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IECON 50th ANNUAL CONFERENCE OF THE IEEE INDUSTRIAL ELECTRONICS SOCIETY
Chicago | Illinois, November 3-6, 2024

Challenging the Deep

Johann W. Kolar et al.

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

Nov. 4th, 2024

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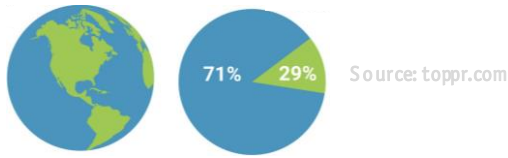
Outline

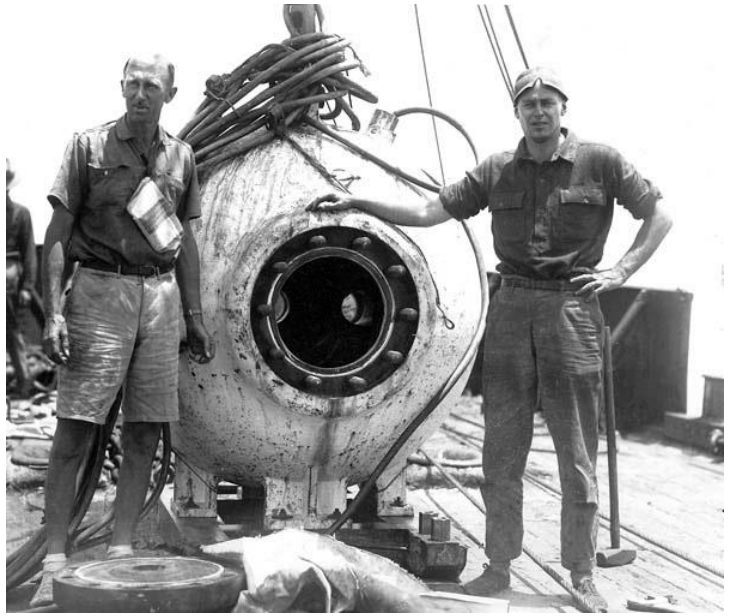


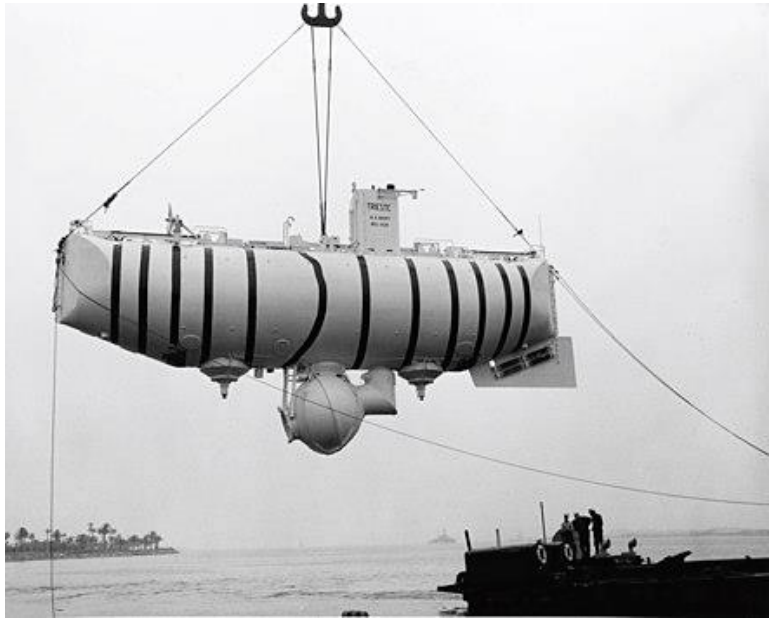
Source: toppr.com

- *Introduction*
  - *Off-Shore RES / Storage*
  - *Subsea Industries / IMR*
  - *Deep-Sea ROVs / AUVs*
- *Future Prospects*

The Human Desire for Exploration

- *1934 — Record-Breaking 3´028 Feet Dive of Ch. Beebe & O. Barton*
- *1960 — D. Walsh & J. Piccard Descended to Deepest Point on Earth („Challenger Deep“, 35´814 Feet)*





- *Exploration is Fundamental to Human Success and Driven by Curiosity &/or Thirst for Profit etc.*

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 | Subsea 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 w/ Mooring Cables*
- *3 Types — Tower-Like Spar Buoy | Semi-Submersible | Tension Leg (Mooring Cables Under Tension)*

Remark World´s Largest Floating Wind Platform

- *Gigantic 16.6 MW OceanX Hybrid Drive Wind Turbine Lauchned 07-2024*
- *2x 182 m Diameter Counter-Rotating (!) 52´000 m² Swept Area Rotors / 16´500 t Floating Platform*

MINGYANG SMART ENERGY 明阳智能

- *Single-Point Mooring System / Swift Wind Direction Alignment – Max. Wind Capture*
- *Designed to Withstand Typhoons & Category 5 Hurricanes (260 km/h, 30 m Waves)*

Floating Off-Shore Solar Plants

- *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*
- *Potentially Lower Cost of Off-Shore Solar Compared to Off-Shore Wind — 2x Higher GWh/km²*

Off-Shore Green-H_2 Production

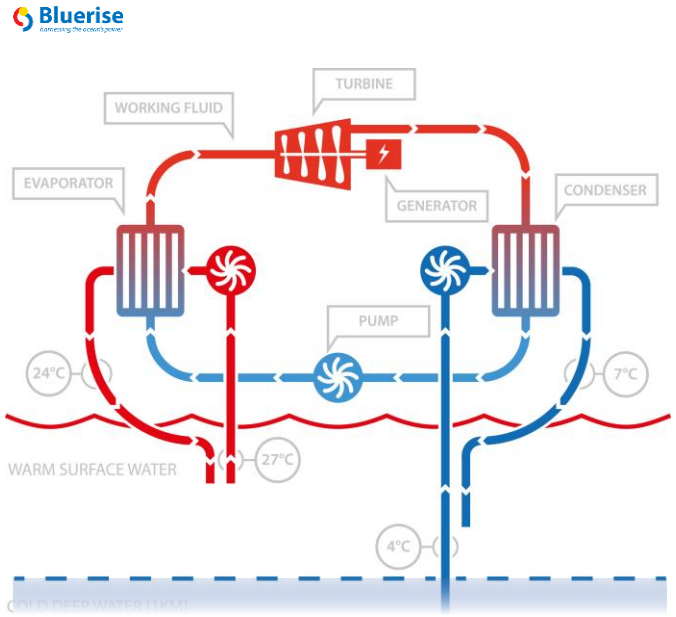
- *Energy Transport via Molecules / Hydrogen Avoids High $$$ of HVDC Cables / Converter Systems*
- *Decline of Oil & Gas Production → Repurposing of Offshore Assets / Platforms, Pipelines etc.*

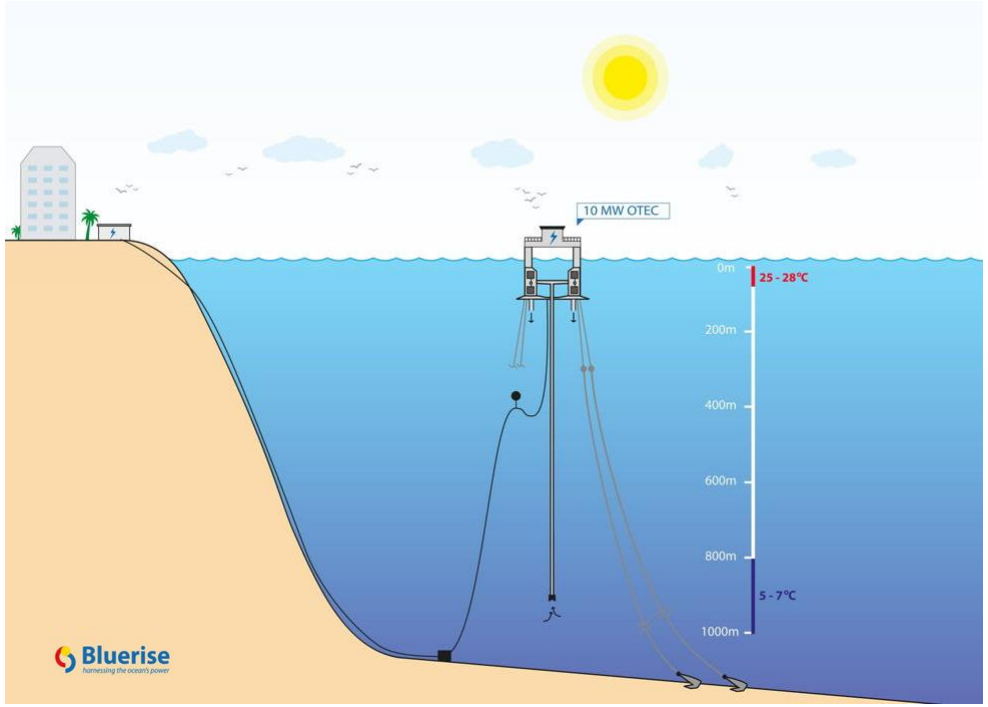
Source: https://tractebel-engie.com

- *P2G → Desalinated H_2O Electrolyzers on Off-Shore Platforms Converting Wind Energy to "Green Hydrogen"*
- *60+% 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*

