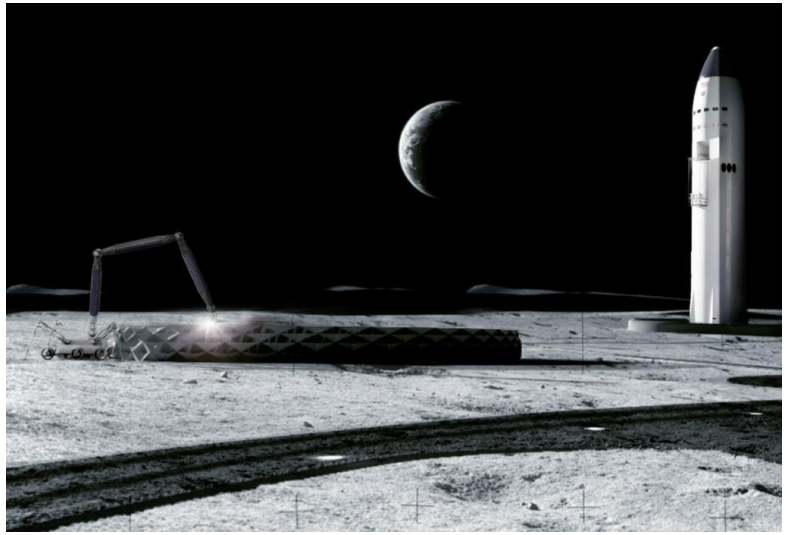


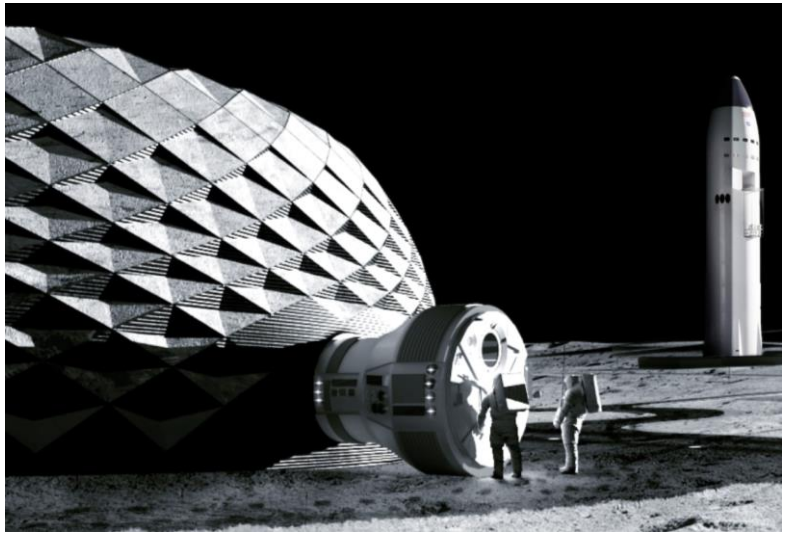
SSST SOLAR SPACE TECHNOLOGIES

- *Several International Programs (ESA, JAXA, NASA, CNSA, etc.)*
- *Caltech — Space Solar Power Prototype Launched into Orbit in 2023*
- *Demonstration of Ability to Beam Detectable Power to Earth*

3D-Printing of Lunar Habitats

- *Lunar Regolith Processed Into Building Material — Local 3D-Printing of Habitats*
- *Extreme Temp. Swings of 120°C … -220°C & Frequent Strikes by Micrometeorites*
- *No Protective Magnetic Shield / Ionizing Radiation from Sun & Deep Space*



