Anchoring & Mooring for Floating Offshore Wind

30th November 2018 OSIF Meeting, Fugro Nootdorp

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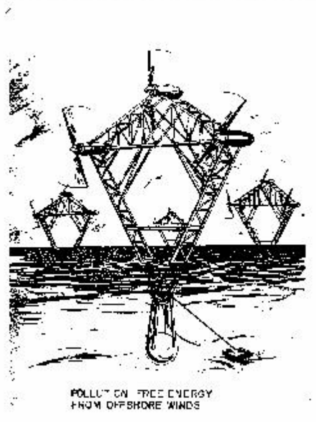


Source: Univ. Mass. 1974

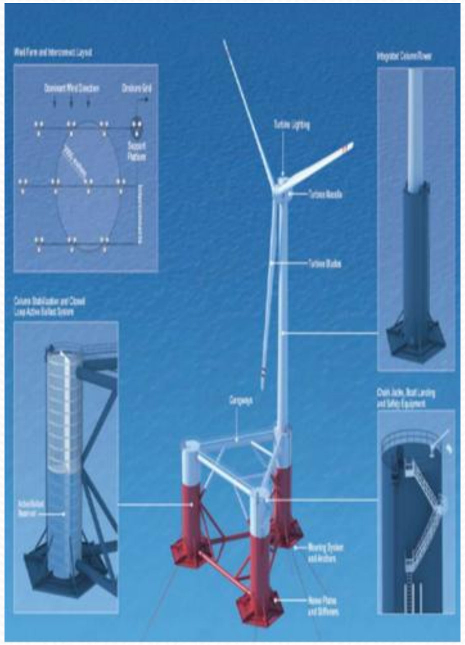
SPAR - HYWIND

Source: Statoil

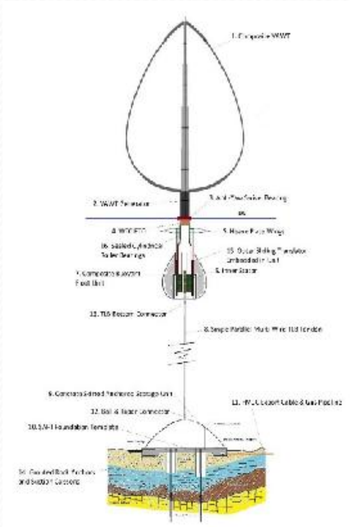
TLP - PELASTAR

Source: Glosten Associates

SEMI SUB WINDFLOAT



Source: WINDFLOAT



BLACKBIRD F-VAWT-TLB

Summary - Anchoring & Mooring Systems For Floating OW

PART 1 FLOATING OFFSHORE WIND

Global Temperature Predictions	[World Bank 2012]
Levelised Cost of Energy Comparison	[Lazards 2018]
Offshore Wind Kinetic Energy	[PNAS 2017, NREL 2012]
Offshore Wind Power	[World Bank/DTU]
Floating Wind – Potential Offshore Resource	[Open Ocean, Statoil]
North Sea/Atlantic Offshore Wind Resource	[Carbon Trust, UK Eval. Group]
Offshore Wind Turbine Fixed "Foundation"	[NGI]
Why is Floating Wind Necessary?	[Atkins 2017]
Examples of Floating Wind Structures	[Various]
Active European Floating Wind Projects	[Inducomm, 2017]

PART 2 – ANCHORING AND MOORING

Offshore Anchor Types

Conventional Anchoring Solutions

Gravity – Drag Embedded – Suction Caisson –
Driven Piles - Others (Drop, Torpedo, VLA, SEPLA)

Anchoring Case Studies

1. Gravity Anchors - Oregon WEC OPT
2. Suction Caissons - HYWIND Buchan Deep
3. Drag Anchors - Principle Power

Mooring Innovations

1: Nylon Rope and Gravity Anchor Bags [TTI]
2: Submerged Taut Moored Substructure [SBM]
3: Dynamic Tether: Elastomer/Spring [TFI]
4: First Subsea "Ballgrab" Platform Mooring Connectors

PART 3 – SEABED ROV GEOTECHNICAL INVESTIGATION & INSTALLATION

1. MEBO-Bauer 2. BGS RD2 Rockdrill 3. Forum ROVDRILL-3 4. Helix/Canyon ROVDRILL-2 5. Fugro-Gregg
6. Cellula Robotics CRD100 7. Benthic PROD 8. IGEOTEST MD500 9. IHC SWORD 10. McLaughlin & Harvey

Seabed Anchored Foundation Template [SAFT]
Bauer Monopile/Jacket Pile Installation Methods
BLACKBIRD F-VAWT-TLB
Non-Renewables Floating Structures

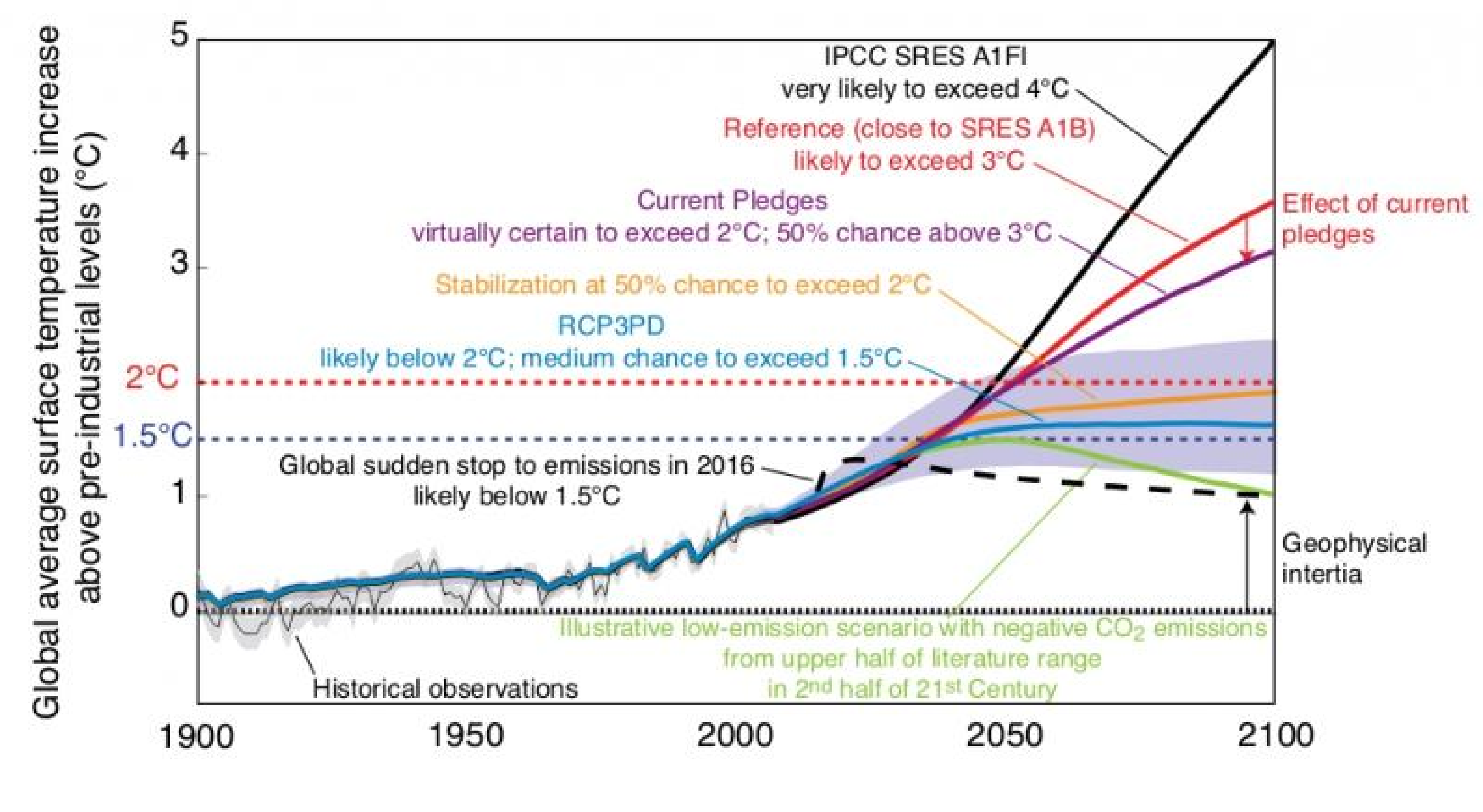
Micropiles Vs Tension Anchors
Floating Vertical Axis – Sandia Labs [FVAWTs]
Floating Wave and Tidal Energy
SMD-BORD JV (2012)

Conclusions

References & Links

Contact Details

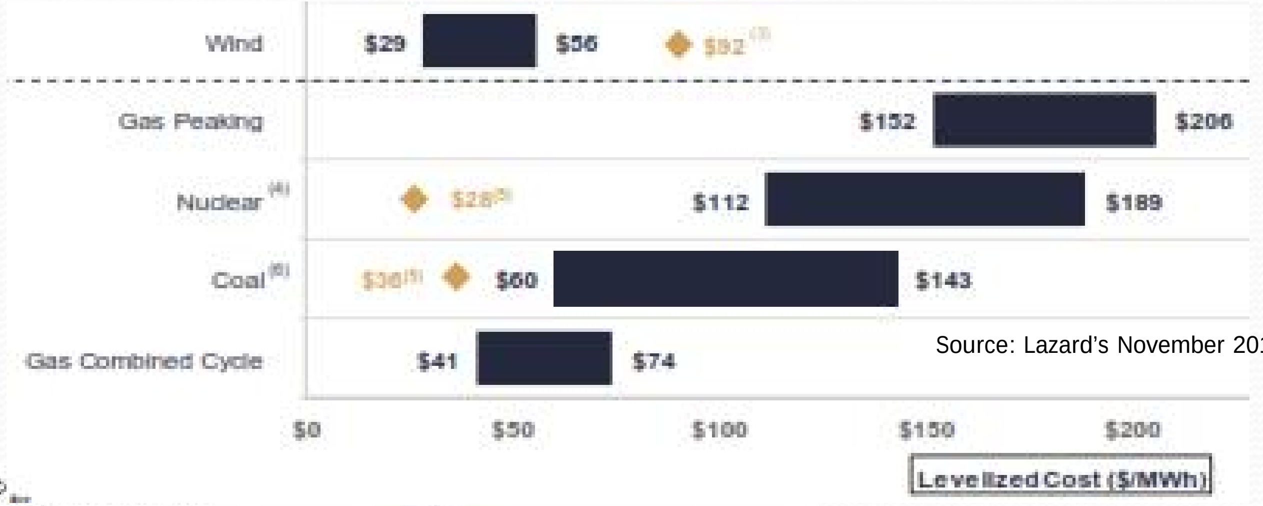
Global Temperature Predictions [World Bank 2012]



