ETH zürich

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

ETH zürich

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

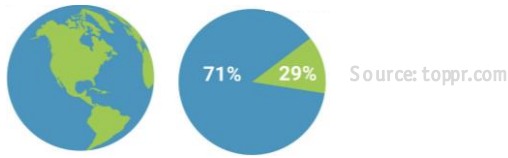
Challenging the Deep

Johann W. Kolar | David Menzi | Jonas Huber

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

Nov. 4th, 2024

Outline

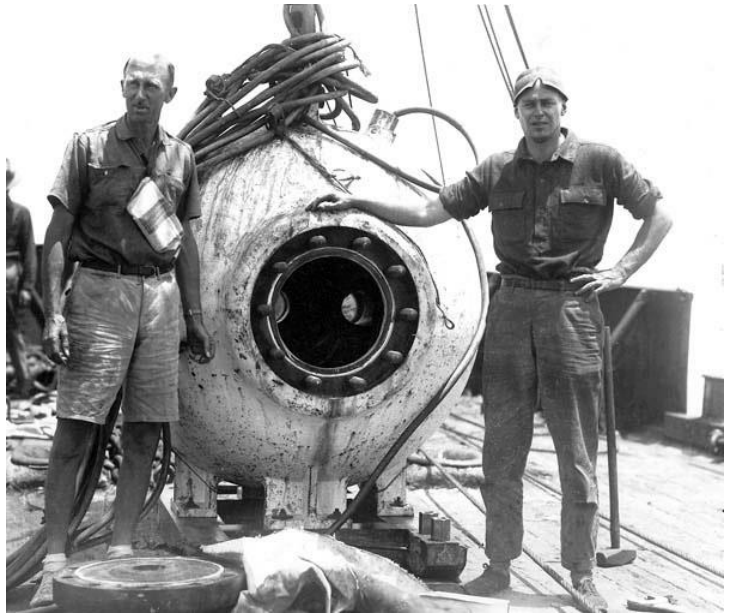


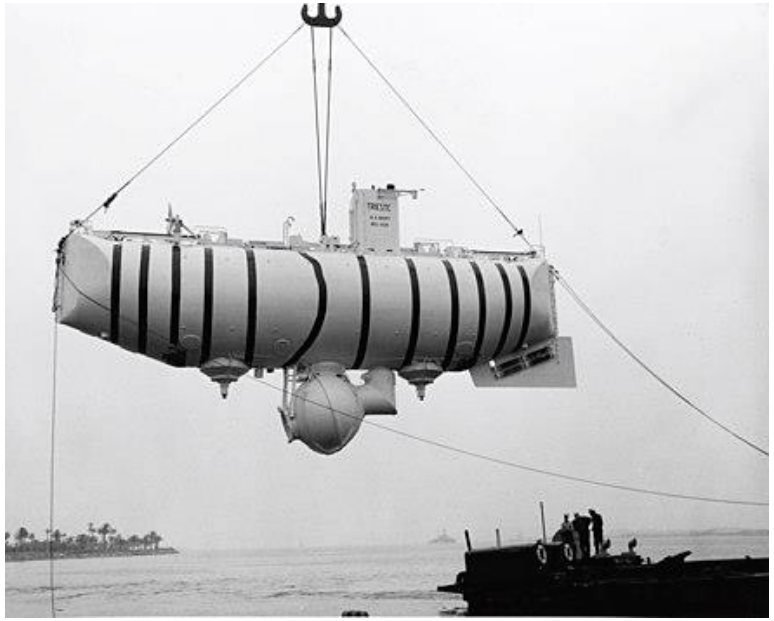
Source: toppr.com

- *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)*

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

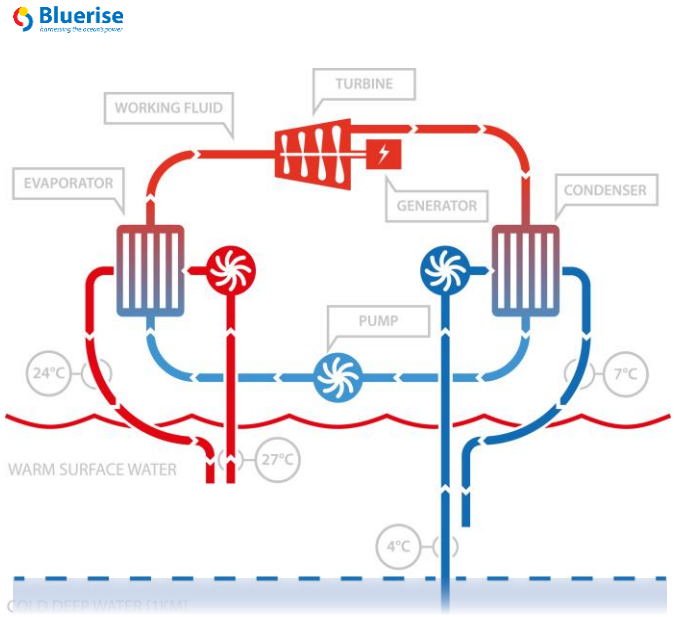
- *Energy Transport via Molecules / Hydrogen Avoids High $$$ of HVDC Cables / Converter Systems*
- *Decline of Oil & Gas Production → Repurposing of Offshore Assets / Platforms, Pipelines etc.*