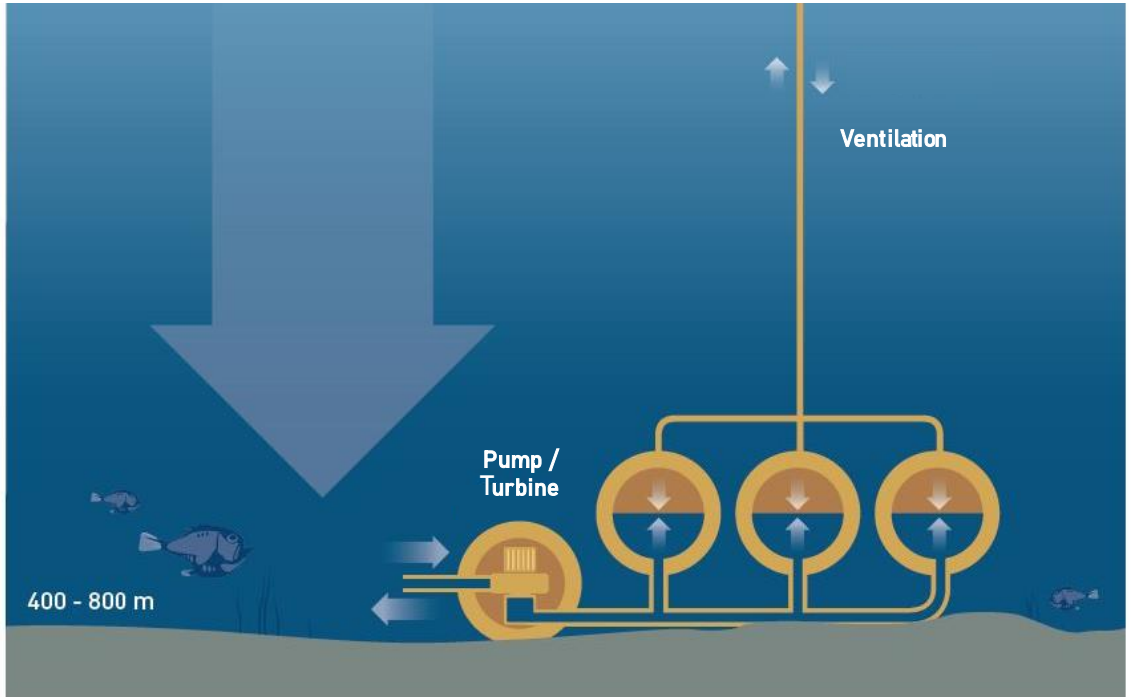




- *Solar Energy Absorbed by 23 Million Square Miles = 250 Billion Barrels of Oil*
- *10MW OTEC Pilot Planned in Southern China by Lockheed Martin & Reignwood Group*

Subsea Pumped Hydro Storage

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

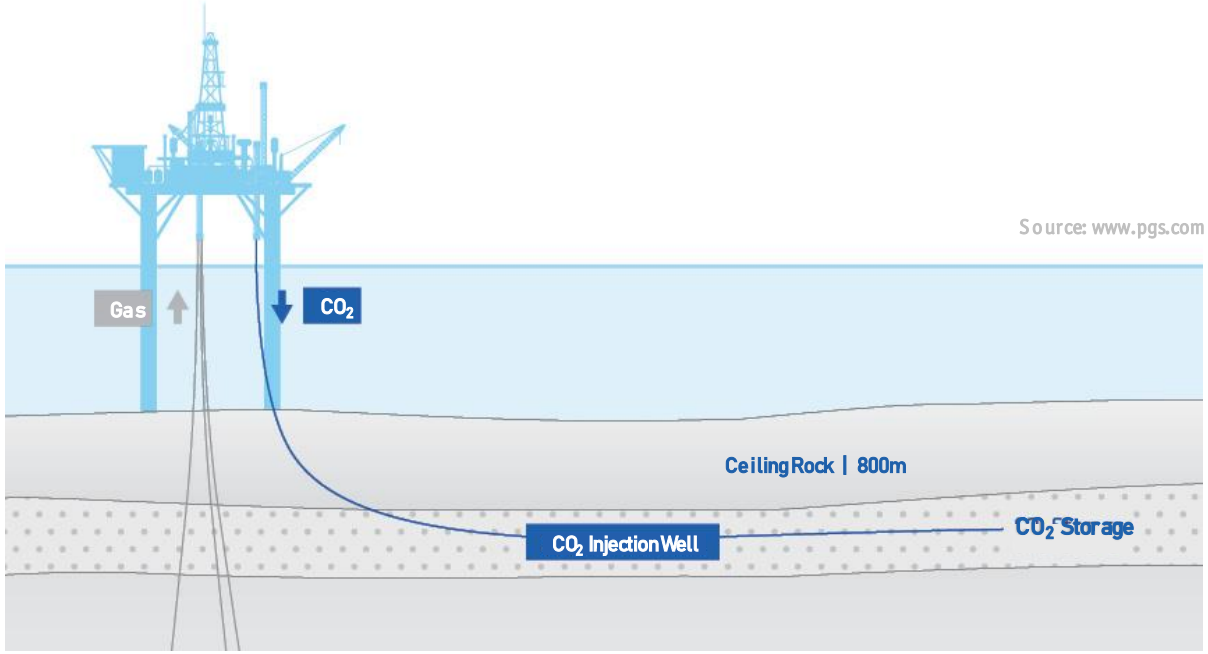


Source: SINTEF

- *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

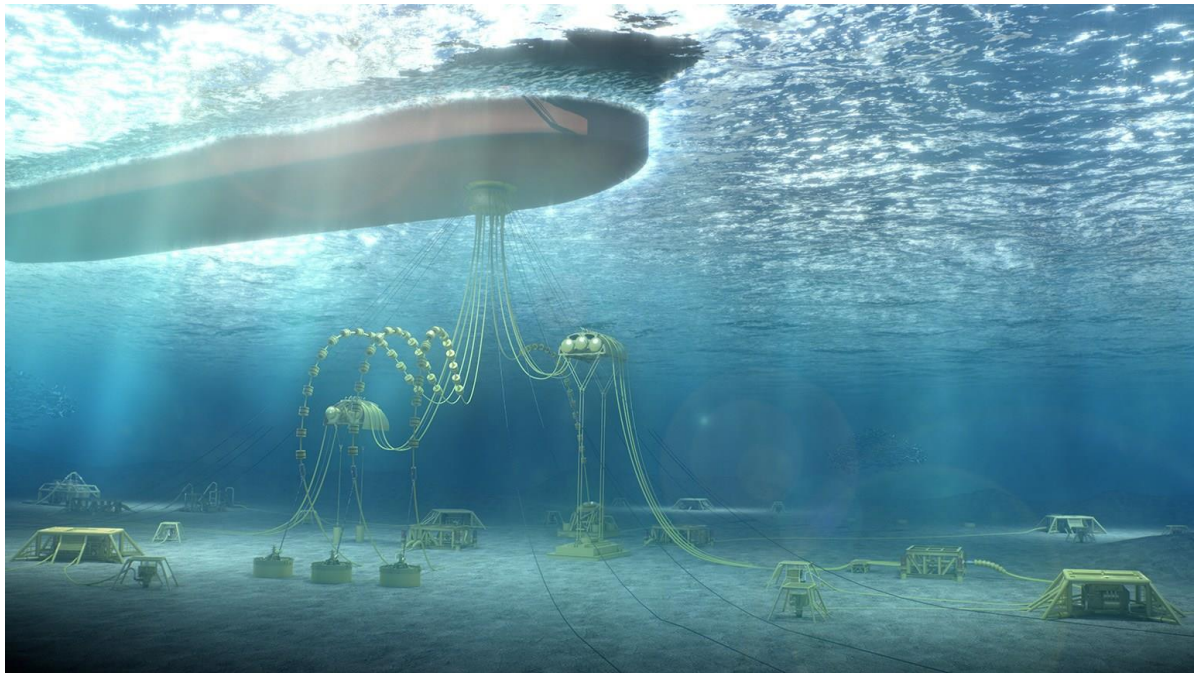
- *CO_2 Capture & Storage (CCS) → Main Element of Energy Transition to Low Carbon Future*
- *Future CCS Value Chain → CO_2 Transported by Ships & Stored in Off-Shore Formations*



- *World´s 1st Off-Shore CCS Plant Operating since 1996 in Sleipner Natural Gas Field*
- *Norwegian CO_2 Tax since 1991 → CO_2 Contained in Nat. 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"*