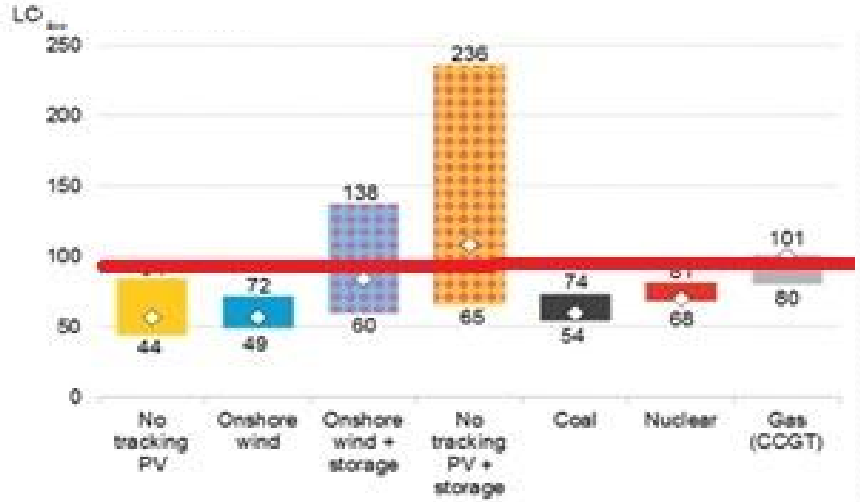
Source: World Bank/Potsdam Institute November 2012

Levelised Cost of Energy Comparison—Unsubsidised Analysis

LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS — VERSION 12.0 November 2018



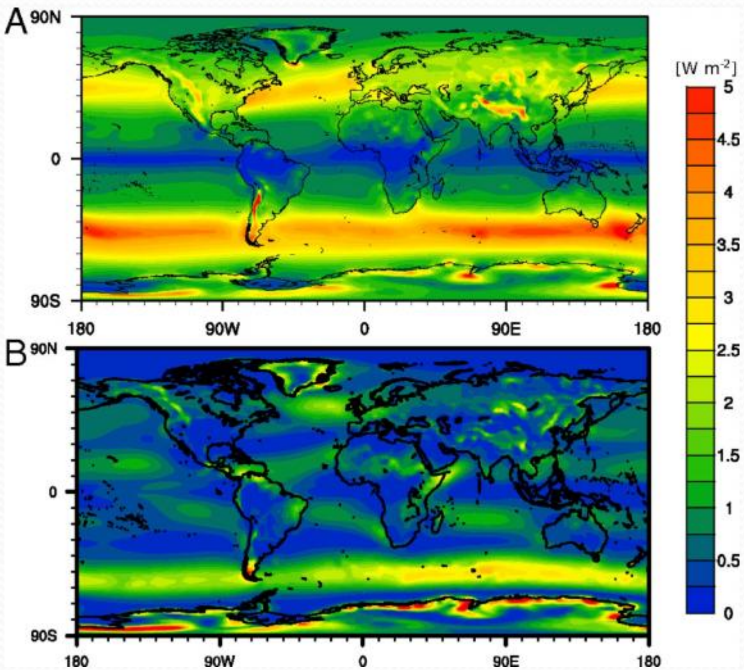
Source: Lazard's November 2018



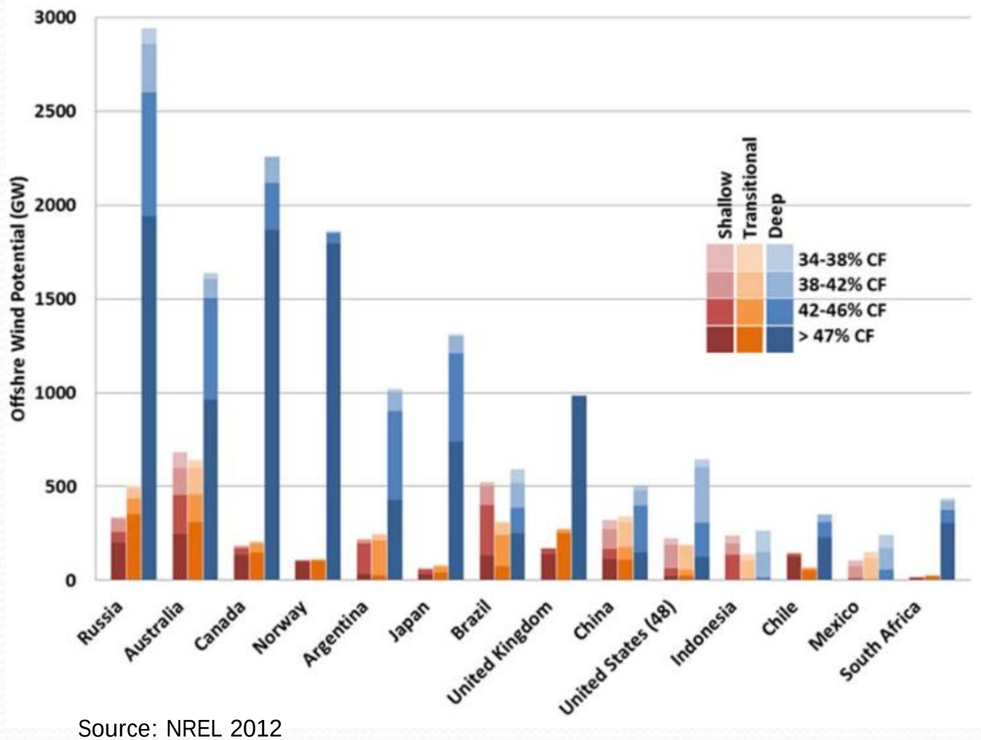
OFFSHORE WIND Q4 2018 LCOE $ 92

Source: Bloomberg New Energy Finance New Energy Outlook November 2018: bnef.turtl.co/story/neo2018

Offshore Wind Kinetic Energy



Source: Possner & Caldera [PNAS] 2017

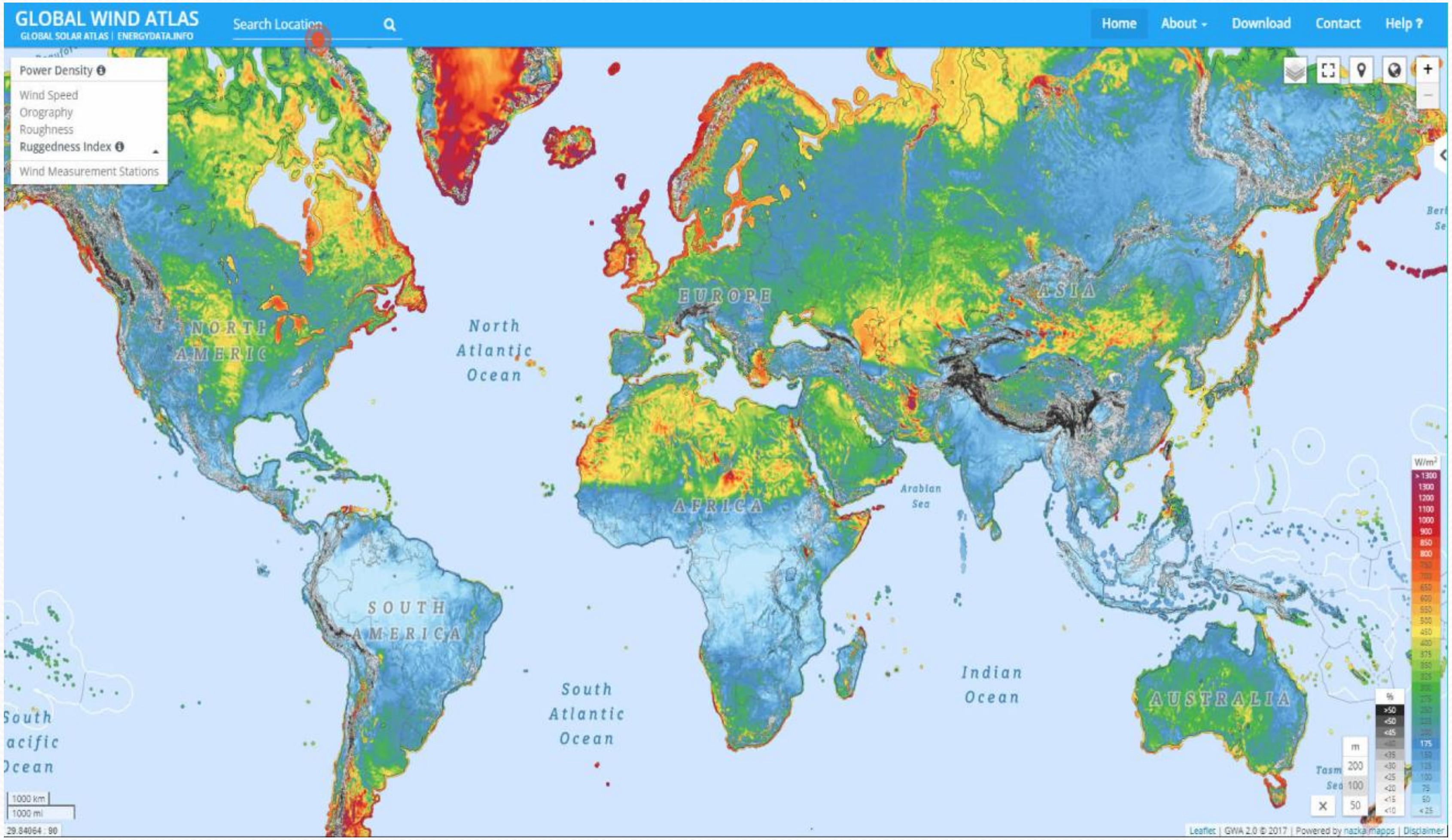


Source: NREL 2012

A: Climatology of Kinetic Energy Extraction (KEE) B: Annual Mean Kinetic Energy (KE) Dissipation into Boundary Layer.