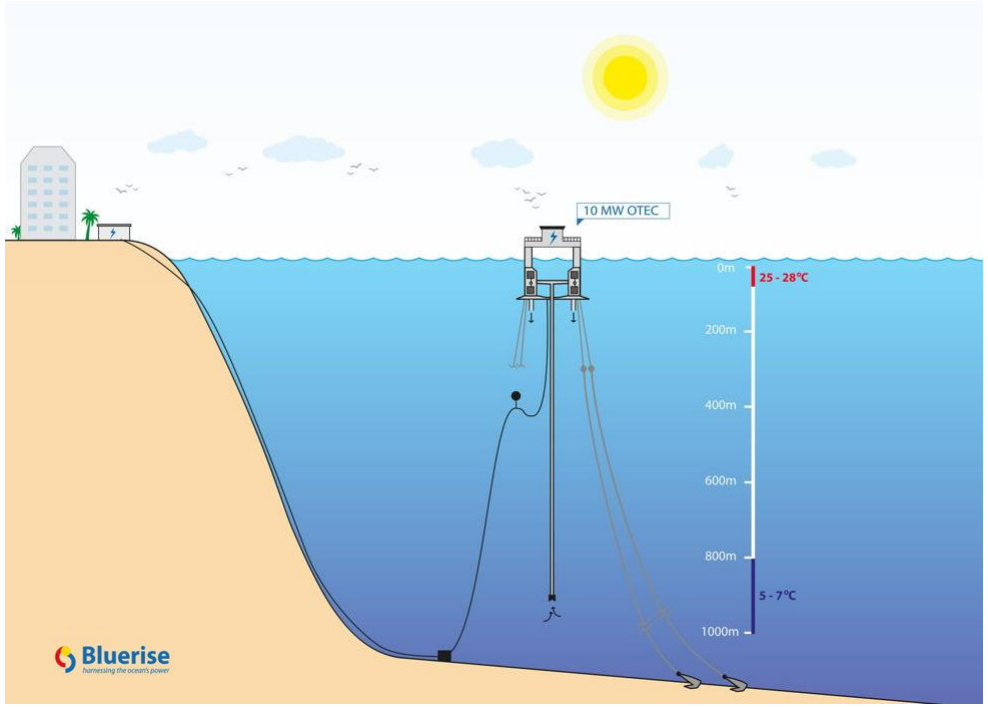
Source: https://tractebel-engie.com

- *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*

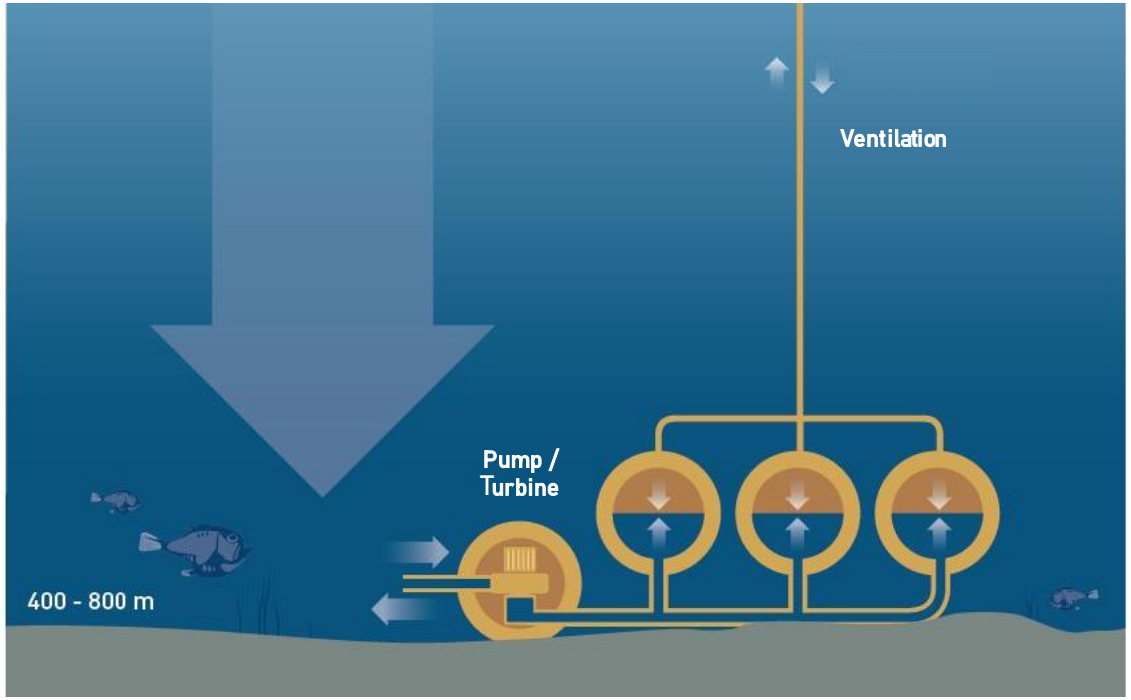




- *Solar Energy Absorbed by 23 Million Square Miles = 250 Billion Barrels of Oil*
- *10MW OTEC Pilot Planned in Southern China by Lockheed Martin & Reignwood Group*

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.*

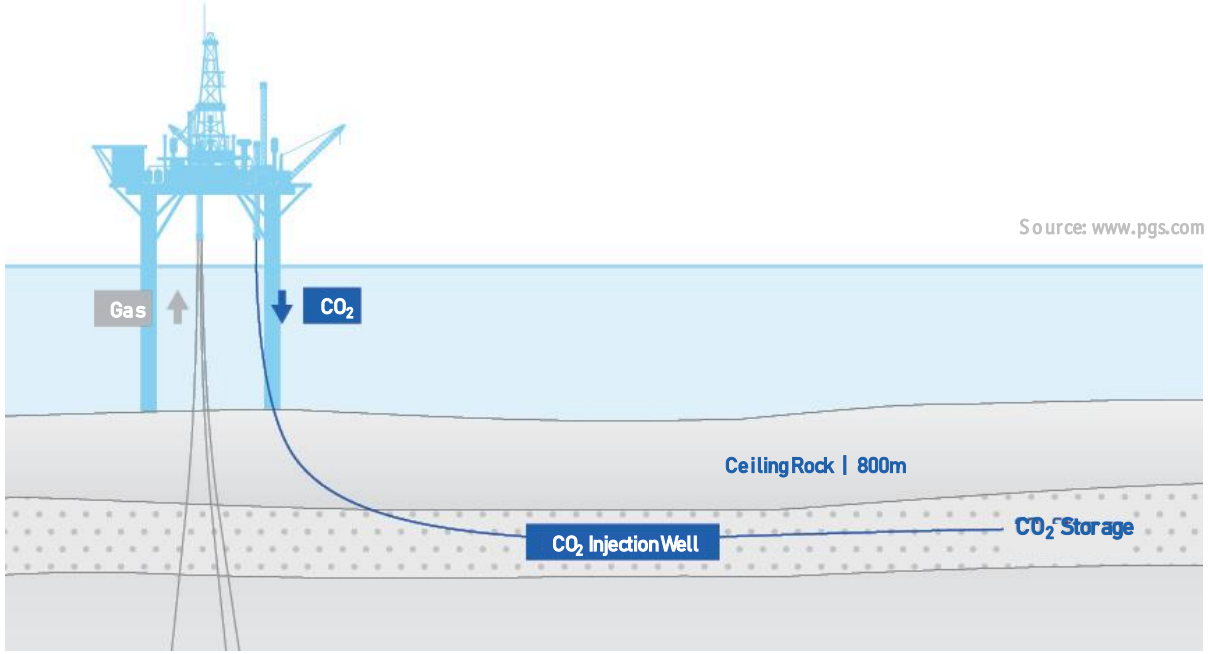


Source: SINTEF

- *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

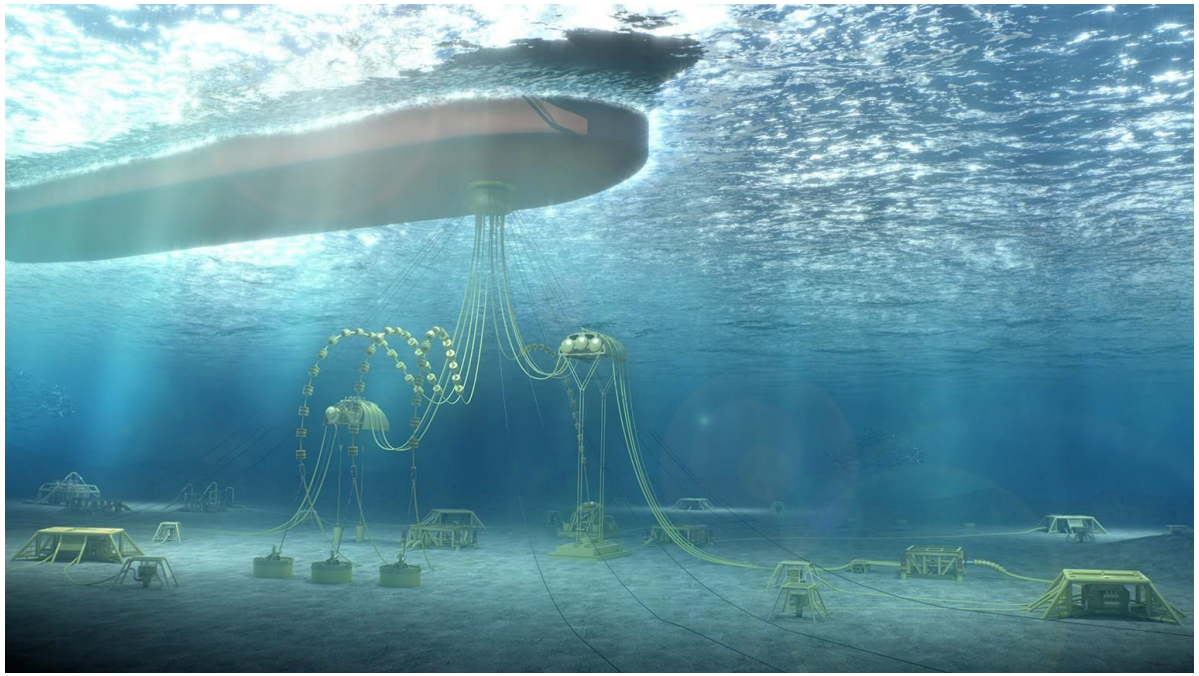
- *CO_2 Capture & Storage (CCS) → Main Element of Energy Transition to Low Carbon Future*
- *Future CCS Value Chain → CO_2 Transported by Ships & Stored in Off-Shore Formations*