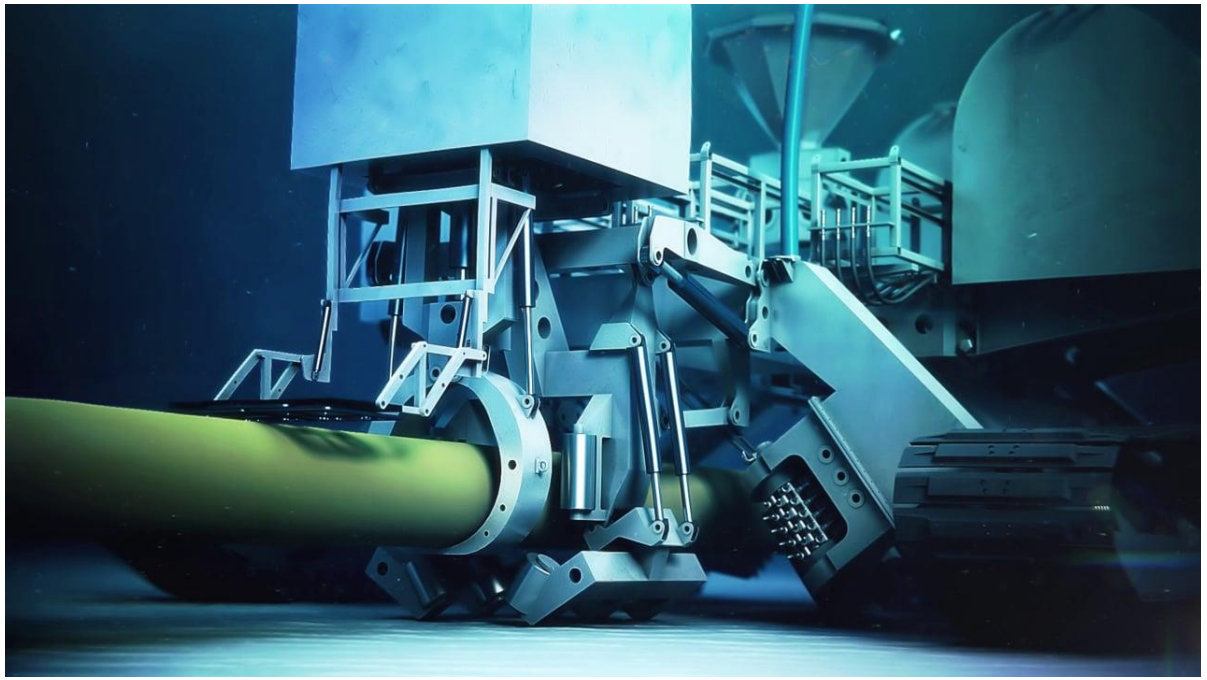


Source: www.ocean-5.com

- *Hydraulic Wells → High Eff. All-Electric Wells / No Hydraulic 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 1000 m Operation Depth*



Source: DEEPOCEAN

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

Seabed Interventions – 2/2

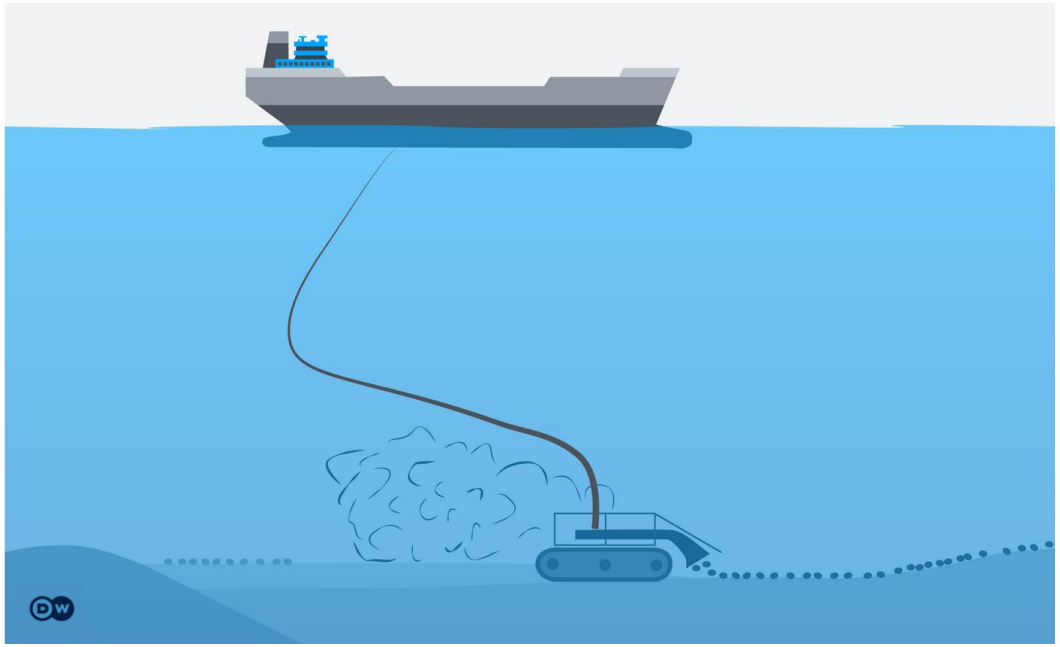
- *Burial of Subsea Pipelines and Cables*
- *Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000 m Operation Depth*

Source: DEEPOCEAN

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

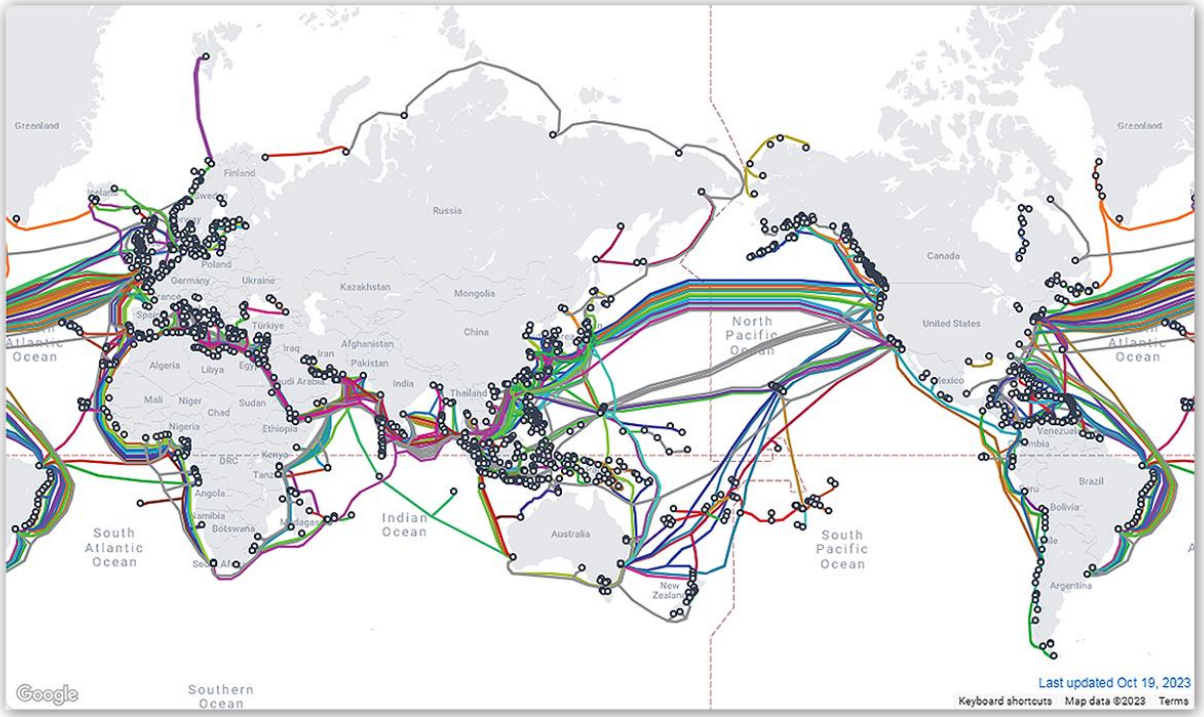
- *Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000…6000m)*
- *Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel*

Source: GSR

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

Submarine Cables — The Invisible Backbone

- *Subsea Cables are the Backbone of the Global Internet & Integrated Data World*
- *500+ Active & Planned Submarine Cables / 1.4 Million km / Built-In Network Redundancy*