Shallow	0-30 m	Transition	30-60 m
Deep	> 60 m	CF = Capacity Factor	

Offshore Wind Power

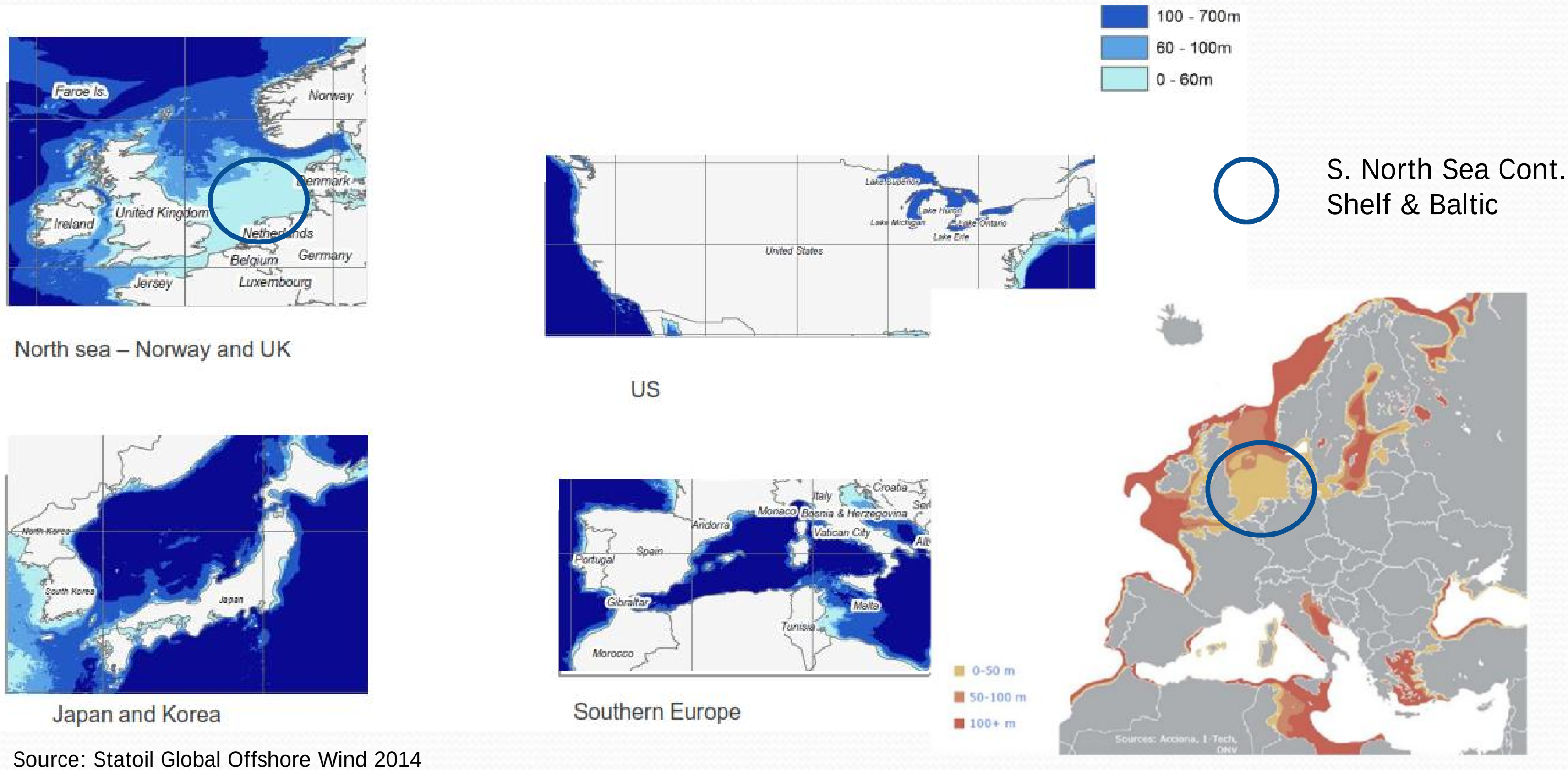


Source: World Bank/IFC/DTU 2017: www.globalwindatlas.info

Floating Wind – Potential Offshore Resource

Majority of OW developments have been in the Southern North Sea, a relatively flat shallow water continental shelf, mainly dense sand, stiff glacial clayey soils & soft sediment filled paleo-valleys.

Not globally representative. Most coastal areas are steep, rocky, with thin (< 5 to 10 m) soil cover. Piling is costly for fixed or floating structures. Soils insufficient for drag or suction caisson anchoring.



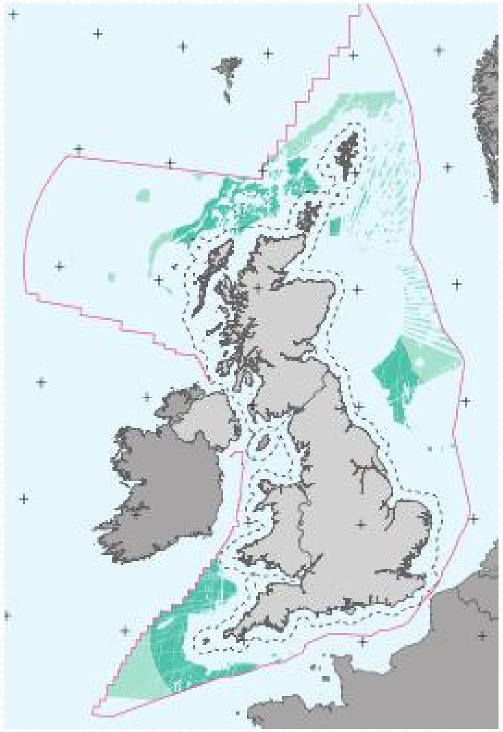
Source: Statoil Global Offshore Wind 2014

North Sea/Atlantic Offshore Wind Resource

Source: www.openocean.fr 2017

A UK ETI study found that with appropriate foundation technology for suitable sites, coupled with ongoing technology and supply chain innovation in other areas could deliver LCoE of less than Euro 100/MWh from the mid 2020's [USD 120]

Source: Carbon Trust "Floating Offshore Wind: Market and Technology Review", June 2015

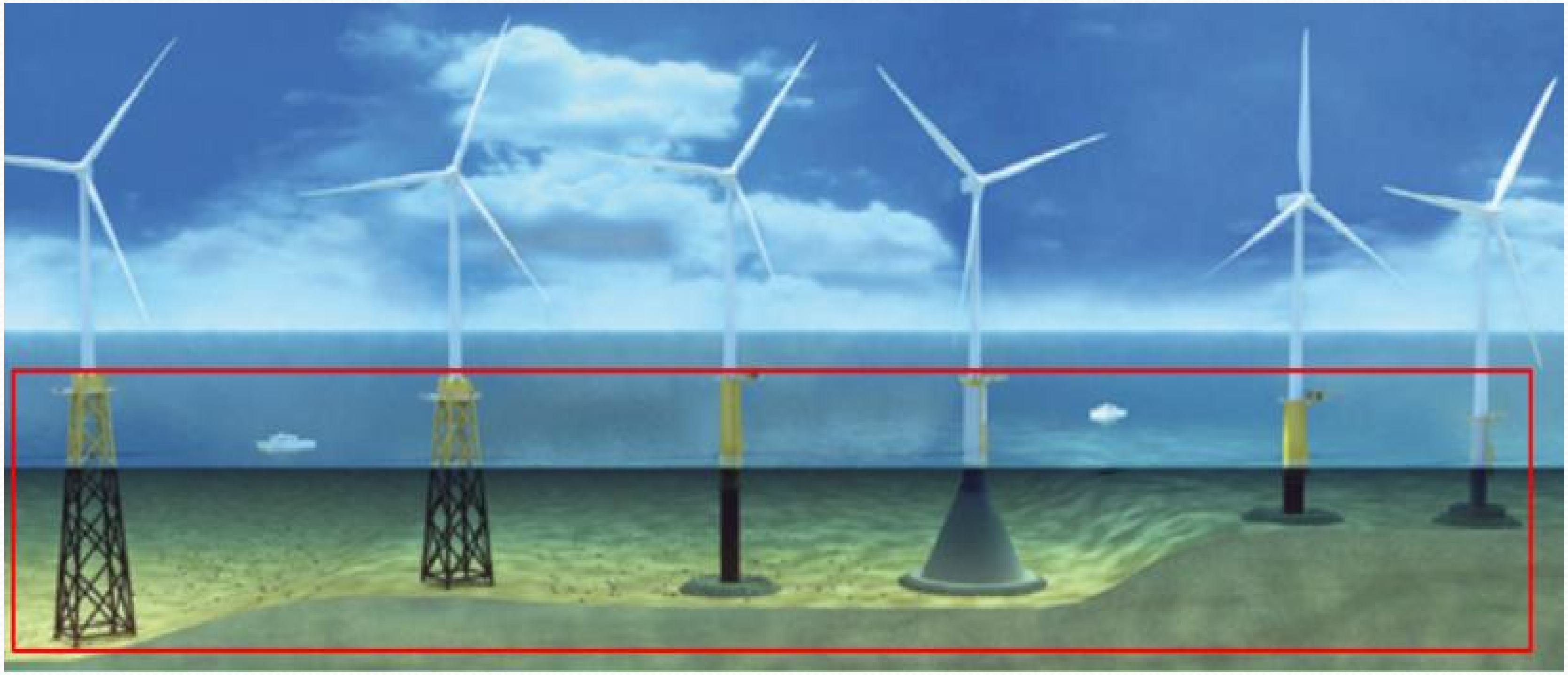


"We find ourselves in a comparable position to that of the nascent UK oil and gas companies in the 1970s"

Source: UK Offshore Valuation Group (2010)

Offshore Wind Turbine Fixed “Foundation” Definition

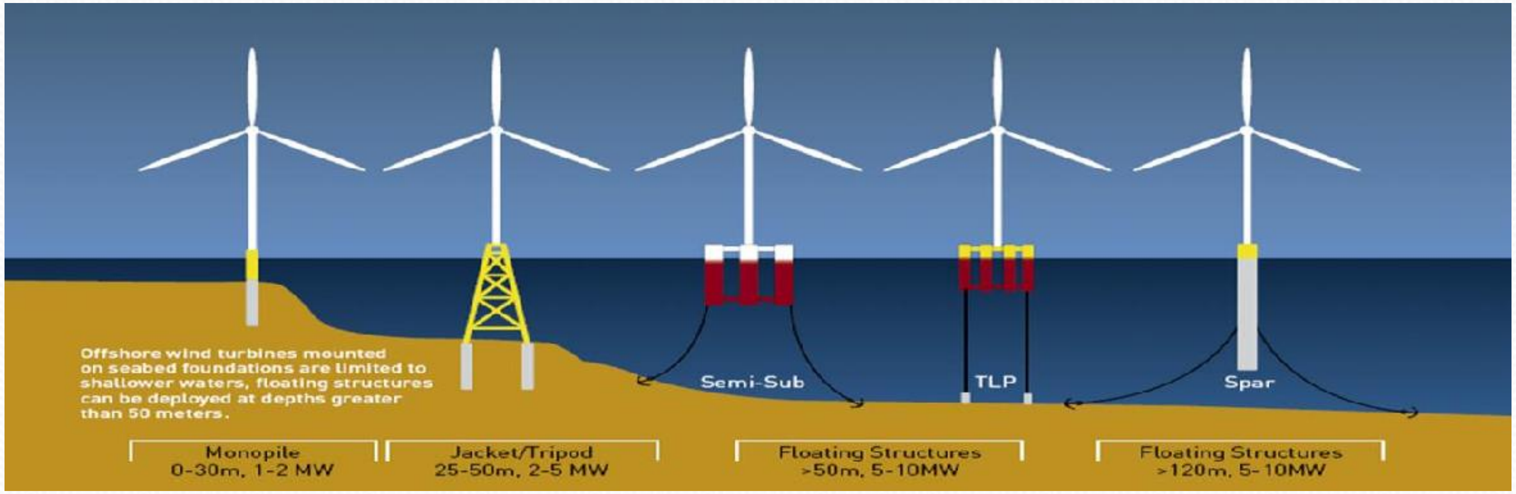
- Civil Engineering - “Foundation” = Everything Below Ground/Seabed
  - Sub-Structure = Supporting Structure
- Offshore Wind - “Foundation” = Everything Below Tower Transition Level