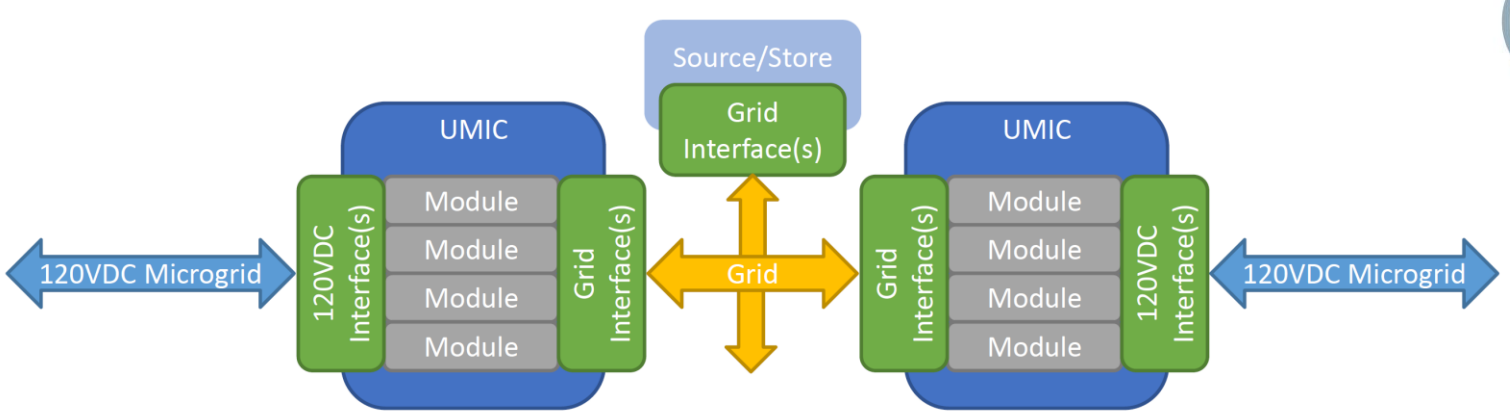


Source: ICON

- *Regenerative Closed-Loop Life Support Systems | Wireless Connections to El. Power System*
- *NASA "LunaGrid"— km-Range MV Transmission btw µ-Grids w/ Solar Power Gen. & Storage & Loads*

Lunar Power Distribution

- *28 Days Rot. / 2 Weeks of Darkness — Lunar Base Placed @ South Pole for Continuous Sunlight*
- *Tether-Based MV Grid for Connecting Islanded Microgrids Comprising Generation-Storage-Loads*
- *Power Beaming for Robotic Exploration of Craters & WPT Rover Charging Outposts*



- *Example of Univ. Modular Microgrid Definition & Interface Conv. for Planetary Surfaces – UMIC/UMIPS*
- *Bidir. Converter Interface btw Transmission Voltage (typ. 1.5 kV$_{DC}$) & Prim. Distribution Voltage (120 V$_{DC}$)*
- *Power Levels btw. 100+ kW for In-Situ Resource Utiliz. / Mining - 50...100 kW / Habitat - 1...5 kW / Rover*

Lunar Cruiser

- *Contribution of JAXA (Japanese Aerospace Exploration Agency) & Toyota to NASA Artemis Program*
- *Pressurized Vehicle | 13 m³ Living Space for 2 ... 4 Astronauts | 10´000 km Range*

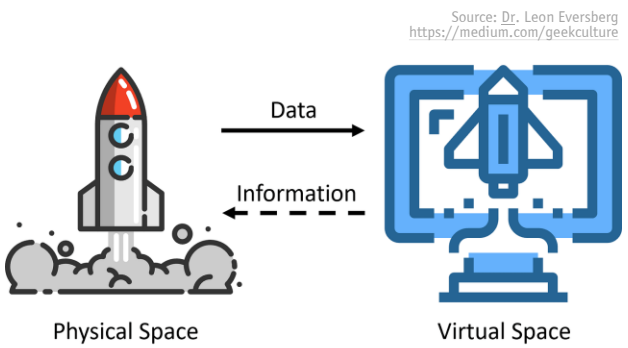
TOYOTA JAXA

- *10 Tons | 6 m x 5.2 m x 3.8 m | Metal Tires*
- *Fuel-Cell EV Technologies (Lunar Nights) | H_2O Electrolysis System (Mitsubishi) for H_2 Production*

Conclusion

The Future of Education & Engineering

- *Digital Twin (DT) — Virtual Representation of Physical Syst. Updated w/ Real-Time Data — IIoT / Industry 4.0*
- *Cognitive DT (CDT) — Cognitive Capabilities / Autonomy / Continuous Evolvement / Full Lifecycle Coverage*