- *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"*

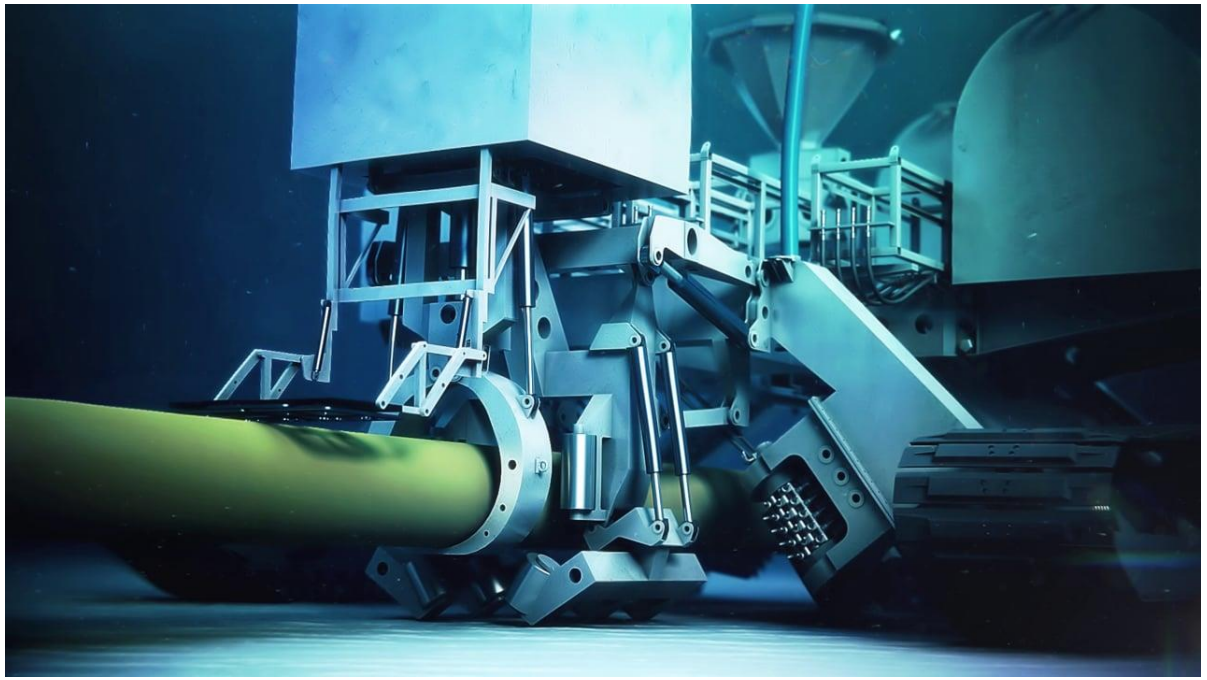


Source: www.ocean-5.com

- *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

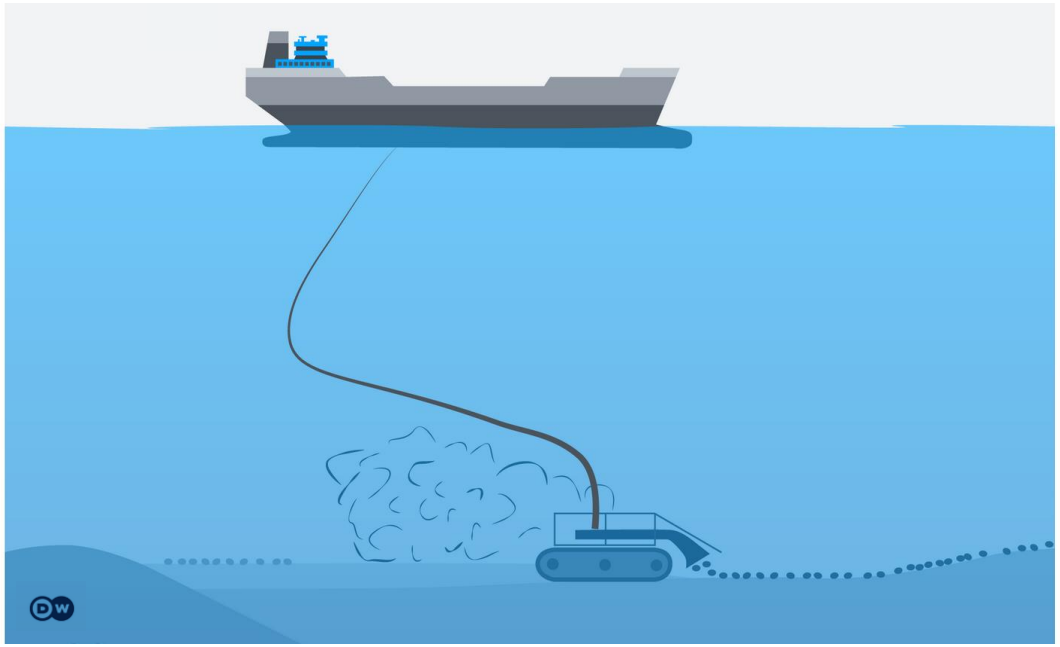
- *Burial of Subsea Pipelines and Cables*
- *Jet Trenching ROVs | Ploughs | Mechanical Trenchers — x 1000 m Operation Depth*

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

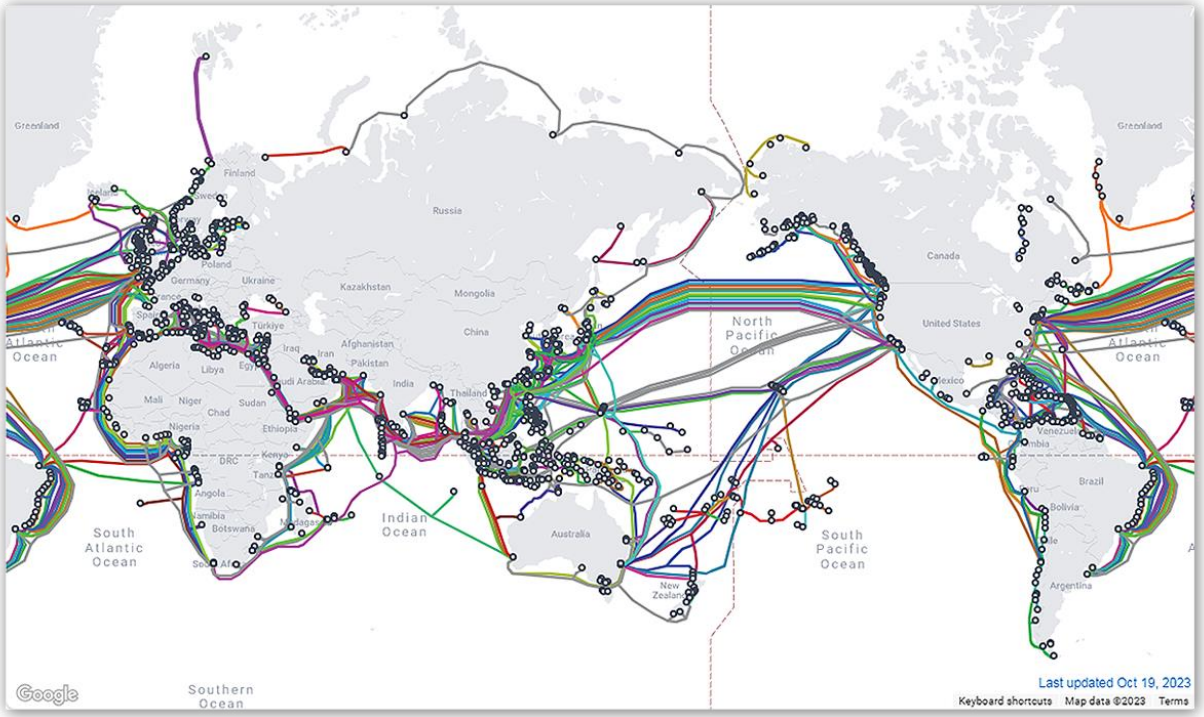
- *Suction of Polymetallic Nodules (Mn, Co, Cu, etc.) @ Seabed (4000…6000m)*
- *Subsea Crushers & Pumps for Transportation of the Minerals to Supporting Vessel*