Source: Norwegian Geotechnical Institute

Why is Floating Wind Necessary? (Atkins, 2017)

Increased Wind Exploitation	Stronger, more consistent winds & higher capacity turbines
Quayside Assembly	Eliminates heavy lifts, reduces risk, less weather dependency
Larger Resource Base	Not restricted to shallower water depths (typically >50m)
Reduced Seabed Installation Risk	Compared to driven or suction piled bottom fixed structures
Conduct Major Repairs/Upgrades	Ability to tow floating structures to shore if necessary
Deployment Further Offshore	Reduced planning risk and visual impact
Anchored Moorings	Pre-installed anchors & mooring lines > no driven/drilled piling
HSE	WTG installation at quay, less activity offshore > no jack-ups



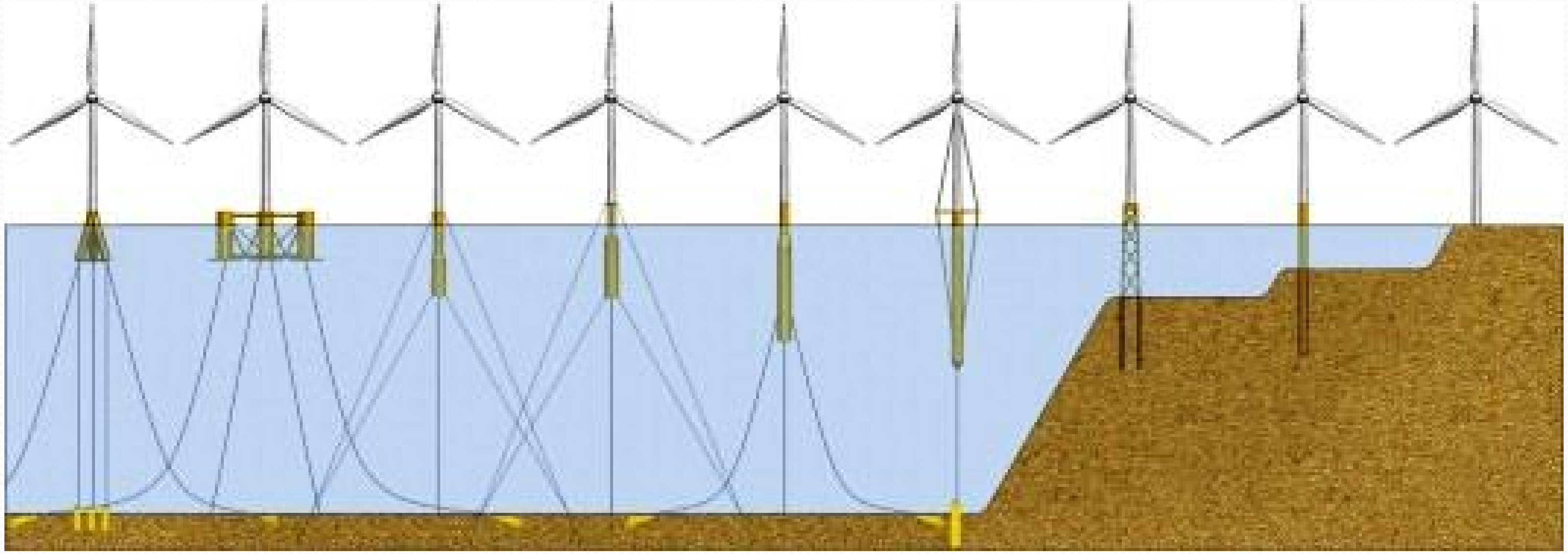
Source: Roddier & Weinstein, 2010

Examples of Floating Wind Structures

Approx. 30 floating wind concepts under development: see map of Floating Wind Energy Projects of The World, Inducomm, 2017

Offshore turbines mounted on seabed foundations are limited to shallow waters < 50 m. Floating structures can be deployed at WDs > ~50 m.

Innovation lies with the <u>Design & Installation of Support Structures</u>



Source: Myhr et al, 2014.

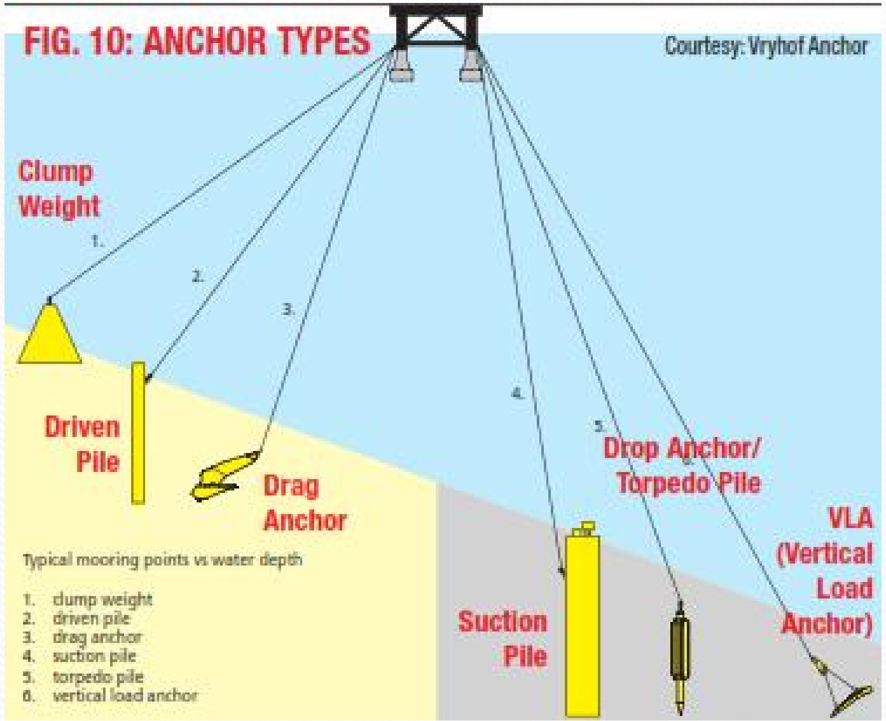
Active European Floating Wind Projects

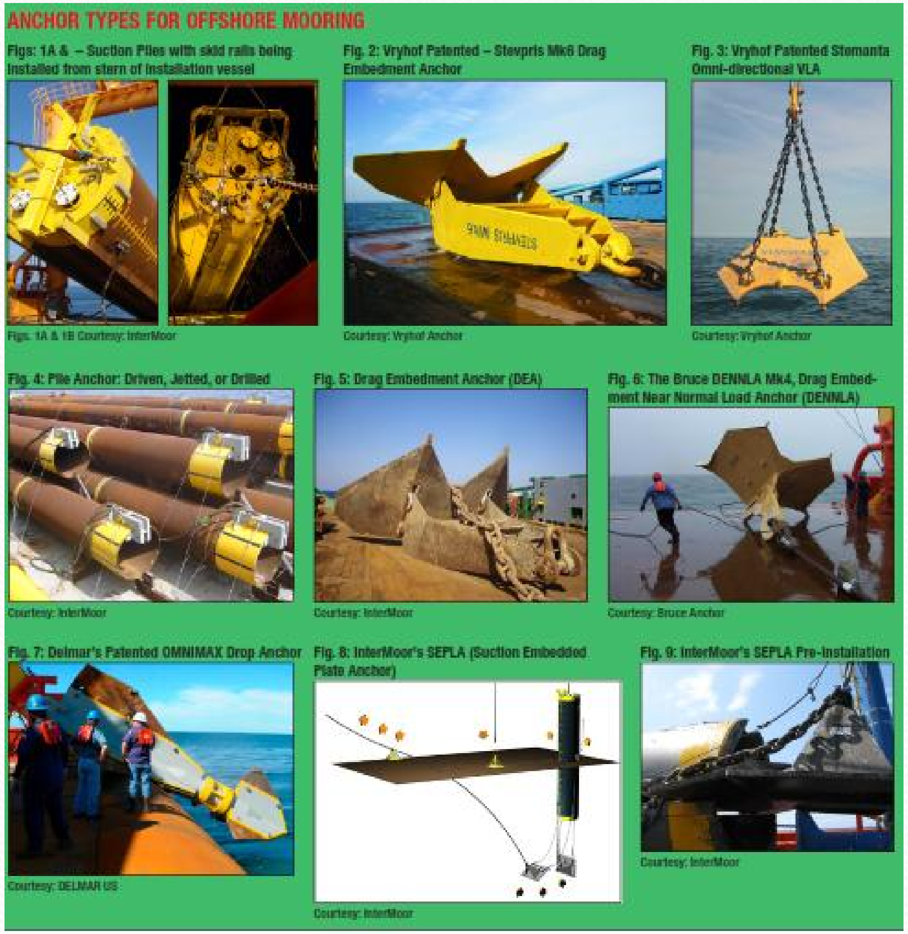
Project	Operators	System	Website	Turbine	MW	WD/L	Mooring	Date
Deep Spar Buoys								
HYWIND	Statoil	Hywind Spar	statoil.com/en/TechnologyInnovation	Siemens	5x6	100/25	Catenary 3	2017
WINDCRETE	Fenosa/U. Catalunya	Concrete Spar Buoy	windcrete.com	n/a	n/a	wd>90	Catenary?	n/a
COBRA	Kincardine OWL	Cobra Semi Spar	pilot-renewables.com/	Senvion	8x6.15	62/15	Catenary 3	2020
SPINFLOAT	Eolfi (Veolia Env.)	Gusto MSC	eolfi.com/en/eolfi-research-development/spinfloat	Spinfloat	6MW	90/20	Catenary 6	n/a
Semi-Submersibles								
FLOATGEN	IDEOL-Bouygues-ECN	IDEOL Damping	ideol-offshore.com/en	Vestas	2MW 4x6.15	30/20 50/15	Cat./Taut 6 Catenary 6	2017 2020
WINDFLOAT	Principle Power	Semi-Sub	principlepowerinc.com/products/windfloat	GE Haliade	4x6 [Fr] 6 [Jap]	70/20 70/30	Catenary 6	2020 [2]
SEA REED	DCNS-Vinci-Eolfi	Sea Reed	eolfi.com/en/eolfi-research-development/spinfloat	GE Haliade	4x6	70/20	Taut 3	2018
Tension Leg Platform								
GICON-PELASTAR	Gicon-Glosten Assocs	Pelastar TLP GICON-SOF	gicon-sof.de/en/sof1 pelastar.com	Siemens	6Mw	18/21	Teth/Taut 4	2021
TLPWIND	Iberdrola/UKCatapult	Semi-Floating Spar	ore.catapult.org.uk/our-knowledge-areas/foundations-substructures/foundations-substructures-projects/tlpwinduk/	n/a	5MW	81/25	Tethered	2020-2025
Taut Moored "Barges"								
SBM	SBM-EDF-IFP-Siemens	SBM-Taut Moored	sbmoffshore.com/what-we-do/our-products/renewables/	Siemens	n/a	n/a	Tethered	n/a