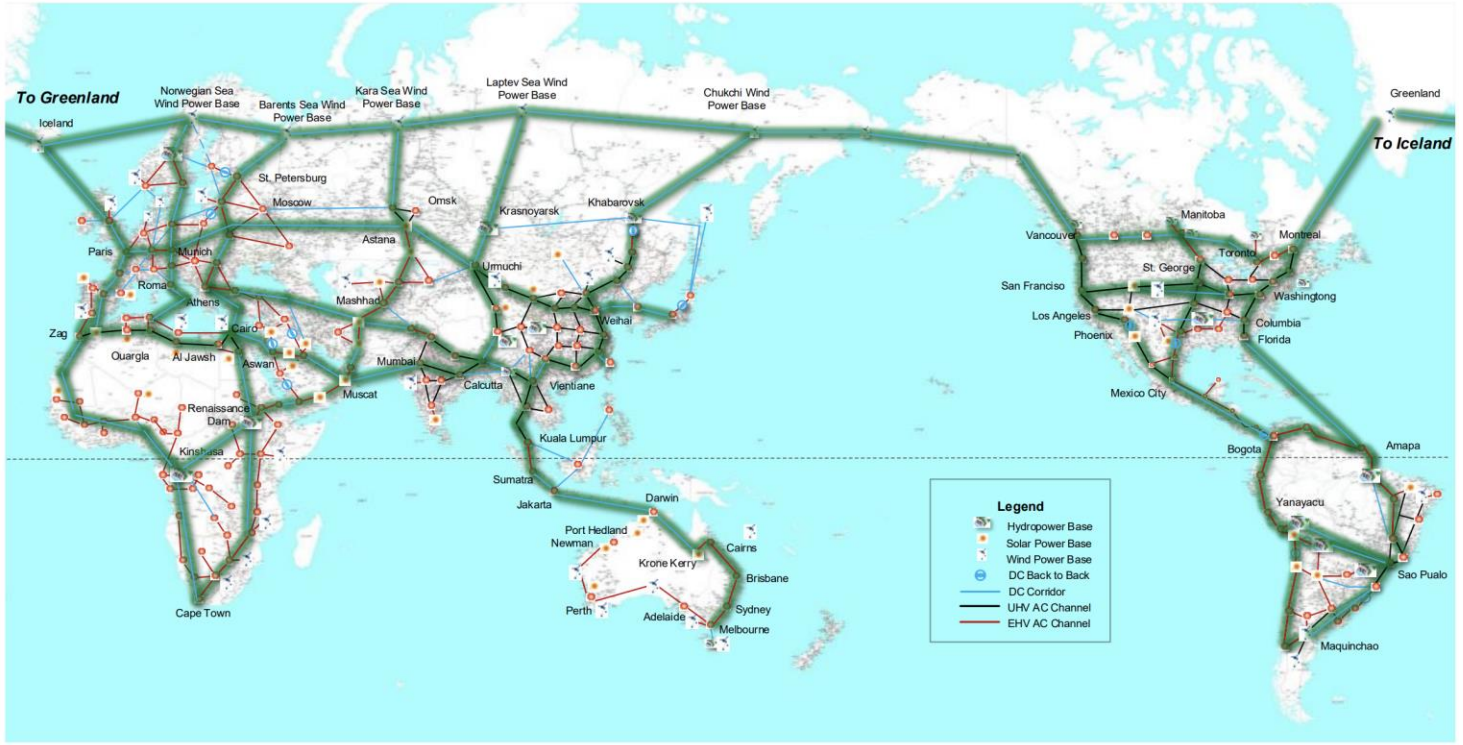
- *Crucial Strategic Importance — Potential New Front in the Ongoing Geopolitical Tensions*
- *Regular Maintenance / Surveillance & Protection of Critical Cable Routes / Threat Response*

Remark

Future Global Power Grid

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

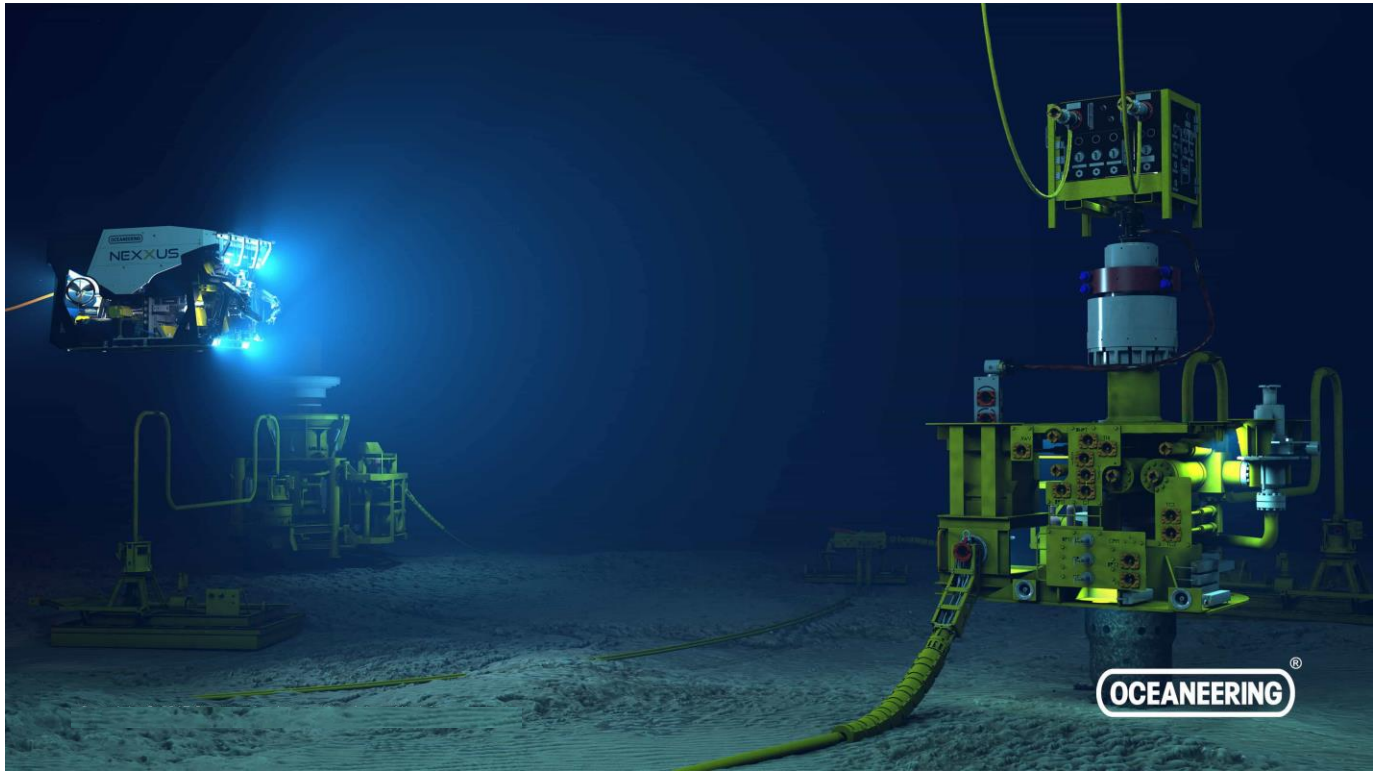
Source: GEIDCO 2018



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

Subsea IMR — Inspection / Maintenance / Repair

- *Complex / Inaccessible Subsea Infrastructures → Inspections & Interventions*
- *Oil & Gas Industry → Well & Infrastructure Diagnostics | Remediation of Damaged Wells etc.*



- *Operation Depths > 2500 m*

Classification of Underwater Vehicles

- *ROV — Remotely Operated Underwater Vehicle | Connected to Surface Vessel via Umbilical*
- *AUV — Autonomous Underwater Vehicle*

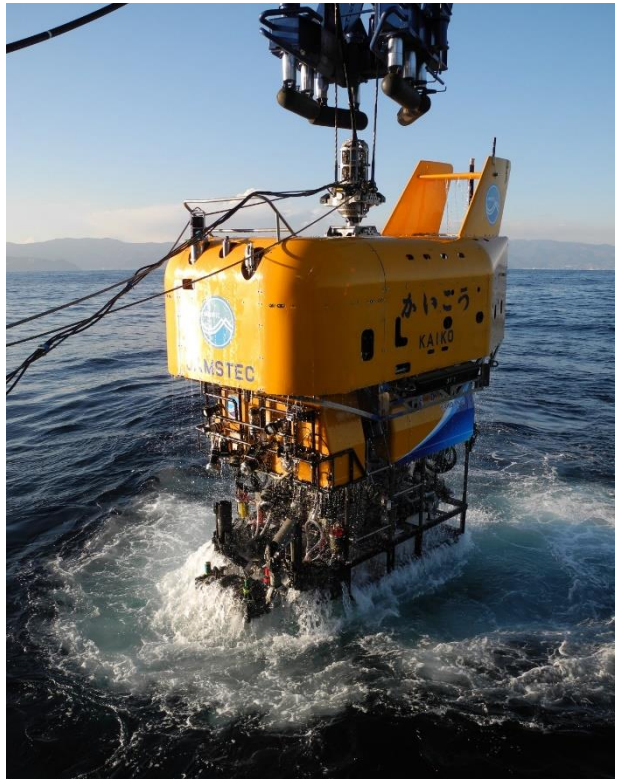
Source: SCHMIDT OCEAN INSTITUTE

- *Global Annual ROV Market — $3.5 Billion in 2020 / 11.5% CAGR in 2021...2026*
- *74% Increase in AUV Demand in 2022*