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*



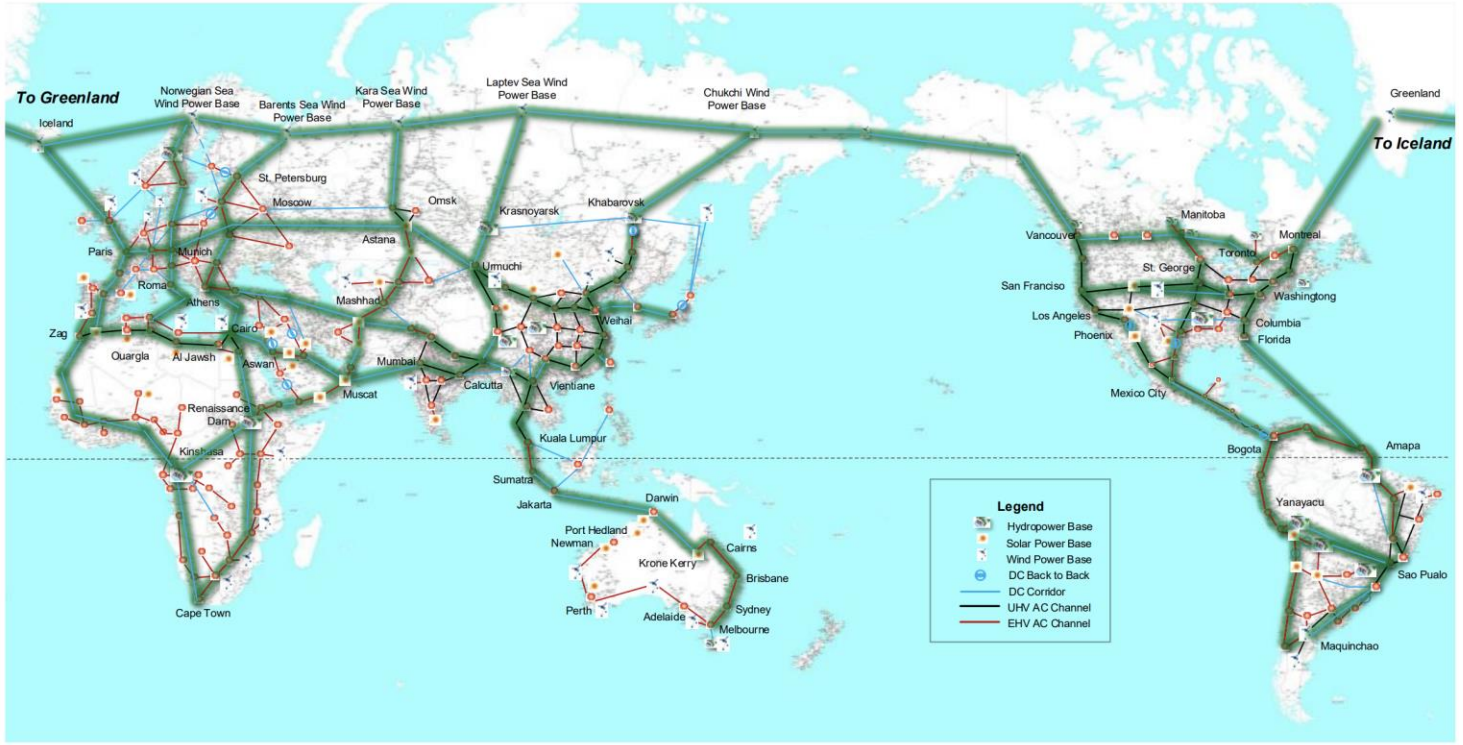
- *Crucial Strategic Importance — Potential New Front in the Ongoing Geopolitical Tensions*
- *Regular Maintenance / Surveillance & Protection of Critical Cable Routes / Threat Response*

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*

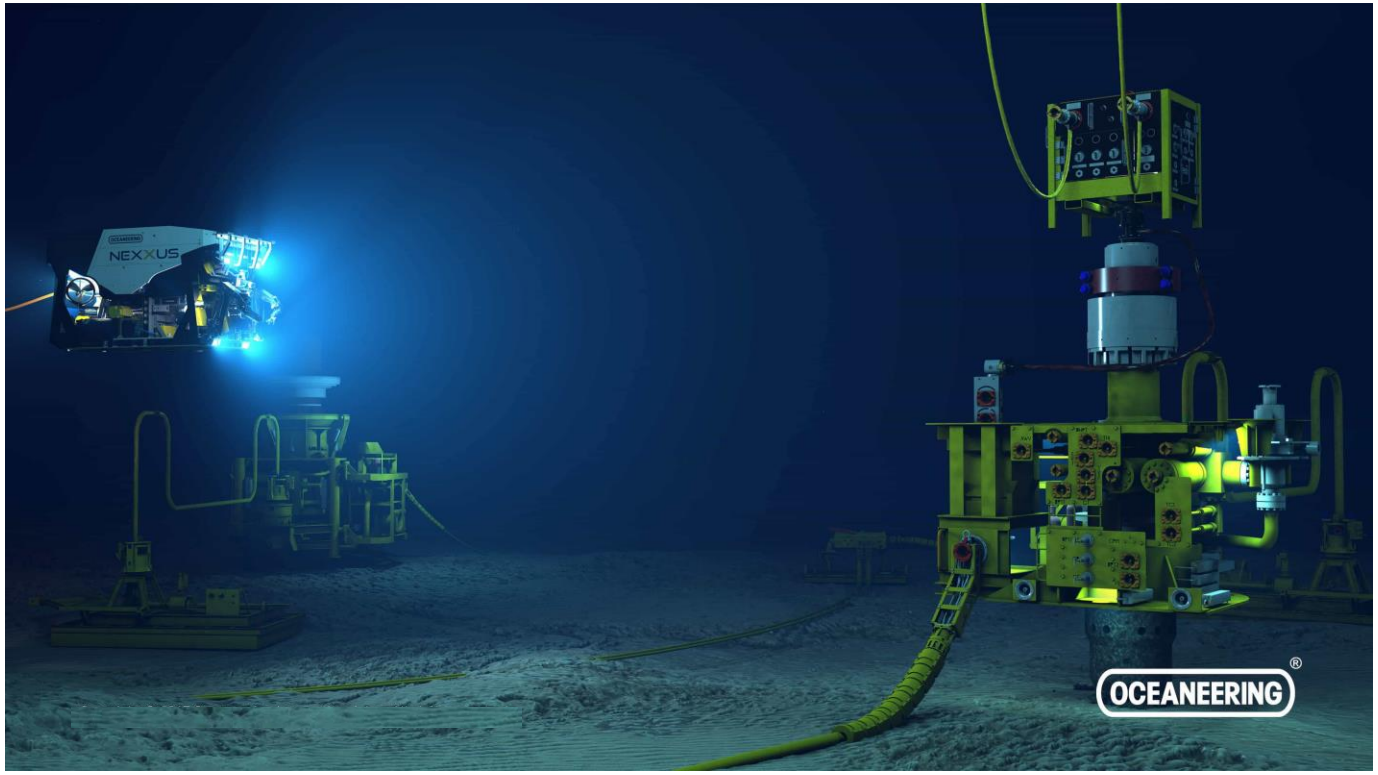
Source: GEIDCO 2018



- *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*

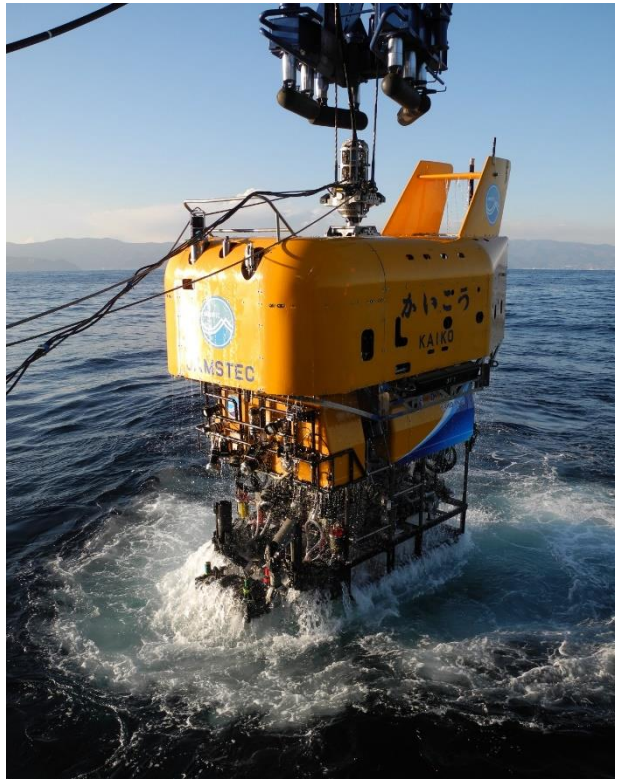
Source: SCHMIDT OCEAN INSTITUTE

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

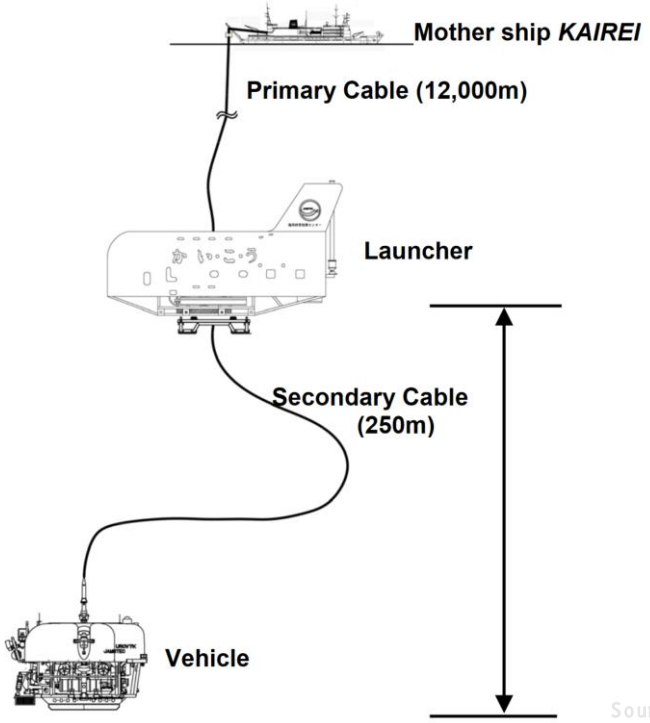
RESEARCHANDMARKETS
THE WORLD'S LARGEST MARKET RESEARCH STORE

Scientific Exploration of Ocean Depths – 1/2

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



Source:

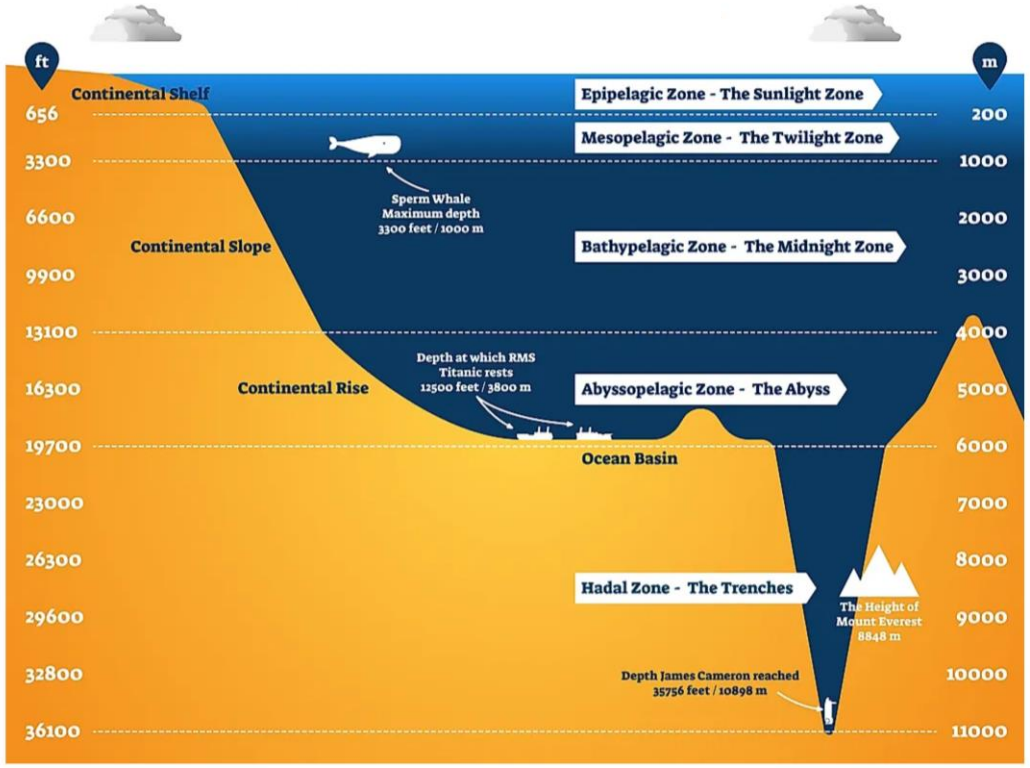


Source: Murashima et al, 2005

- *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

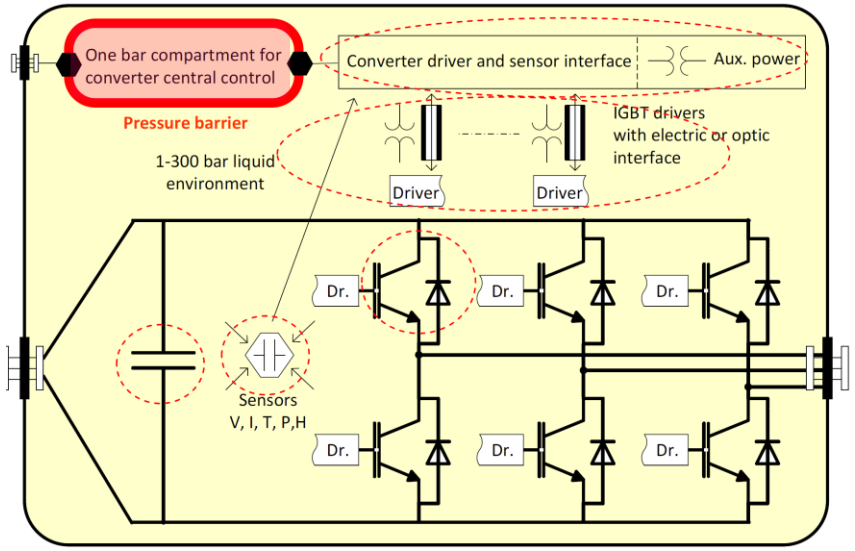
Source: VectorMine/Shutterstock.com

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

Remark Electronics Pressure Housings

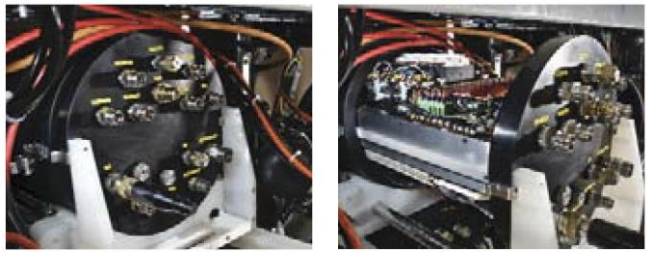
- *Air or Gas Filled Components → Would Implode in Large Depths (e.g. 6000m → 600bar)*
- *One-Atmosphere Housings → Maintain Constant Inside Pressure / Cylindrical or Spherical Shape*
- *Pressure Balanced Housings → Int. ≈ Ext. Pressure / Oil Filled – No Voids / Not Shape (Cooling) Restricted !*

Source: M. Hernes SINTEF



Source: SAAB

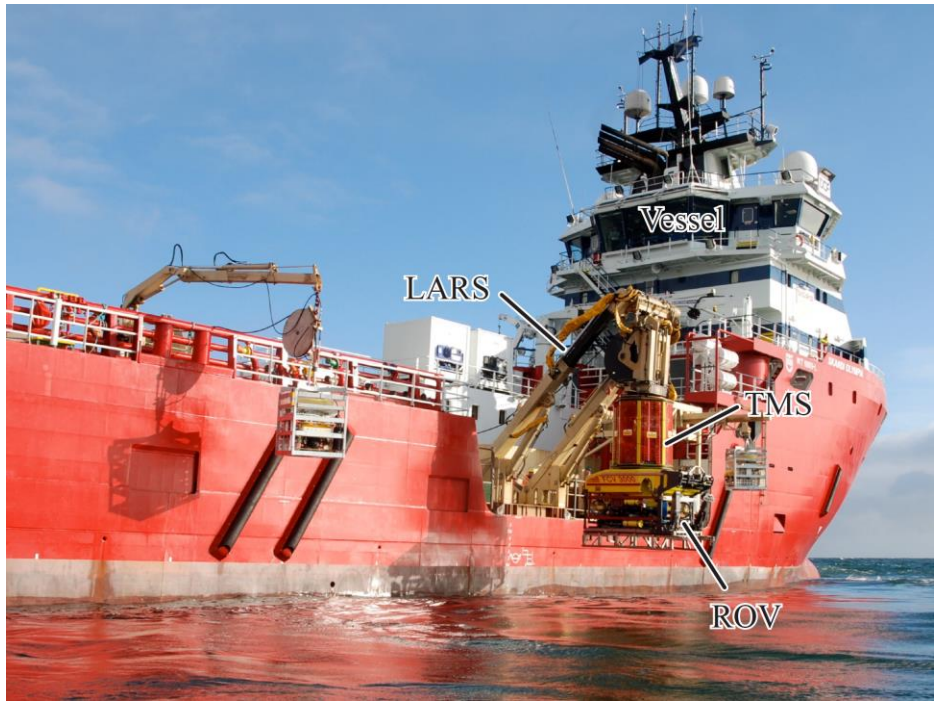
Electronics Compartment of Seaeye Jaguar