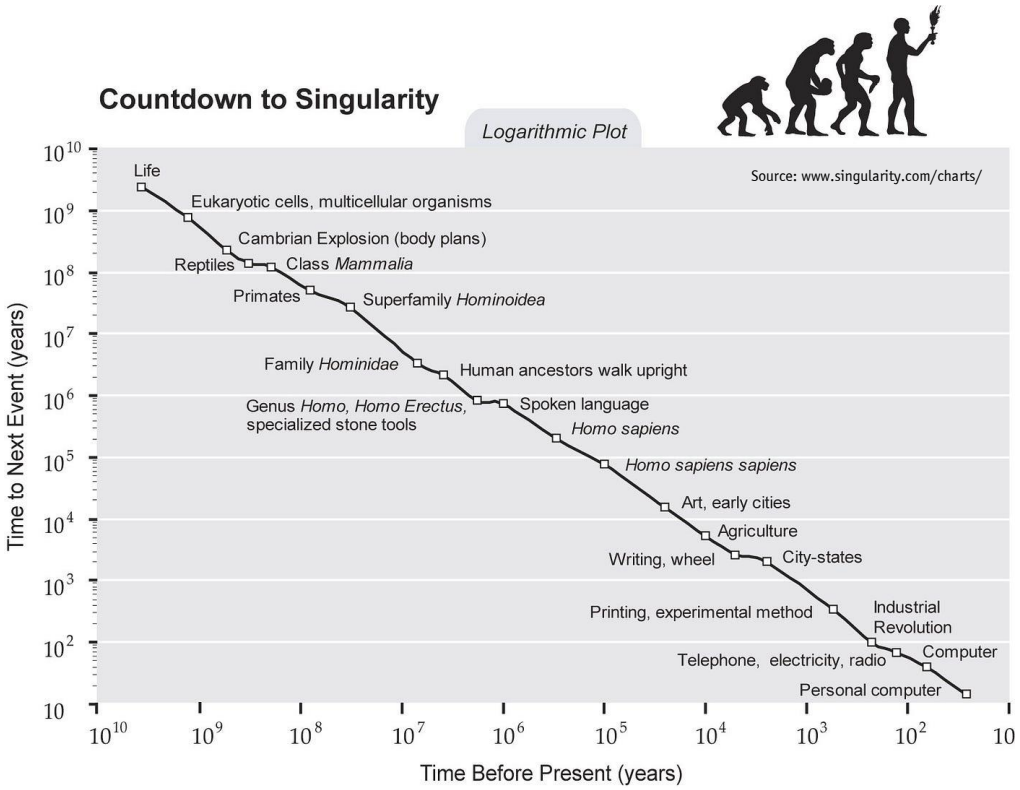


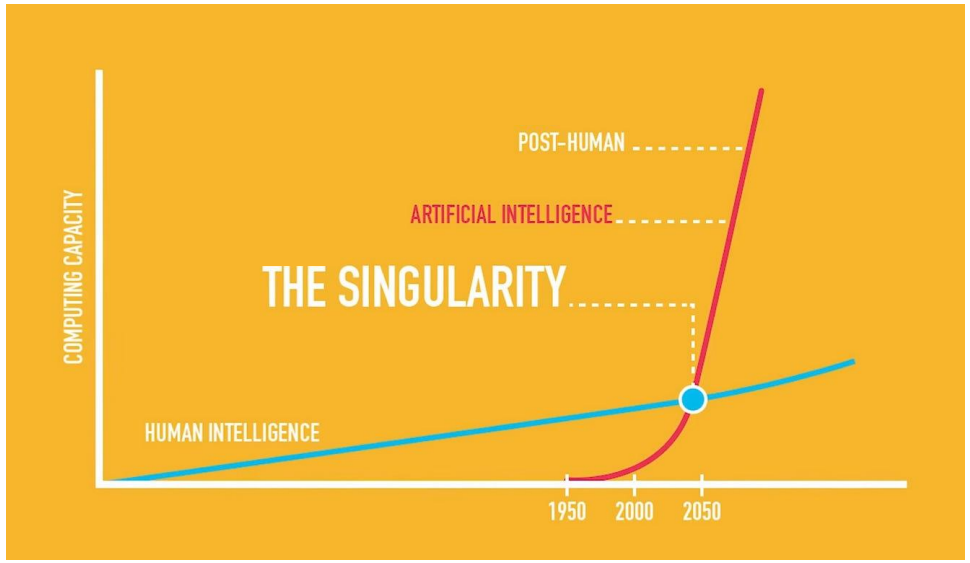
Source: www.twi-global.com

- *Students Grow Their (!) CDT Throughout College & Academia*
- *CDT Retains Record of Learned & Add. Acquired Knowledge / Knows Anything-Anytime-Anywhere / Is Immortal (!)*
- *Personalized Generative AI Assistance — Potentially Disrupting Engineering & Education on All Levels*

Countdown to Technological Singularity (?)