RESEARCHANDMARKETS
THE WORLD'S LARGEST MARKET RESEARCH STORE

Scientific Exploration of Ocean Depths – 1/2

- *Oceans Cover 71% of Earth´s Surface | 5% Explored*



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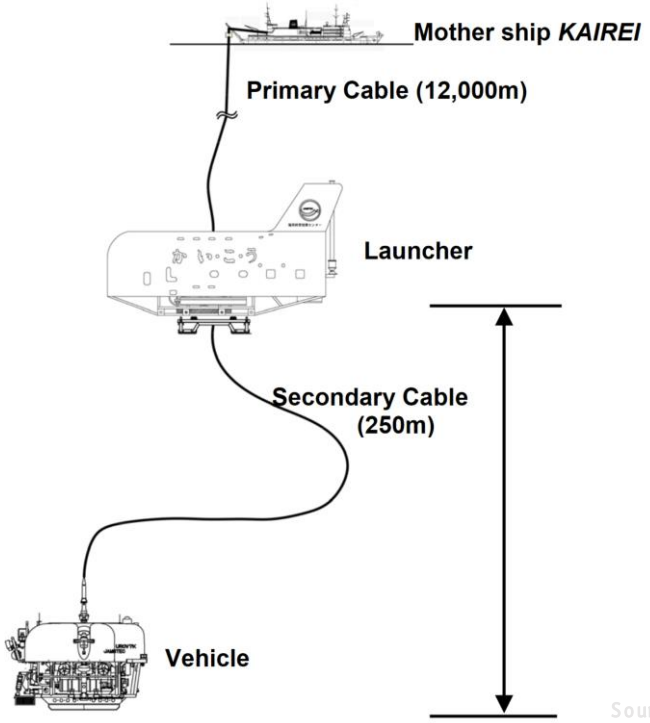
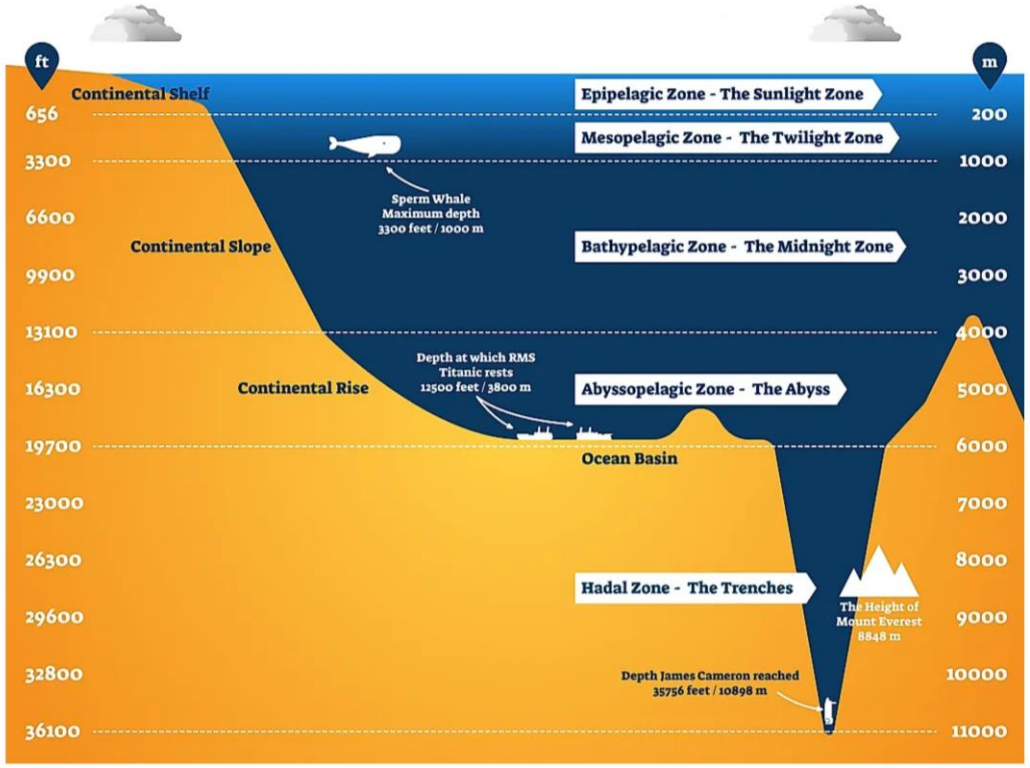


Source: Murashima et al, 2005

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

Scientific Exploration of Ocean Depths – 2/2

- *Surveys of Submarine Volcanoes / Hydrothermal Vents / Subduction Zones*
- *Collection of Seabed Sediments / Microorganisms*



▼ Deep Ocean

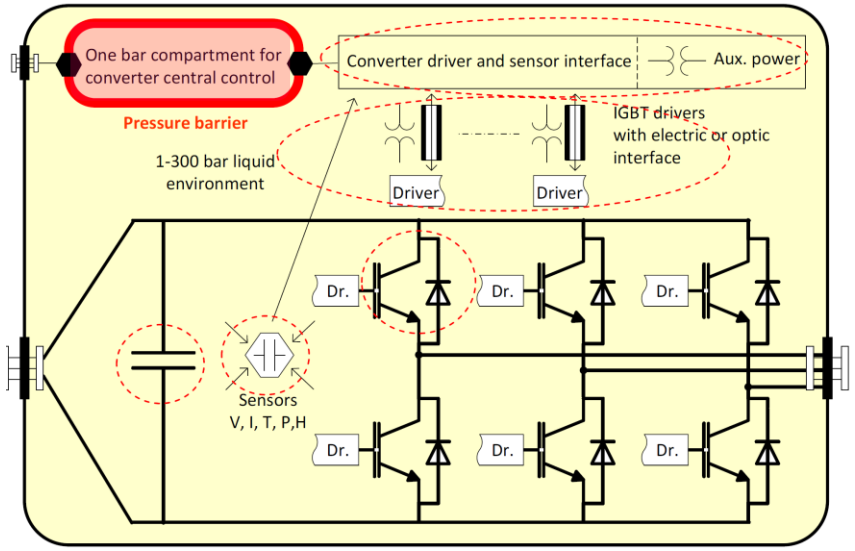
Source: VectorMine/Shutterstock.com

- *5 Zones | 3´700m in Average | Deepest Location → "The Challenger Deep" @ 11´034m (≈4°C)*

Remark Electronics Pressure Housings

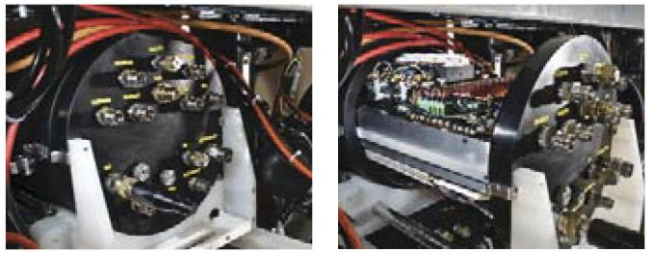
- *Air or Gas Filled Components → Would Implode in Large Depths (e.g. 6000m → 600bar)*
- *One-Atmosphere Housings → Maintain Constant Inside Pressure / Cylindrical or Spherical Shape*
- *Pressure Balanced Housings → Int. ≈ Ext. Pressure / Oil Filled – No Voids / Not Shape (Cooling) Restricted !*

Source: M. Hernes SINTEF



Source: SAAB

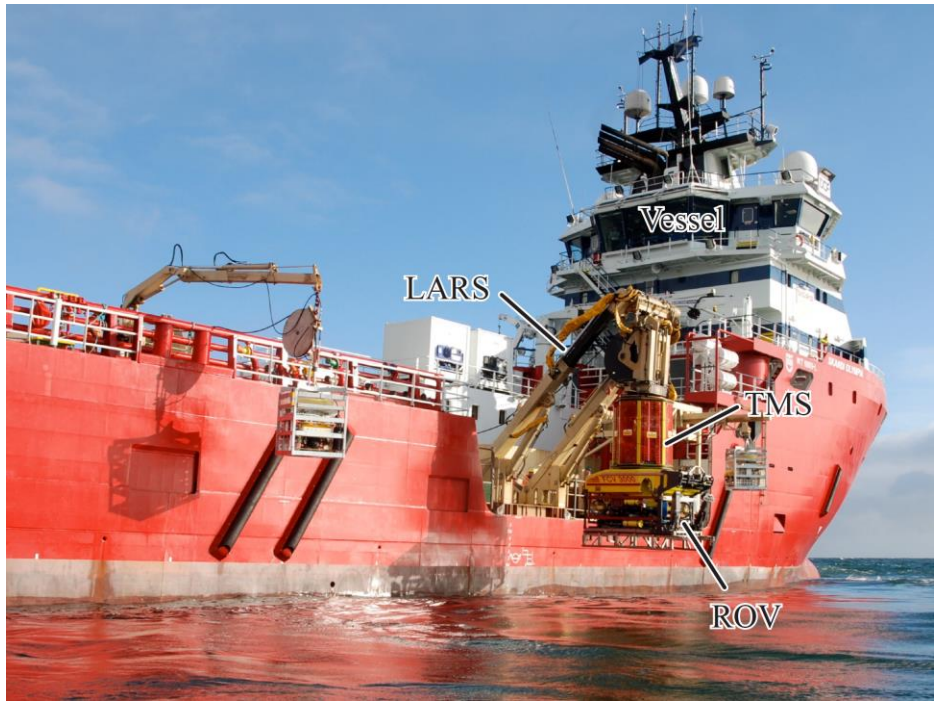
Electronics Compartment of Seaeye Jaguar