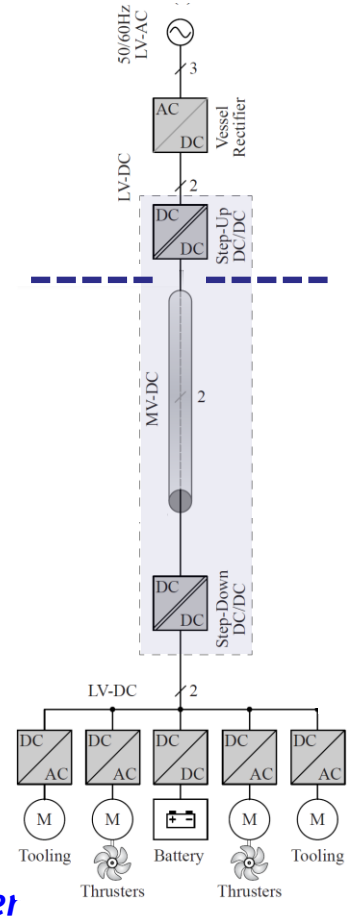


- *Research on Pressure-Tolerant Power Electronic Components (300bar) @ SINTEF*
- *IGBTs → Sw. Behavior Unaffected / Chip Interface Needs to be Protected from Surrounding Liquid*
- *Pressure Affects BH-Curve of Magnetic Cores & Impairs Self-Healing of PP Film Cap. → Voltage Derating*

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*

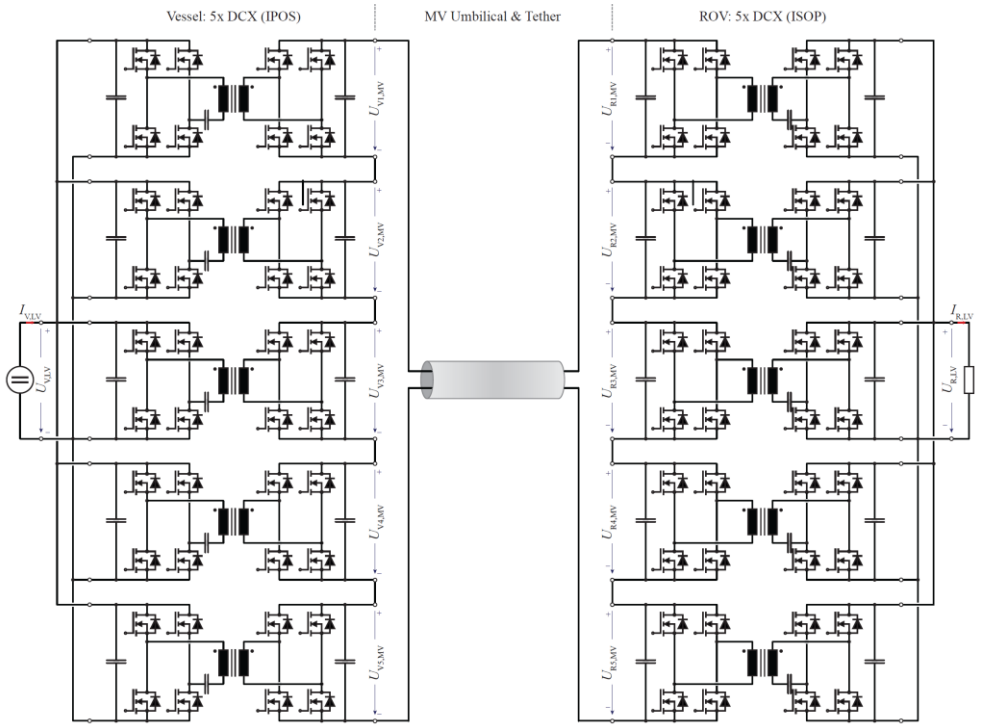


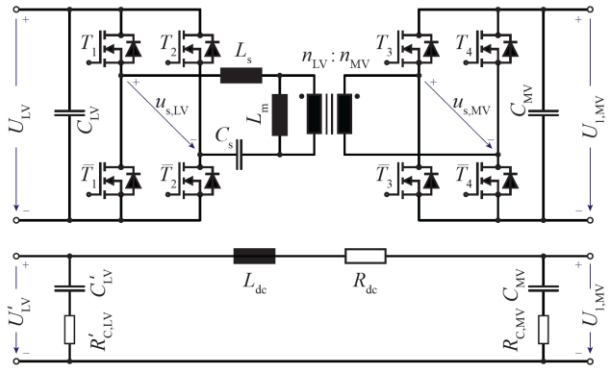


- *Utilization of DCX-Based MV DC-Transmission Instead of 400...800 Hz AC*
- *Lower Losses & Higher Power Transmission Capacity for Given Umbilical Diameter*

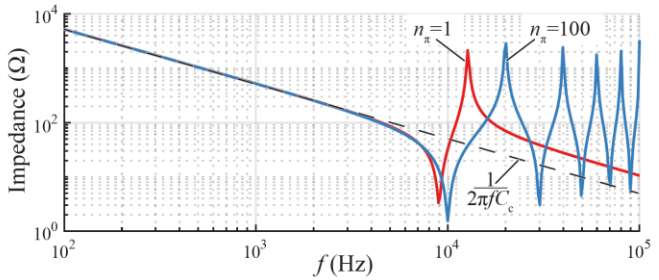
Deep-Sea E-HyDrone MV_{DC} Power Supply – 2/4

- *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

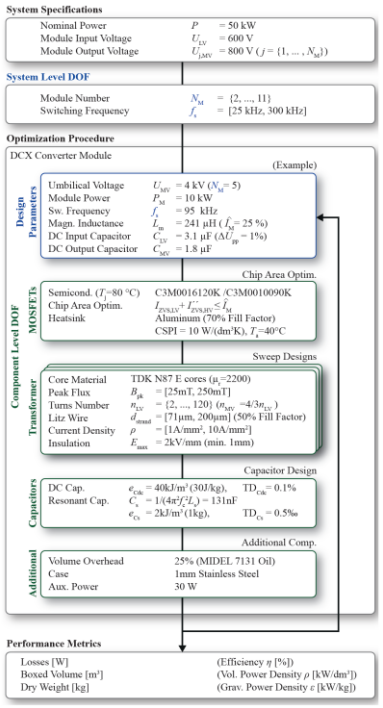


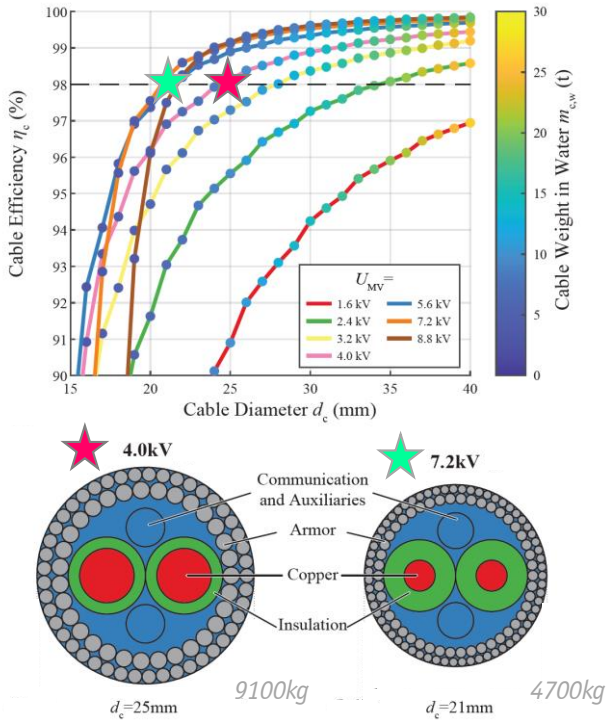
Umbilical
Impedance
Characteristic

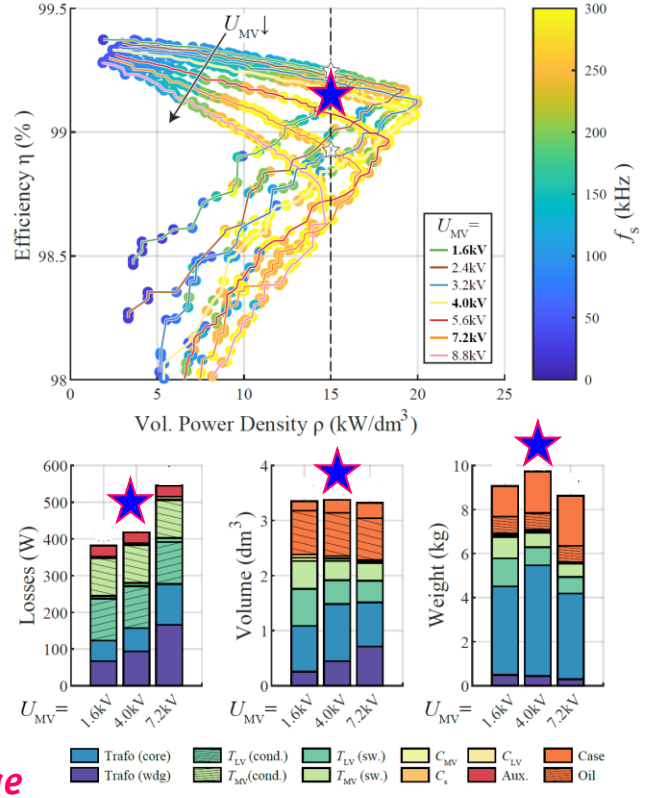
- *Optimal Selection of Transmission Voltage / Number of DCX Modules / Sw. Frequency*