Source: Floating Wind Energy Projects of The World, Inducomm, 2017

Offshore Anchor Types

1. Gravity (Clump)
2. Drag Embedment
3. Suction Caissons/Piles
4. Driven Piles
5. Others (Drop, Torpedo, VLA, SEPLA)





Source: Course Notes: Mooring Components Ngee Ann Polytechnic Singapore

Conventional Anchoring Solutions

Gravity Anchors

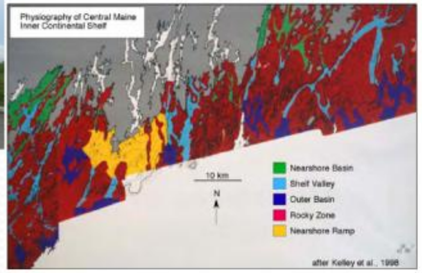
Needs Hard Seabeds for Sliding, Settlement

Suction Caissons

Needs ~ > 1*D NC Clays and/or Sands

Drag Embedment Anchors

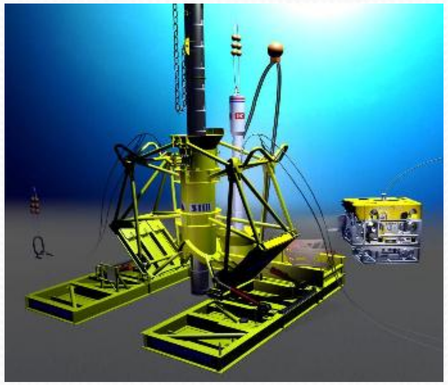
Needs Adequate Soil Layering/Depth



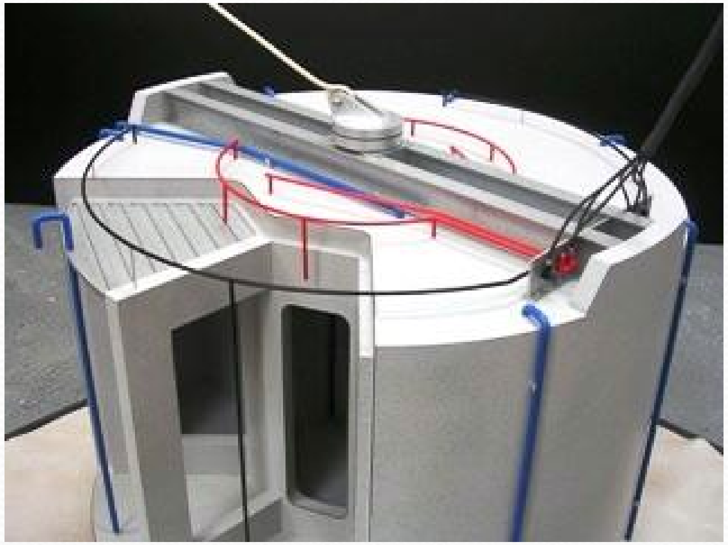
Recommended: Intermoor Mooring Chart 2013

Anchor Piles

Steel Driven/Drilled & Grouted



Case Study - Gravity Anchors – Oregon WEC OPT
Gael Force Sea Limpet



Source: Gael Force UK (Video: bit.ly/2hdldcE)

Designer: Gael Force Inverness
Client: US Ocean Power Technologies
Initial 3 No. 460-tonne Patented Sea Limpet
Flooded Compartment Ballast Tanks
Fabricated on Quayside

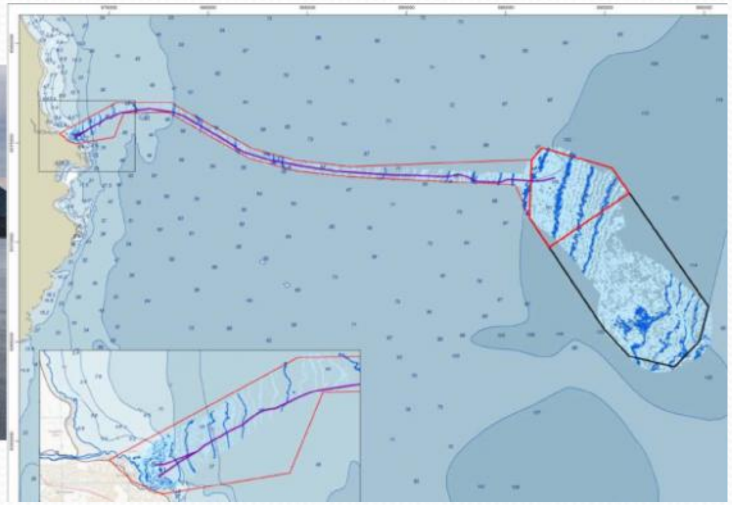
Triple Line Taut Moored WEC
OPT PowerBuoy WEC
Oregon - Contract $1.48 million)
Cross Beam Stiffened
Floated Out and Towed

Design Issues: Settlement- Tilt Predictions, Bearing Capacity, Sliding Capacity, Cyclic Loading from Taut Line. Load Case Def.

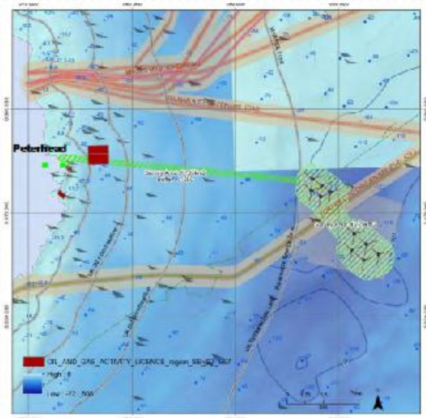
Case Study - Suction Caissons - HYWIND Buchan Deep

- NGI Suction Anchors: 5 No. 6 MW Siemens turbines. 110 Tonne Suction caissons in sandy conditions. Designed & installed by Norwegian Geotechnical Institute.
- Buchan Deep park is 4km^2, 25 km east of Peterhead, 95-120 m WD. Investment of Euros 210 M > Euros 7 per MW, 70% reduction on Statoil single prototype off Norway 2009.
- Technology now well understood. Design and Installation procedures and analytical rules for both sands and clays are now defined from Oil & Gas experience. High quality Geological Desk Studies, Geophysical & Geotechnical investigations are essential.
- Handful of experienced competent specialist contractors. Care in contractor and designer selection. Claims and disputes can arise relatively easily.

Source: @SiemensGamesa



Source: Buchan Deep Env. Statement Ch. 8. Fig. 8.4



Source: HYWIND Scotland Geotech.Desk Study. Xodus Group

Case Study - Drag Embedment Anchors – Principle Power

Contractor : Vryhof Anchors
Location: 5 km off Agucadoura, Portugal. Sandy site. No bedrock.
Products: 4 x 9.5mT STEVSHARK® with 3.5mT ballast with special cutter points, mooring chains, wire ropes, connectors, chain clamps, plus STEVTENSIONER®

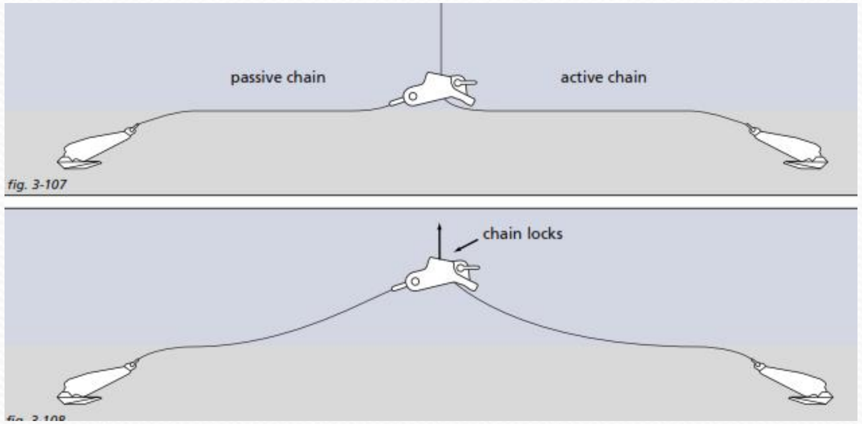
Anchoring & Mooring: ~ 20% costs.

For complex deployments, deep water & difficult geology, installation costs can be ~50%

Vryhof Anchors STEVTENSIONER , used in Oil & Gas for >20 years, allows cross-tensioning of opposing anchors.

Repeated heaving up and slacking of the system in a yo-yo action builds up mooring chain load to required tension.

Reduction in bollard pull demand allows use of smaller vessels.



Source: Vryhof Anchors
Video: vryhof.com/filmpjes/tensioning/tensioner.html

Innovation 1: TTI Nylon Rope and Gravity Anchor Bags (Ref. 2)

IDEOL SEM-REV Windfloat & Bluewater Texel NL Tidal Floater

Innovate UK, Scottish Govt., Carbon Trust Project

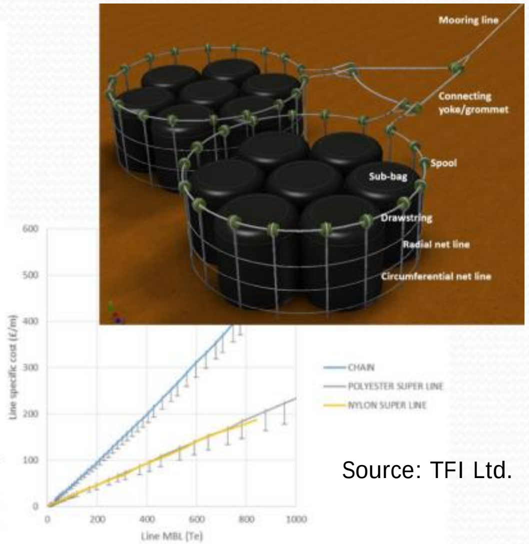
MRCF: Testing, Qualification of Advanced Mooring System: Wave & Tidal Arrays

MESAT: Synthetic Fibre Rope Polymer Line Fairleads

- Develop & Qualify technology & mooring for wave & tidal unit station-keeping
- Mooring subsystem qualification programmes: Carbon Trust & TSB
- Gravity anchor bag to DNV-RP-A203 & Nylon Rope to Lloyd's Register
- Methodologies & guidance for design of Nylon based mooring systems
- Demonstrate step changes in cost reduction, increasing mooring array density.
- Technology viability through open water testing.

Source: Bluewater

Source: IDEOL



Source: TFI Ltd.