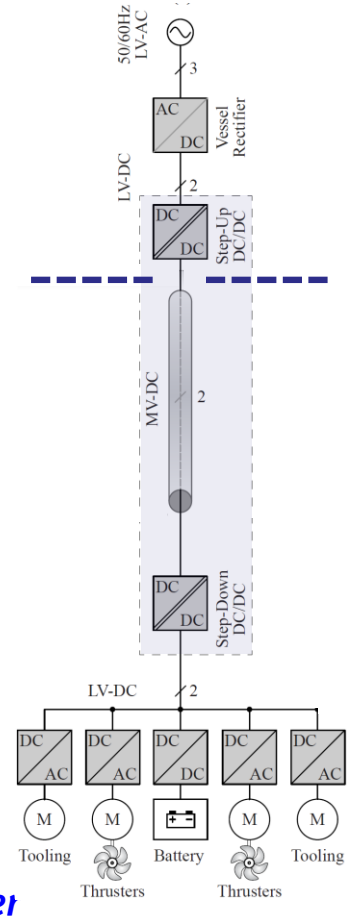


- *Research on Pressure-Tolerant Power Electronic Components (300bar) @ SINTEF*
- *IGBTs → Sw. Behavior Unaffected / Chip Interface Needs to be Protected from Surrounding Liquid*
- *Pressure Affects BH-Curve of Magnetic Cores & Impairs Self-Healing of PP Film Cap. → Voltage Derating*

Deep-Sea E-HyDrone MV_{DC} Power Supply – 1/4

- *Electric ROVs — Hydraulic Manipulators / Thrusters → Electric Systems*
- *Fewer Moving Parts / Lower Maintenance $$$ / More Compact / Lower Weight*

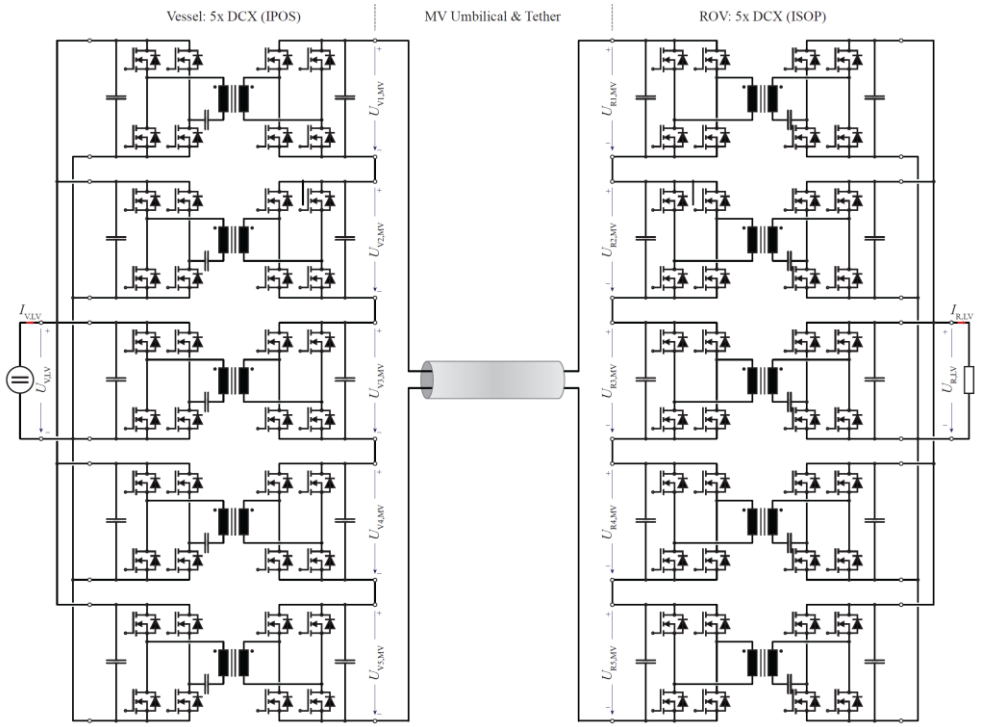


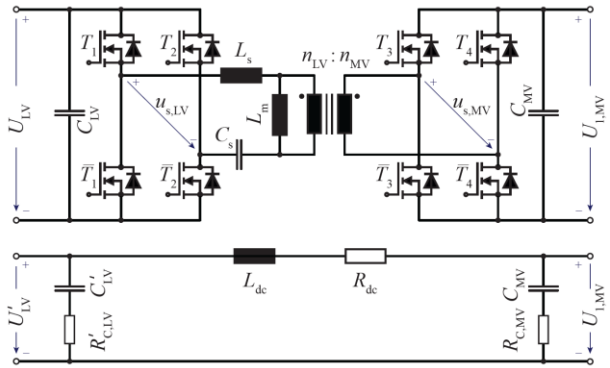


- *Utilization of DCX-Based MV DC-Transmission Instead of 400...800 Hz AC*
- *Lower Losses & Higher Power Transmission Capacity for Given Umbilical Diameter*

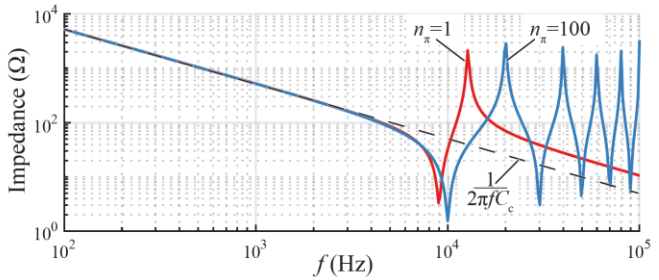
Deep-Sea E-HyDrone MV_{DC} Power Supply – 2/4

- *Concept Study for 50 kW Work-Class ROV Power Supply / 4000 m Umbilical*
- *Uncontrolled (!) Modular IPOS / ISOP SiC DC-Transformer (DCX) – Natural Volt. Balancing & Full ZVS*





DCX-Module
DC Equiv. Circuit

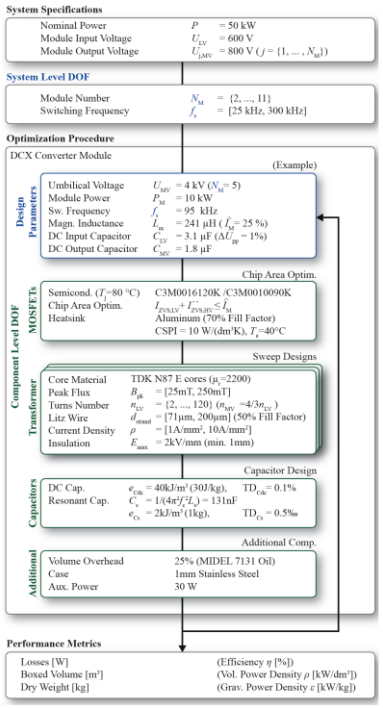


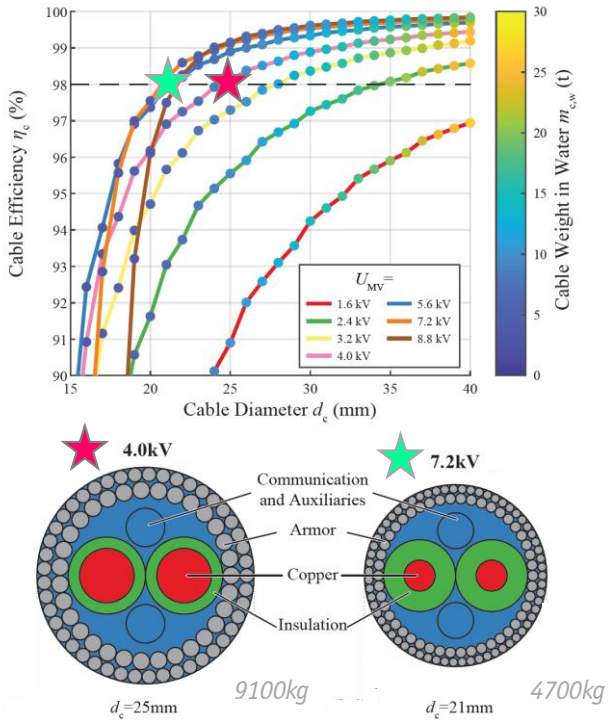
Umbilical
Impedance
Characteristic

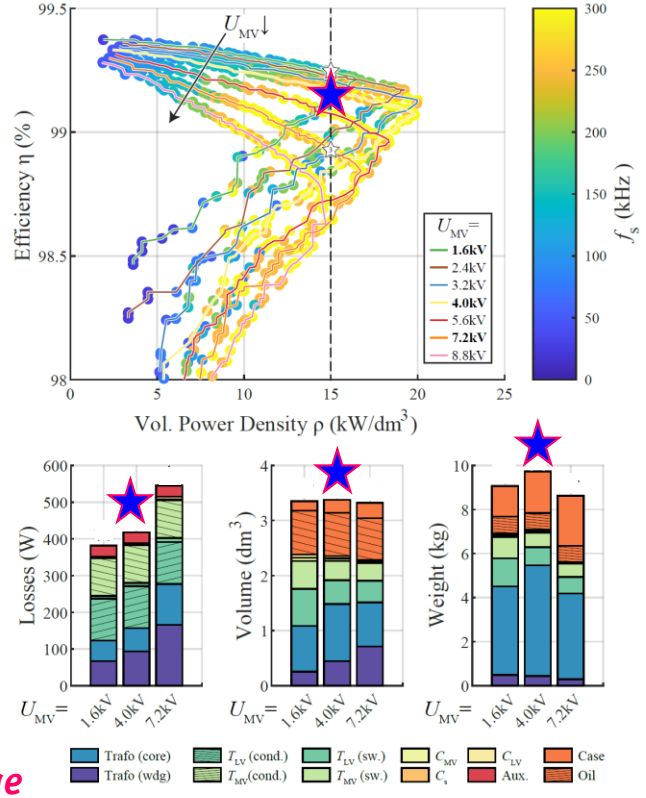
- *Optimal Selection of Transmission Voltage / Number of DCX Modules / Sw. Frequency*