- *Each Generation Builds on Previously Achieved Results — Accelerating Exponential Growth of Technologies*
- *Documented by Biological & Technological Evolution Milestones — «The Singularity is Near», Ray Kurzweil, 2005*

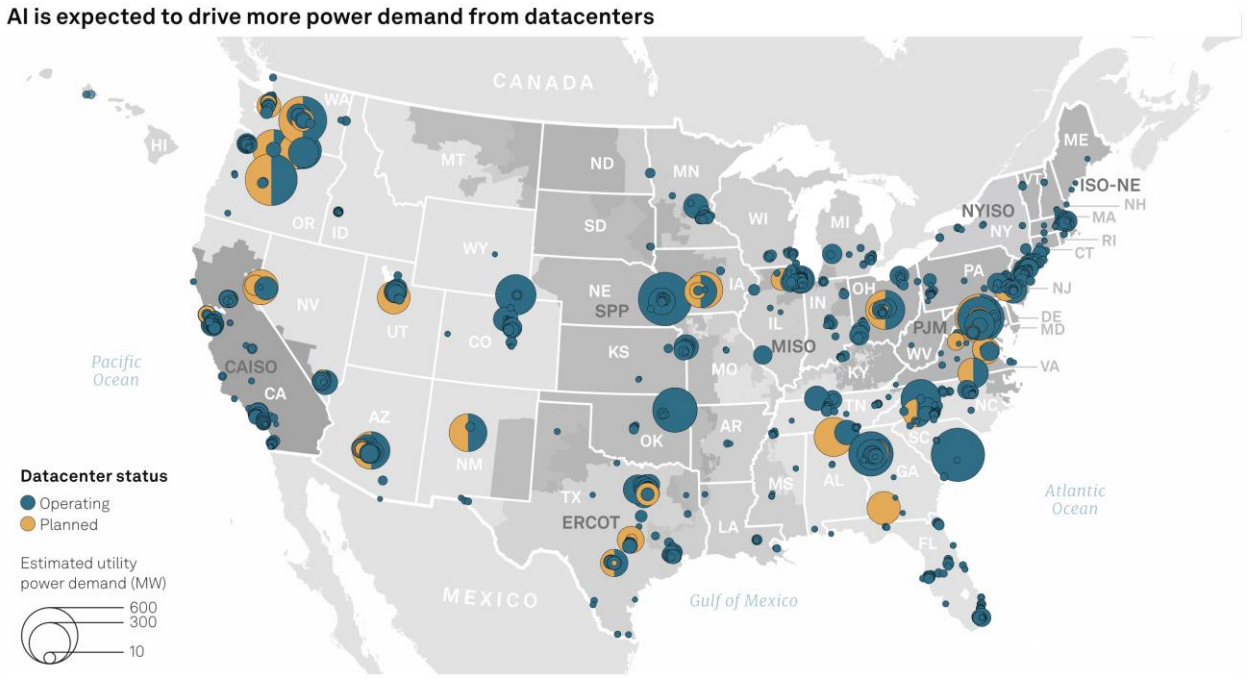




- *Singularity (2045) — AI-Based Creation of a Self-Aware Machine Intelligence Capable of Recursive Self-Improvement*
- *Uncontrollable / Irreversible Technological Growth — Potential Massive Social & Geo-Political Consequences (!)*

Remark Future Gigawatt-Scale Datacenters

- *Explosion of AI — « Hyperscale » Datacenters Evolving into « Exascale »*
- *Gigawatt Power Levels Despite High Power Usage Effectiveness (PUE)*



Sources: S&P Global Market Intelligence; 451 Research; S&P Global Commodity Insights

- *Plans for 2.5 … 6 Gigawatt Campuses Co-Located w/ Nuclear Power Facilities —* BALANCING ENERGY LANCIUM
- *Collaboration w/ Utilities — Datacenters as Responsive Loads for Balancing Solar & Wind Power*

GREAT Challenges Require GREAT Answers (!)

- *Shut Down Skepticism / Don´t Catastrophize — We Need Visions & Utopian Dreams*

Source: www.redbubble.com

- *The Dream of Yesterday is the Hope of Today and the Reality of Tomorrow (R. Goddard)*

Thank you!

Source:
www.terencemauri.com