Innovation 2: SBM Taut Moored Submerged Modular Frame Structure

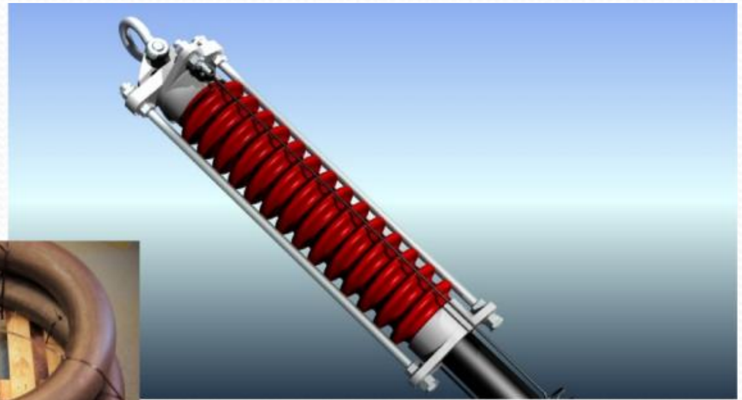
- SBM-EDF-IFP-Siemens
- Light, relatively cheap, small nacelle motions with catenary cable installation.
- Field proven components. No active ballast.
- Mass ratio decreases with larger WTGs
- Small draft for WTG installation @quay, with conventional Wet Tow
- Modularity and low complexity components
- Supply chain based and flexible assembly
- No dry-dock & assembly using standard yard techniques
- Suction caisson or driven/drilled pile anchoring

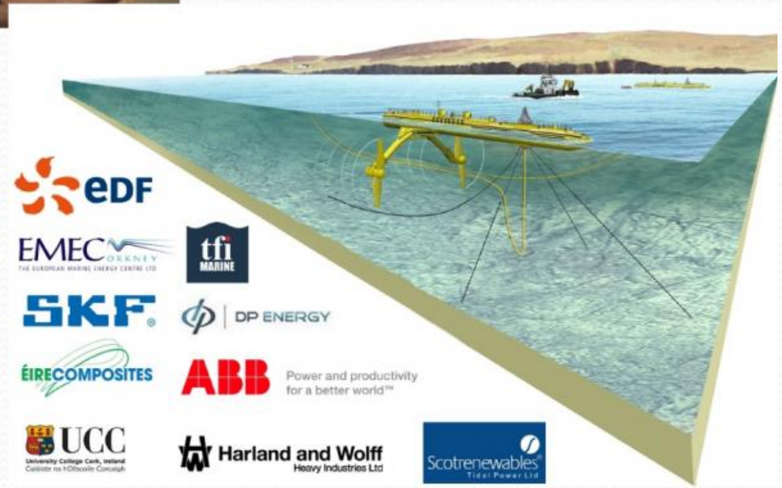
Source: SBM FOWT 2017

Innovation 3: TFI Dynamic Tether: Elastomer Line /Spring

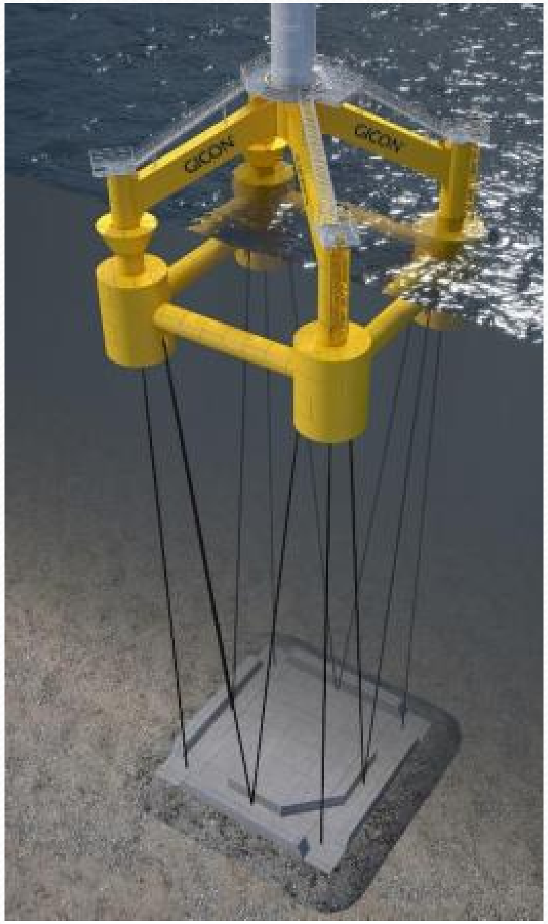
- Significantly reduces peak loads by up to 70%
- Eliminates snatch loads
- Scalable to 300 Tonnes load capacity
- Stabilises floating structure more effectively
- May be installed alongside existing mooring system
- Lower operational costs
- Smaller footprint
- Reduced seabed scour

Sources: tfimarine.com/default-item/products-portfolio/





Innovation 4: First Subsea "Ballgrab" Platform Mooring Connectors (Ref. 1)



Source: GICON TLP OTC 2016

Supported by OW Developers & GROW Offshore Wind

Specialist Mooring Equipment Manufacturer

Spar, Semi-Sub or TLP

Ball & Taper Gripping Technology

Ballgrab Connector

Source: First Subsea

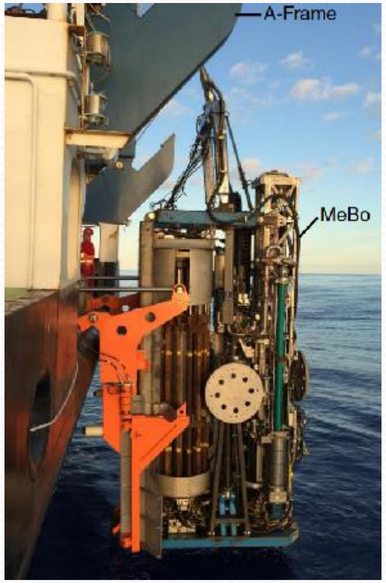
TLP Top Connector

Source: First Subsea

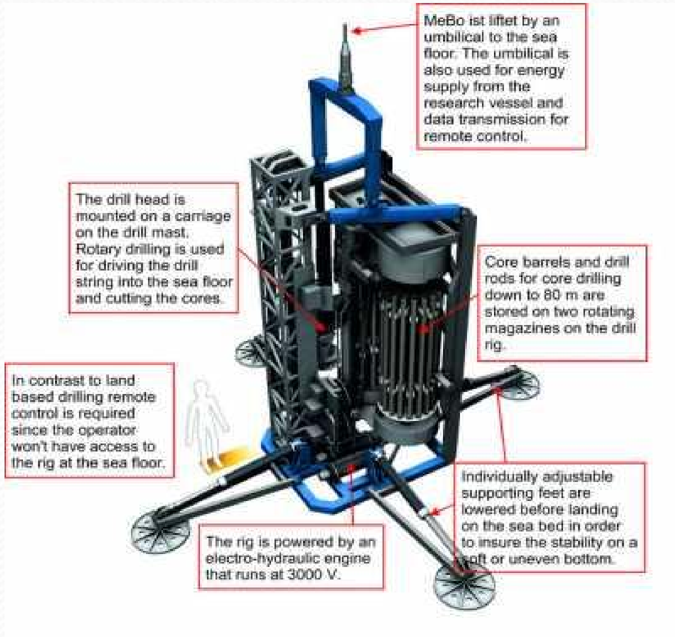
- Automatic connection
- Removes need for expensive chain jacks & fairleads
- Low pretension installation
- Adjustable mooring line length/tension
- Simplifies, speeds up and standardises installation
- No ROV intervention required
- Eliminates the need for divers
- Cost Effective. High load Capacity
- Mature technology from offshore oil & gas applications

MEBO [www.marum.de]

- MARUM-MeBo70 plus LARS
- Total system weight 90 t
- Winch plus 2500 m steel armoured umbilical
- Control cabin, drill tool & workshop containers
- Deck space: 4 containers (6 in transport) for LARS plus MEBO
- Crane or A-Frame min. 20 t SWL.
- Drilling depth at least 50 m with core diameters of 50–80 mm,
- Deployment depth to 2000 m with 4000 m option
- Schilling, Prakla Bohrtekniek, Bauer.



Source: IODP Proc. Vol. 357 (2017)

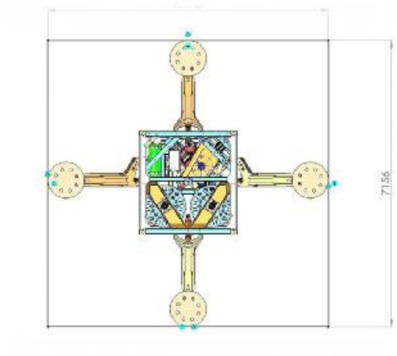


Source: www.marum.de/Infrastruktur/Sea-floor-drill-rig-MeBo.html

www.marum.de/en/Infrastructure/MARUM-MeBo-operational-system.html

Freudenthal, T. and Wefer, G., (2103), "Drilling Cores on the Sea Floor with the Remote-Controlled Sea Floor Drilling Rig MeBo", Geosci. Instrum. Method. Data Syst., 2, 329–337, 2013 www.geosci-instrum-method-data-syst.net/2/329/2013/ doi:10.5194/gi-2-329-2013, p. 10.

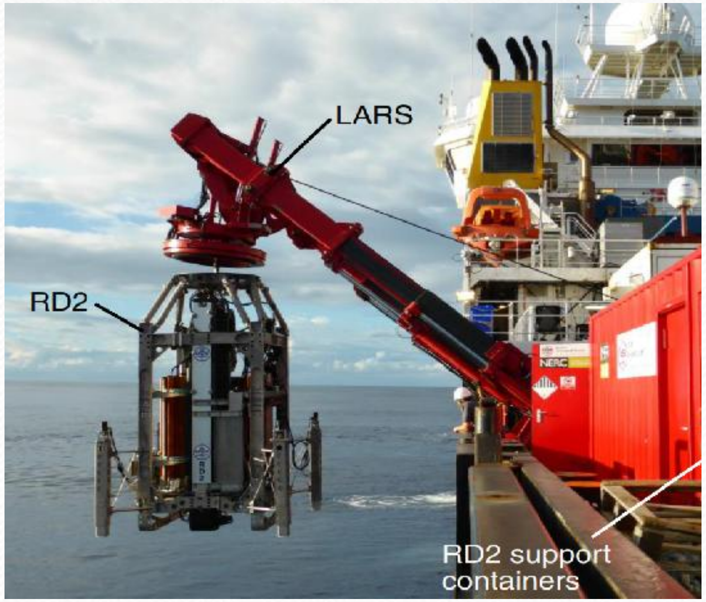
Spagnoli, G. and Freudenthal, T. (2013), "Underwater Drilling Rig for Offshore Geotechnical Explorations for Oil & Gas Structures", Oil Gas European Magazine, December 2013, Vol. 39(4): p.185-189.



Source: Bauer, Univ. Bremen, ETH Zurich. OTC 25081-MS

BGS RD2 Rockdrill [www.bgs.ac.uk]

- Total system Weight: 102 tonnes
- Personnel 8 to 10
- 7x20 ft Containers (Control, Mechanical, Electrical, Stores, 2 No. High Cube - LARS System, Winch, RD2 Removable Hardtop
- Dimensions: 4.75 m high with 3.1 m span at leg extremities
- Weight: in air/water: 6/5 Tonnes
- Water depth: up to 4000 m
- Max. Drill depth below seabed: 55 m
- Core Barrel: HQ3, stainless steel inner tube
- Core size: Diameter: 61.1 mm, Length: 1.72 m
- RD2 & LARS Power: 415 VAC, 3 phase, 50/60 Hz 125 Amps



BGS (2015), ""British Geological Survey Remotely Operated Sea Bed Rockdrills and Vibrocorers: New Advances to Meet the Needs of the Scientific Community", 6th Int. Workshop on Marine Technology, Martech 2015 Cartagena, September 15-17 2015, pp. 19-21.