Deep-Sea E-HyDrone MV_{DC} Power Supply – 3/4

- *Multi-Objective Optimization of Umbilical & DCX*
- *Trade-Off → Losses vs. Cable Diameter or Volume & Weight*



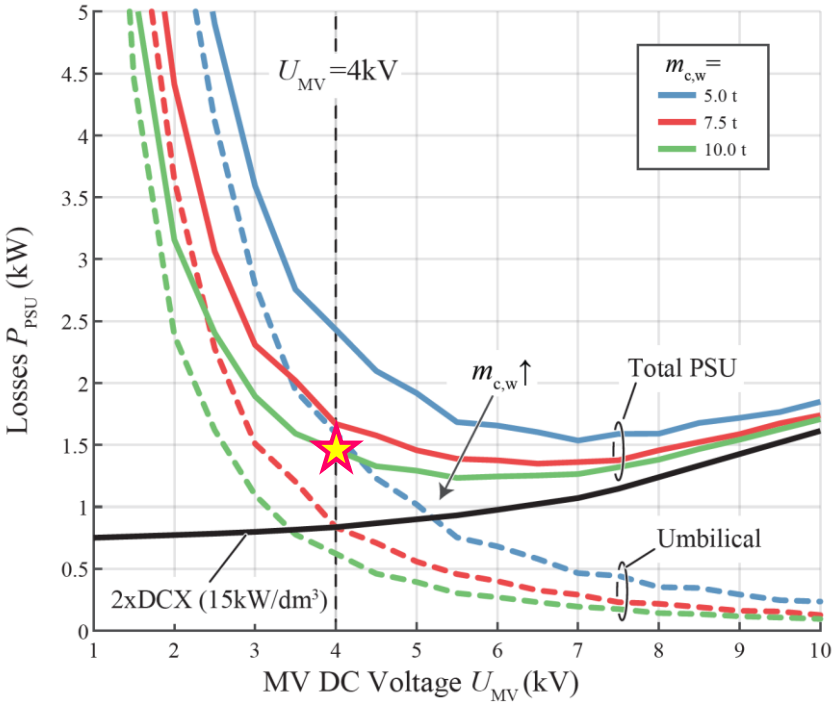


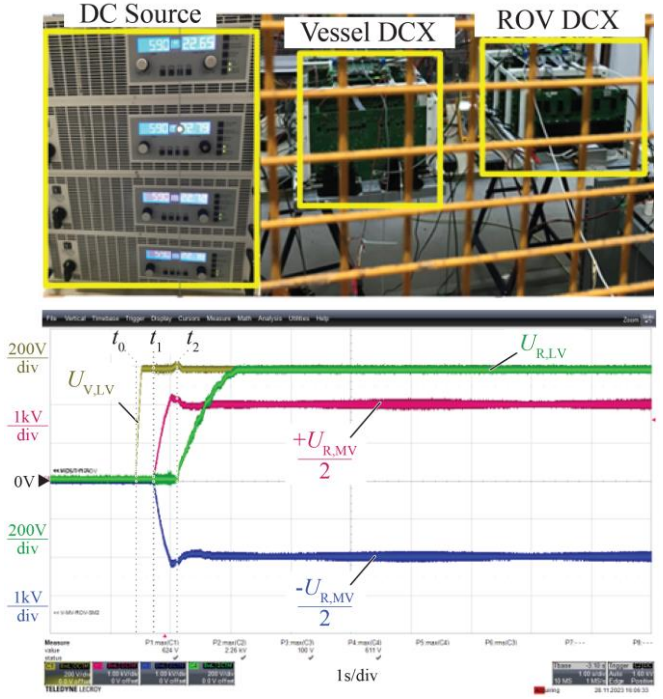


- *Given Cable Diameter → Weight Reduces w/ Increasing Voltage*
- *Increasing Sw. Frequ. → Higher Power Density @ Lower Eff.*

Deep-Sea E-HyDrone MV_{DC} Power Supply – 4/4

- *Higher DC Voltage → Higher DCX Losses BUT Lower Transmission Losses*
- *Selection of N=5 99% Efficient DCX-Modules / 10 t in Water ±2 kV DC Transm. Voltage Umbilical*

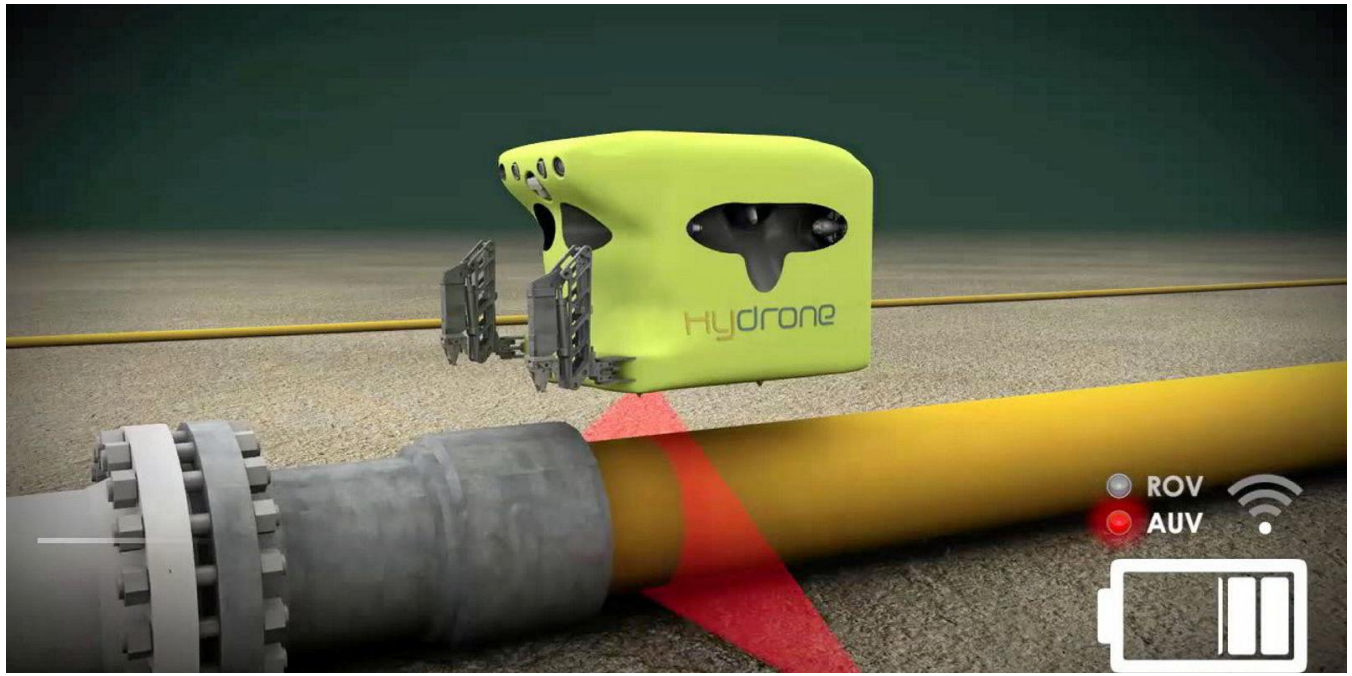




- *97.5% Overall Power Supply Efficiency / Weight Mainly Determined by Umbilical and TMS*
- *0.5ms Ramp Time of 100% ROV Load Steps – Minor Ringing of DCX — Umbilical — DCX*