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*



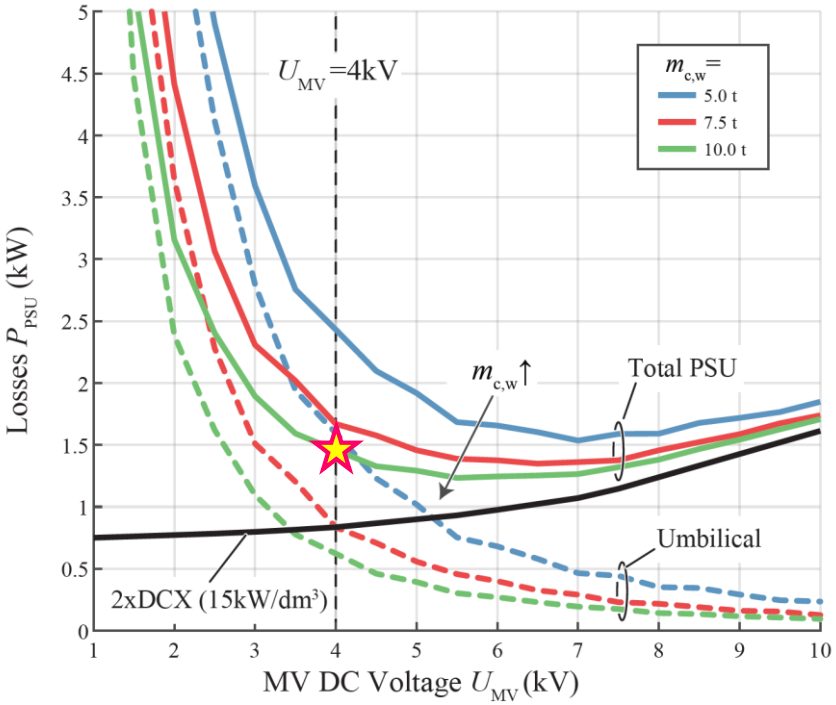


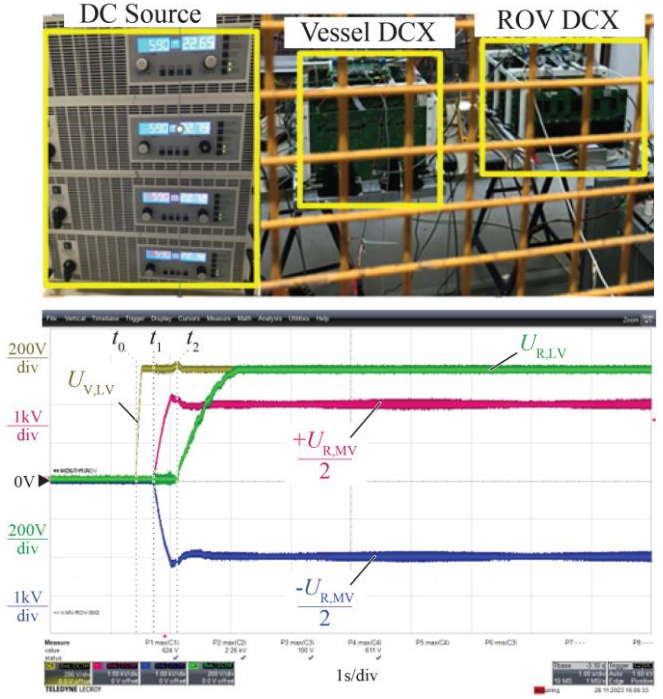


- *Given Cable Diameter → Weight Reduces w/ Increasing Voltage*
- *Increasing Sw. Frequ. → Higher Power Density @ Lower Eff.*

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*

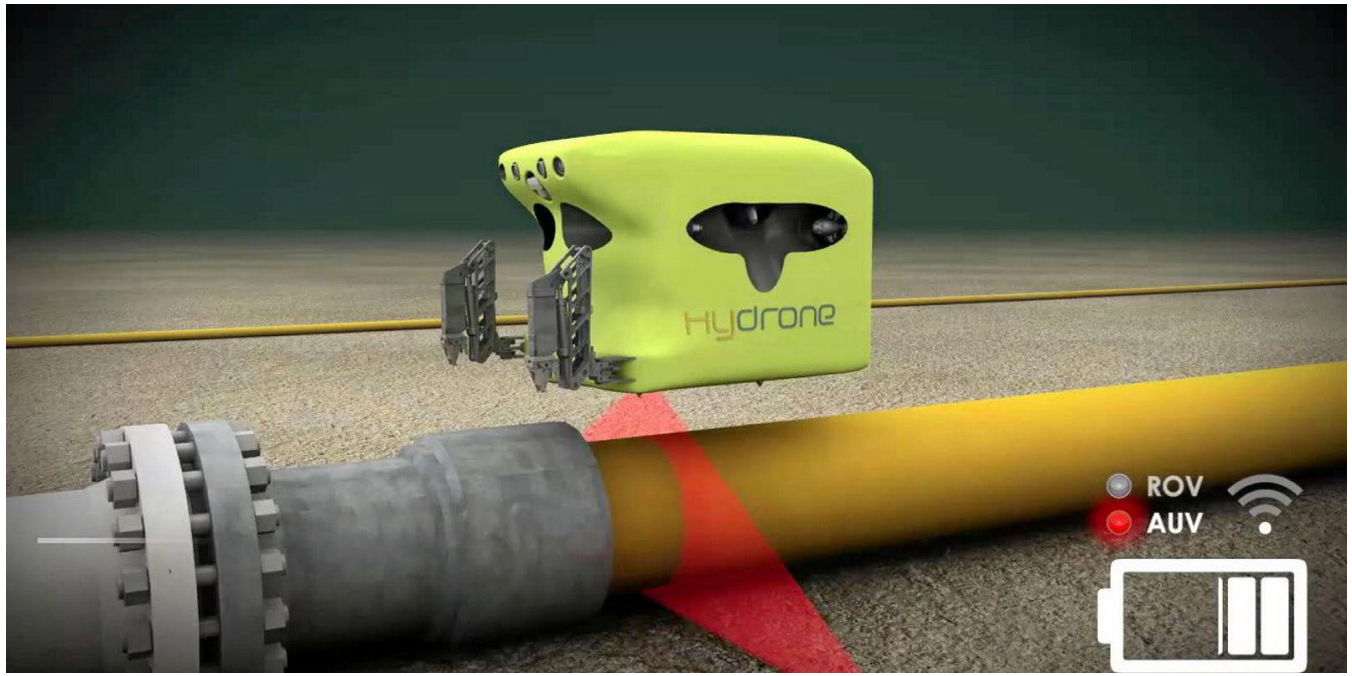




- *97.5% Overall Power Supply Efficiency / Weight Mainly Determined by Umbilical and TMS*
- *0.5ms Ramp Time of 100% ROV Load Steps – Minor Ringing of DCX — Umbilical — DCX*