BGS Rockdrill 2 (RD2) Promo Video (22nd June 2016): www.youtube.com/watch?v=aR08tAWRWCk

Source: British Geological Survey : www.bgs.ac.uk

Forum ROVDRILL 3 [f-e-t.com]

Source:: www.f-e-t.com/products/drilling-and-subsea/subsea-technologies/rovdrill-overview

Interchangeable foundation assemblies–suction caisson/skirted mudmat or4-leg jack-up assemblies.

ROV intervention kit, intervention basket, hydraulic & electrical hot stab assemblies, docking latches & electrical/hydraulic interface kit.

Forum ROVDRILL 3 Vessel of Opportunity Requirements

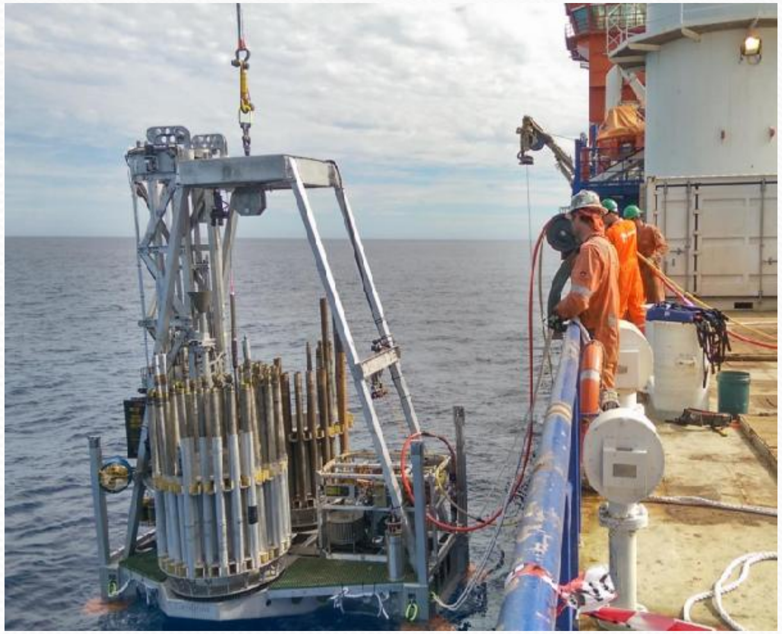
- 150 HP Workclass ROV Spread:
- Subsea hydraulic power:59gpm @ 207 bar (3000psi) via ROV auxiliary pump.
- Subsea electrical power: Single phase power, 20 amps at 120 V.
- Access to single mode fiber in ROV umbilical & ROV's telemetry system for data transfer.
- Deck mounted offshore crane or A-frame, 60 Te SWL, minimum for SS6 operations.
- Fast deployment wire winch(preferably heave compensated) or crane with similar capability.

Helix/Canyon ROVDRILL 2 [helixesg.com]

Source:: Helix-Canyon Offshore

- Helix Energy Solutions Group, Inc.'s robotics subsidiary, Canyon Offshore Limited (U.K.)
- ROV and rig interconnected inside cage. No ROV of opportunity option available.
- Launched as conventional work-class ROV system from DP2 vessel.
- Depth Rating 2500 m.
- Tool & Rod Capacity 48 x 3m Tools.
- In-Air Weight 18 Te.
- Mx. Drill depth 114 m.
- Max. depth of rock coring 50 m.
- Continuous 10 & 15 cm^2 CPT capability - 96 m.
- 2 x 3 m long CPT Assemblies.
- Continuous Shelby & L70 Tube Sampling - 31.5 m.
- L90 Tube Sampling – 42.0 m, 21x 1.5m long.
- Piston Tube Sampling full bore or through casing – 29.4m.
- Maximum Push-Down Force 100 kN, Max. Pull-Up Force 114 kN.
- Rotary Boring Cased & Uncased & polymer based Mud System.

Fugro-Gregg Seafloor Drills [fugro.com]



Source:Gwynn, M. (2015), "Seafloor Drill Presentation" Autonomous Underwater Technology, 22nd October, 2015, p. 18.

Concept conceived in 2011. Gregg, MARL technologies and Schilling Robotics. Fugro-Gregg JV announced 2012.

Walker Ridge Block 313 GoM 2015. Water depth record of 2,923 m. Combined sampling & PCPT) borehole to 62 m below seabed with MARL Seafloor Drill I.

Recent (2105) projects in GoM, NW Shelf Aus, Caspian, East Africa.

Seafloor Drill II includes coiled tubing PCPT capability & automated handling of drill rods & tools.

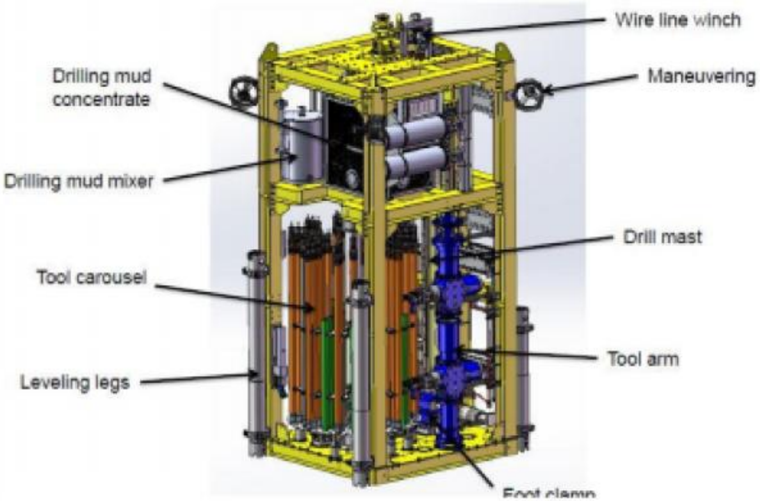
Ref: Robertson, P.K., Gregg, J., Boyd, T. & Drake, C. (2012), "Recent Developments In Deepwater Seafloor Geotechnical And Mineral Exploration Drilling", Ref. SUT-OSIG-12-23, Society for Underwater Technology, Offshore Site Investigation & Geotechnics: Integrated Technologies - Present and Future, 12-14 September, London, UK, 2012.

Gregg Seafloor Geotechnical Drill: www.youtube.com/watch?v=gh5L6rMxyRg
Fugro: www.youtube.com/watch?v=QMr6ver4uIg

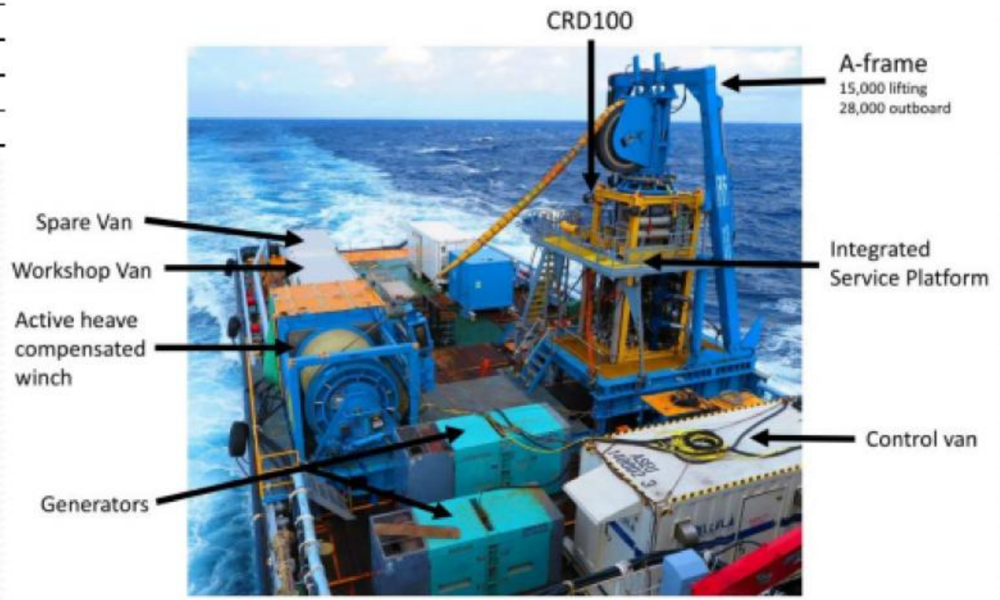
Specifications	SFD-1	SFD-2	
Water Depth	4000 m		• Wireline sampling, N through P sized tooling in 2 m lengths • Rated for drilling/sampling/in situ testing to depths up to 150 m below seafloor • Dual direction rotary (forward and reverse) at speeds 0-660 rpm • Lightweight core barrels handled and stored by robotic manipulator arm • Seabed CPT • 30 m pen. & 1.5 tons pushing force
Weight in Air	9 Te	8 Te	
System Dimensions	W = 3.8m, L = 5.4m, H = 6.6m	W = 4.3m, L = 5.4m, H = 7.0m	
Drilling Specifications	Standard Geotechnical Samplers Sample Diameter = 73mm Fugro In-Situ Testing Tools 80kN Thrust Capacity at 2cm/s Polymer Mud Injection - 140L	Main Differences: Automatic Carousel Rod Handling Loading Arm Reduced LARS Footprint Increased Carousel Mud Capacity	

Cellula Robotics CRD100 [cellula.com]

Parameter	Specification
Drilling	Wireline and conventional
Drilling tool	H-size tooling as standard, H-size wire line triple tube core barrels
Core sample	Up to 1500 mm per core
Drilling depth	65 m for H-size 1.5 m
Tool Carousel	Standard: 61 H-size tools
Push/pull force	100 kN mechanical push/pull capability
Drill Performance	0-600 RPM with 80HP hydraulic power
Automation	Tool manipulation, Arm motion
Leveling legs	Hydraulic legs capable of leveling on slopes up to 30°
Weight (in air)	7 Tons empty of mud & tools/ 13 Tons with mud and complete tools
Dimensions	Height = 5.7 m, Width = 3.1 m, Length = 3.1 m
Operating depth	3000 msw
Power to Control Van	25 kW @ 440 VAC 3ø 60 Hz
Power to HV-PDU(s)	105 kW@ 440 VAC 3ø 60 Hz
Voltage to CRD100	3300 VAC at the surface



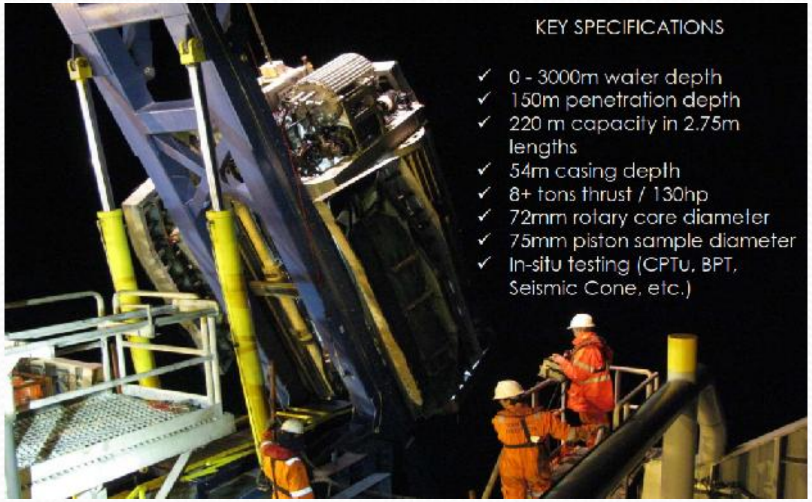
- UNICORN-1 sea trial March 10th-18th, 2016.
- 7 trial BHs off Japanese coast. 60 m drilling @ WD 750 to 900 m. 9 drilling operations for varying seafloor bathymetry/surface conditions.
- Continuous drilling 24 m completed in 10 hours on volcanic rugged and sloping seafloor with core recovery of 70 % in fractured rock with loose infill.
- Wireline operations with cycle times of < 20 mins for 1.5m samples, independent of sample depth.