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*

Industrial Subsea AUV Charging System

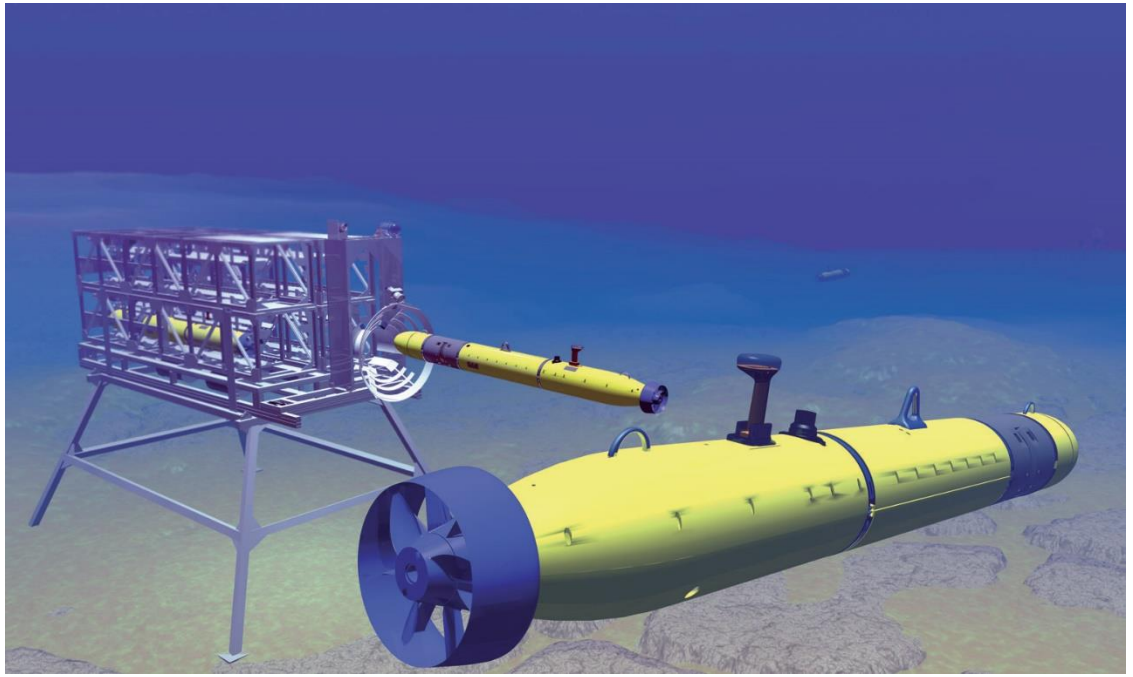
- *"Universal" Open-Standard Docking Station — Interoperability w/ AUVs of Diff. Makes / Shapes / Sizes*
- *2.5 kW @ 95% Efficiency Inductive Power Transfer / 3000 m Operation Depth / 15 Years Lifetime*

Source: UNPLUGGED SUBSEA USB SUBSEA INDUCTIVE SOLUTIONS

- *Homing Mode / Primary Side of Inductive Connector Activated During Vehicle Approach*
- *Drone Utilizes Magnetic Field for Precise Docking*

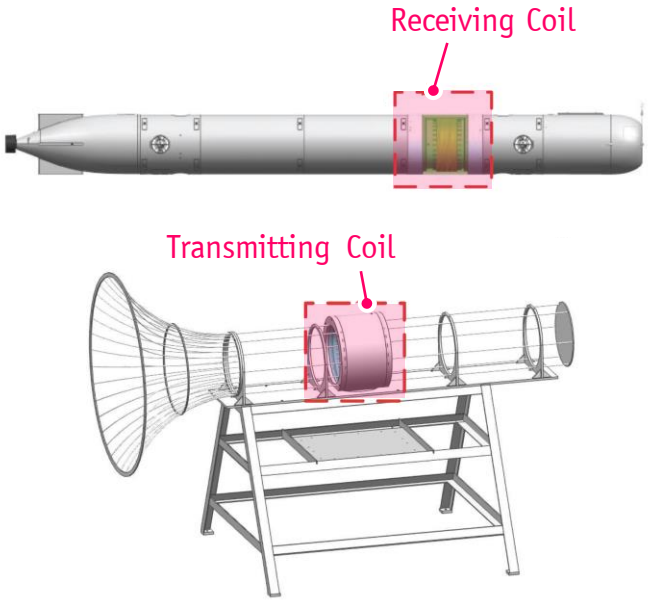
Resonant IPT Wireless AUV Charging

- *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

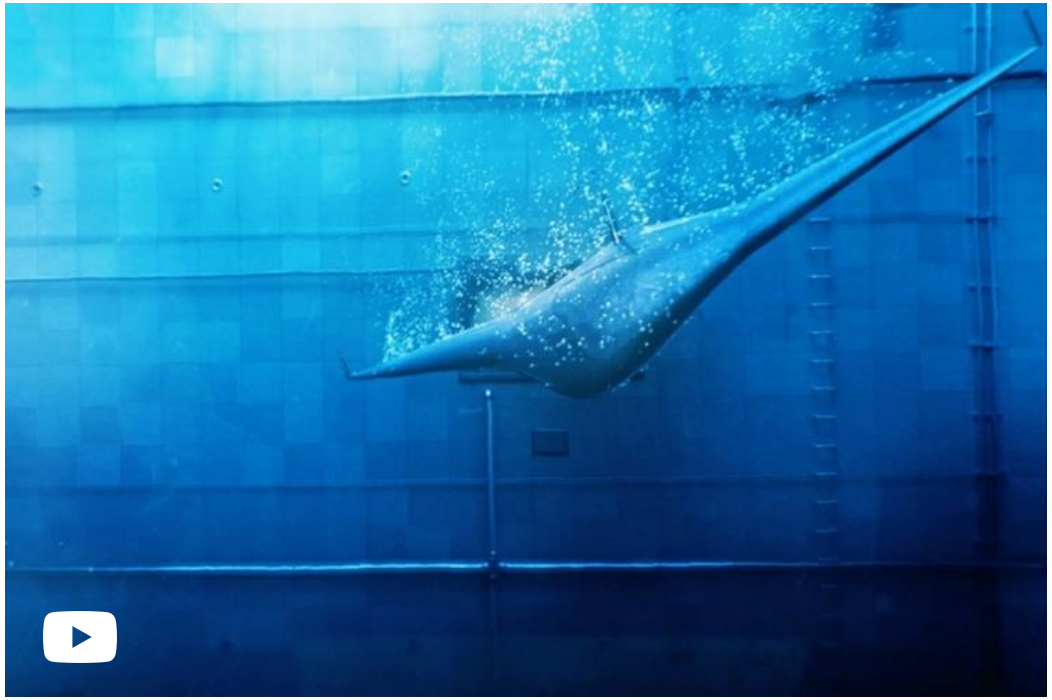
Source: Peizhou Liu et al., 2022



- *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 Exploration

- *US Army's Defense Advanced Research Projects Agency (DARPA) Manta Ray Robot Project*
- *Autonomous Unmanned Underwater XL Glider (9 m) Assembled from Modular Subsections*

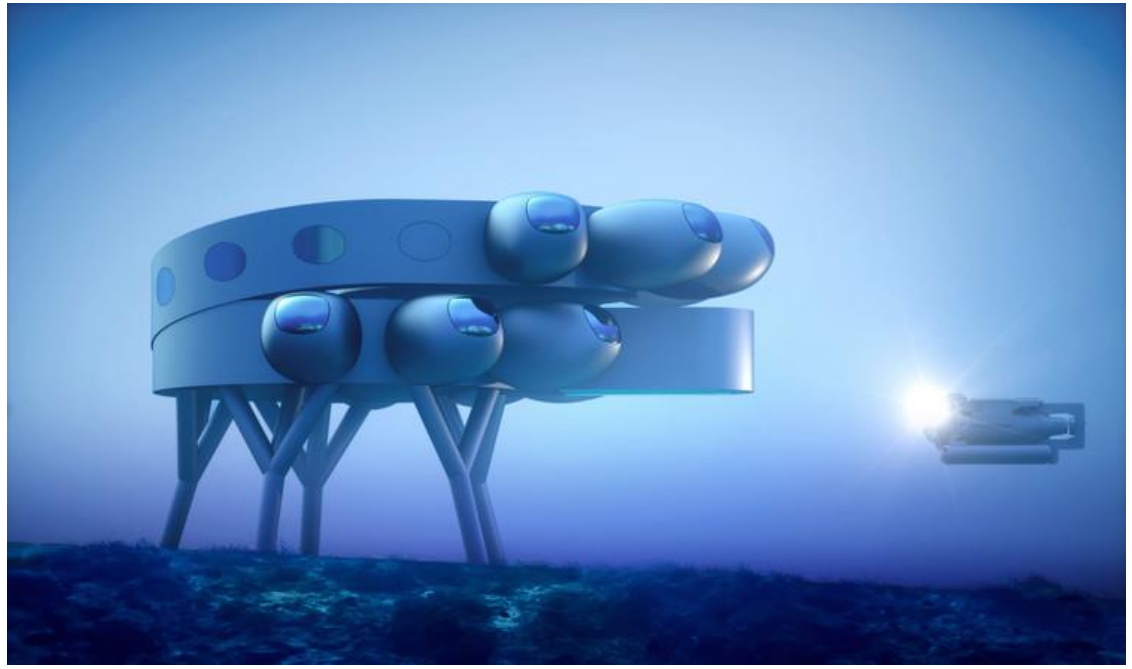


NORTHROP GRUMMAN

- *Low Energy Propulsion / Power Gen. from Ocean Currents, Hydrotherm. Vents, Methane Seeps etc.)*
- *Ability to Hibernate for Energy Saving & Recharge @ Energy & Communication Outposts*

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*

Thank you!