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*

Industrial Subsea AUV Charging System

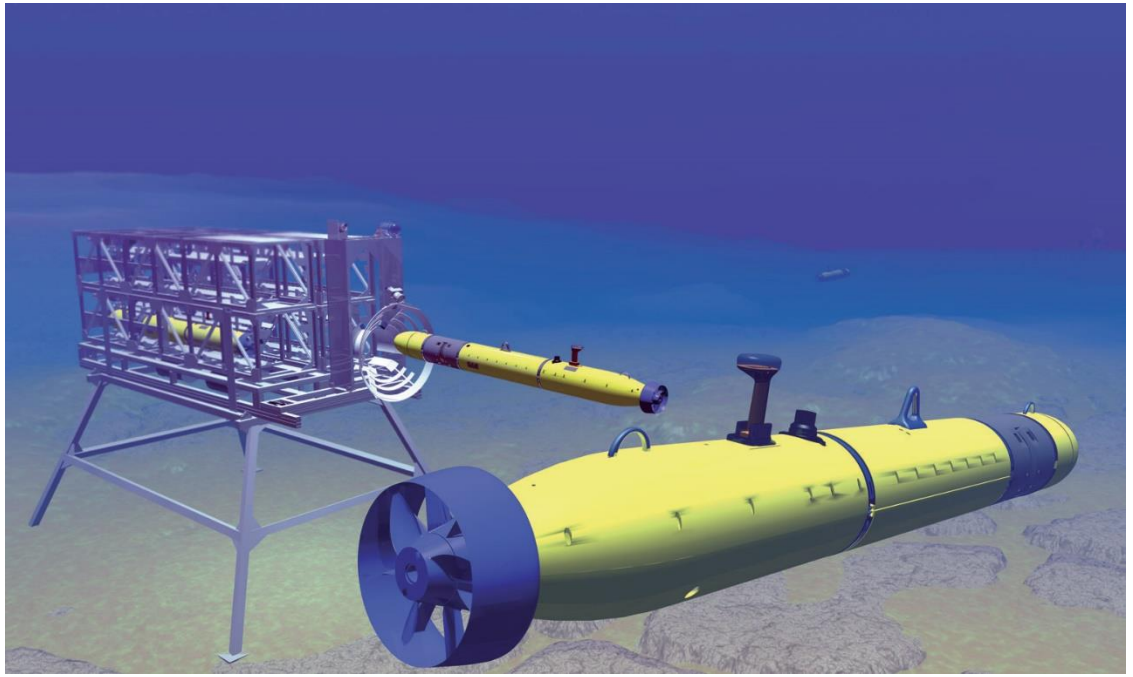
- *"Universal" Open-Standard Docking Station — Interoperability w/ AUVs of Diff. Makes / Shapes / Sizes*
- *2.5 kW @ 95% Efficiency Inductive Power Transfer / 3000 m Operation Depth / 15 Years Lifetime*

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*

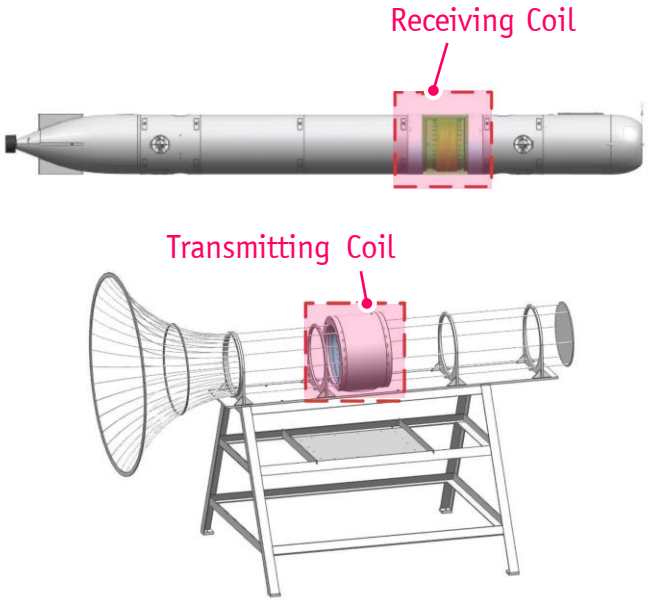
Resonant IPT Wireless AUV Charging

- *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

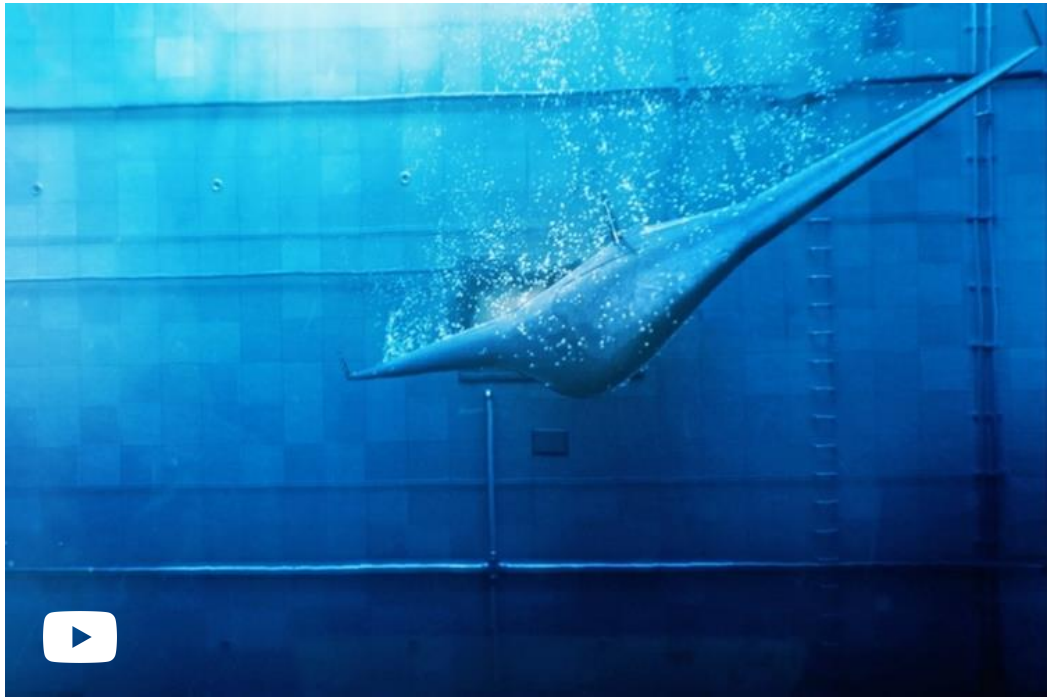
Source: Peizhou Liu et al., 2022



- *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*

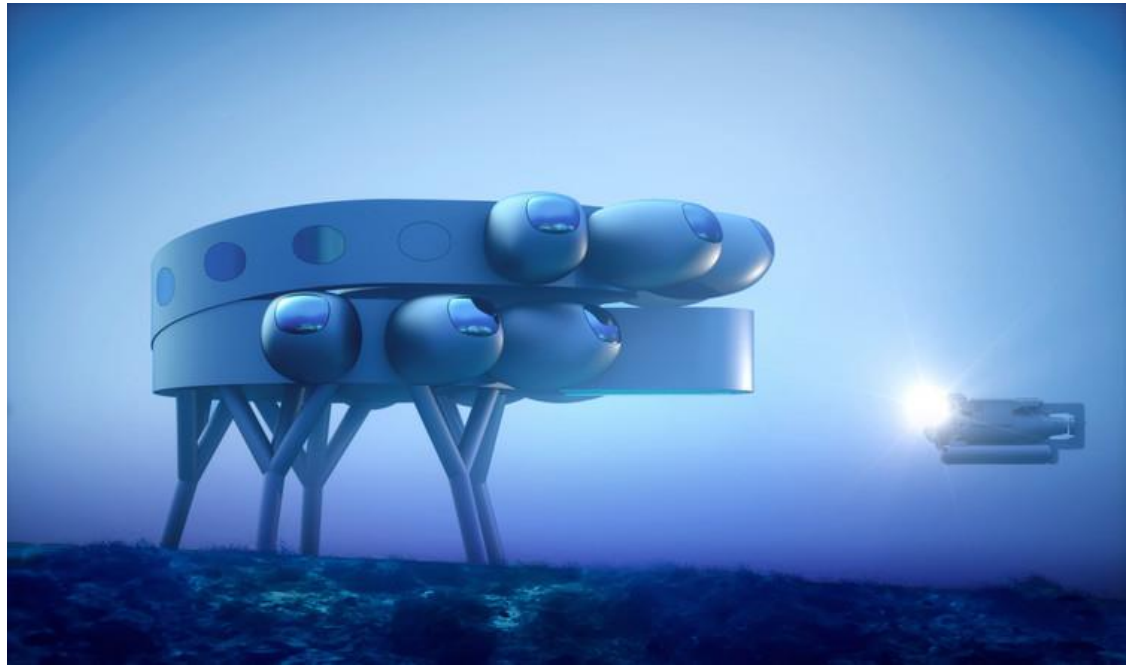
Future Underwater Exploration

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

- *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!