Source: Cellula Robotics

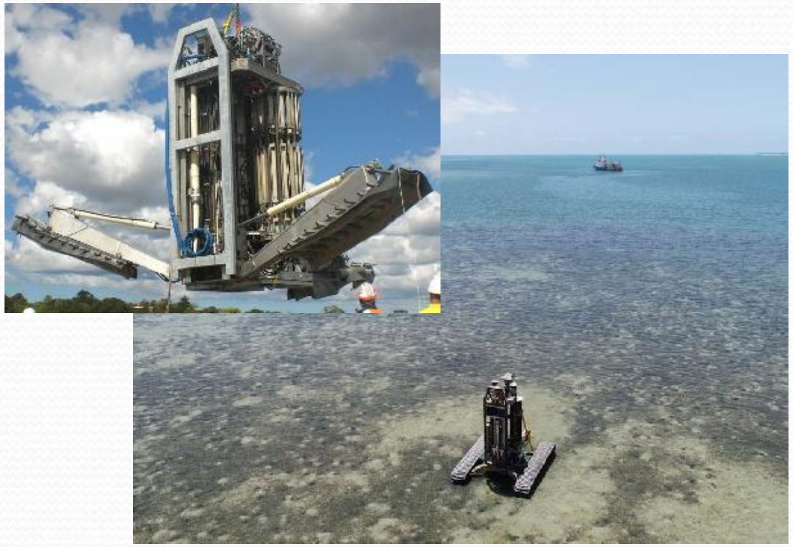
Ref.: Ochi, K. Jackson, E. Hirtz, H. & White, D. (2016), “A New Generation Seafloor Drill UNICORN-1” Proc. OCEANS 2016 MTS/IEEE Monterey, September 2016.

Benthic PROD [benthic.com]



Source: Benthic Geotech

- Proven for deep water soft clay sites such as GoM, Caspian, Brazil, NW Shelf Australia calc. soils.
- PROD 3 to 5 times more productive than vessels in WD > 400m but few advantages at shallow water sand "CPT sites.
- Recent project example. June 2017 Brazil LIBRA cored to 80m depth, in WDs to 2339m.
- Generally provides better quality rock coring SCR, TCR, RQD %s in weaker sedimentary rocks.
- Targeting offshore wind industry but high levels of drillship competition.



Source: "Benthic scoops work off Mozambique with Anadarko" offshoreenergytoday.com/benthic-scoops-work-off-mozambique-with-anadarko/

Source: Benthic Geotech

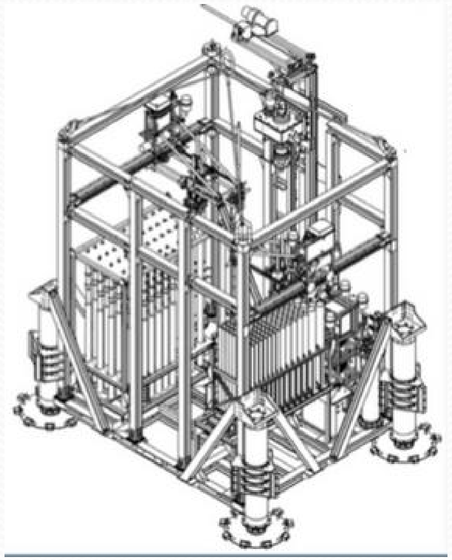
IGEOTEST MD500 [igeotest.com]

EU Funded: Demowind ERA-Net 2015-2017

Partners: IGEOTEST (Spain) MG3 (UK)

Arriaga, A., Devincenzi, M., Pérez, N., Deu, A., Arroyo, M. Automation and control in a submarine drill rig. A: Offshore Site Investigation and Geotechnics International Conference. "Offshore Site Investigation and Geotechnics: Smarter Solutions for Future Offshore Developments: Proceedings of the 8th International Conference". London: Society for Underwater Technology, 2017, p. 1238-1245.

- Operating depth up to 500 m. Weight in air 1.4 Te.
- Conventional drilling system with mud flow system.
- Drilling diameters: 146 mm (GEOBOR-S), 84.8 mm (PWL), 63.5 mm (HWL), 47.6 mm (NWL).
- Max. depth 88 to 176 m dependent upon initial diameter.
- Tool deployment via wireline or rod assembly



Source: IGEOTEST

MD500: Nine main modules:

1. Drilling rig
2. Manipulator
3. Positioning
4. Stabiliser legs
5. Sample tube store
6. Rod storage
7. Electrical, hydraulic and comms unit
8. Drilling mud system
9. Wireline sample retrieval tools

IHC SWORD – TI Geosciences [ti-geo.com]

Sonic Wireline-Operated Remote Drill: Aimed at Deep Sea Mining Surveys: www.bluemining.eu/partners/

Humber Gateway SI: 60 CPT's plus sampling and in-situ testing in 20 BHs, 9 inc. HP Dilatometer and PS Suspension logging.

JU "Vagant". Hydraulic thrust capacity 30 Te, cone tip capacity 15 te for reduced over-drills.

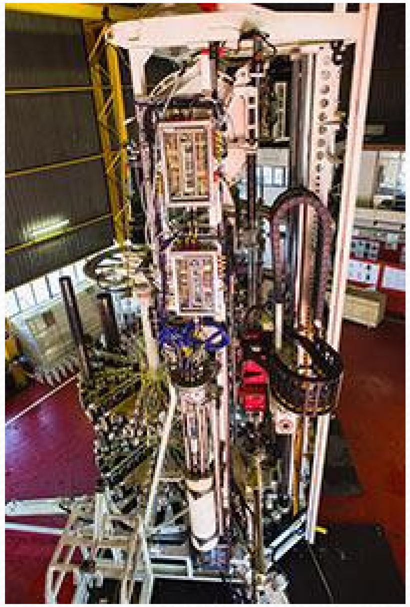
GeoborS triple wireline core drilling in stiff cohesive clays & chalk. 102mm diameter coring with trial sonic sampling in gravels and loose sand. High sample recovery rates.

IHC-Tomkins JV, Darlington UK & Eijkelkamp SonicSampDrill

www.sonicsampdrill.com/files/media/News/PDF/SSD News/Website/ihcinsightarticle.pdf [Spring 2015]

www.offshoreenergytoday.com/ihc-tompkins-enter-ultra-deep-water-partnership/ [26-02-2015]

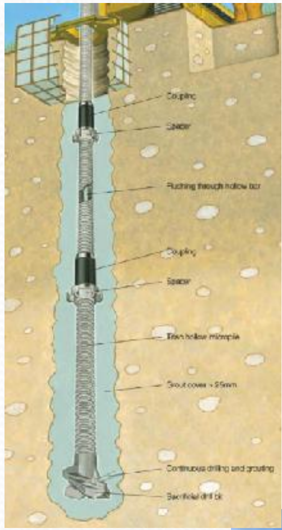
www.marinetechnologynews.com/news/royal-tompkins-launch-geosciences-509054 [17-02-2015]

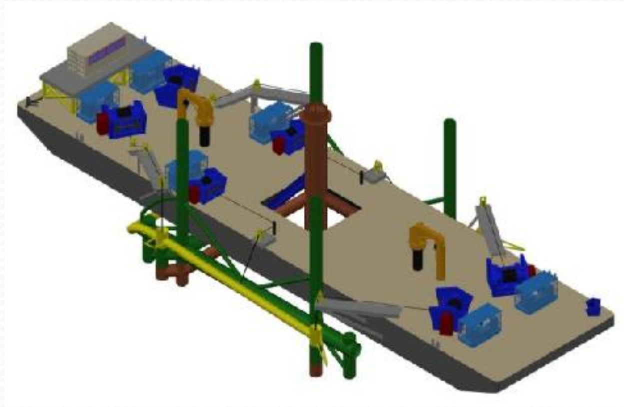


Sources: IHC Insight "Breaking New Ground": Spring 2015

McLaughlin and Harvey Subsea Drilled Anchors [mclh.co.uk]

- ScotRenewables SR2000 mooring for EMEC Orkney floating Tidal Turbine.
- Almost completely bare rocky seabed swept by strong tidal currents.
- Anchor options: (1) Floating & Modular gravity or (2) Drilled and Grouted
- Commercially viable, proven technologies.
- Small diameter drilling with low environment impact.

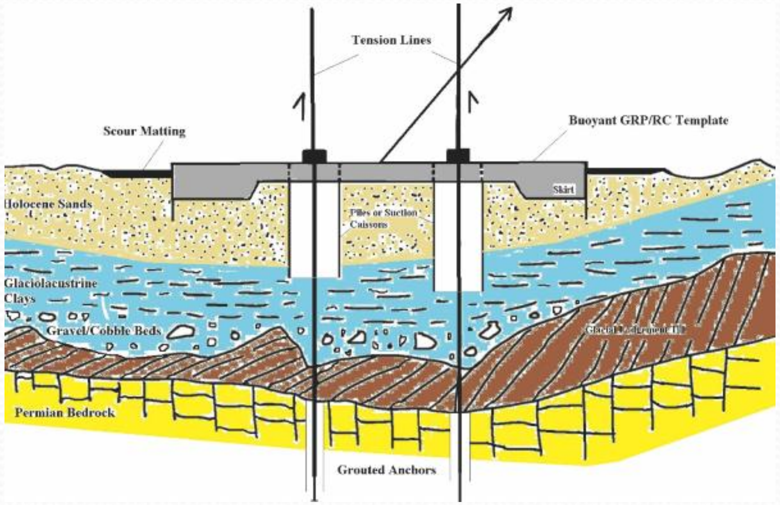




- In-Situ anchor testing/reduced fatigue.
- Serviceable, easily decommissioned, UK patented.
- Collaborative project between MRCF, Invest NI & Carbon Trust.
- Successful design & proof testing of MK2 Rig
- IschebeckTitan 196 / 129 tension anchors 400t SWL / 800t ultimate.

Sources: McLaughlin & Harvey

Seabed Anchored Foundation Template [SAFT] (Ref.3)

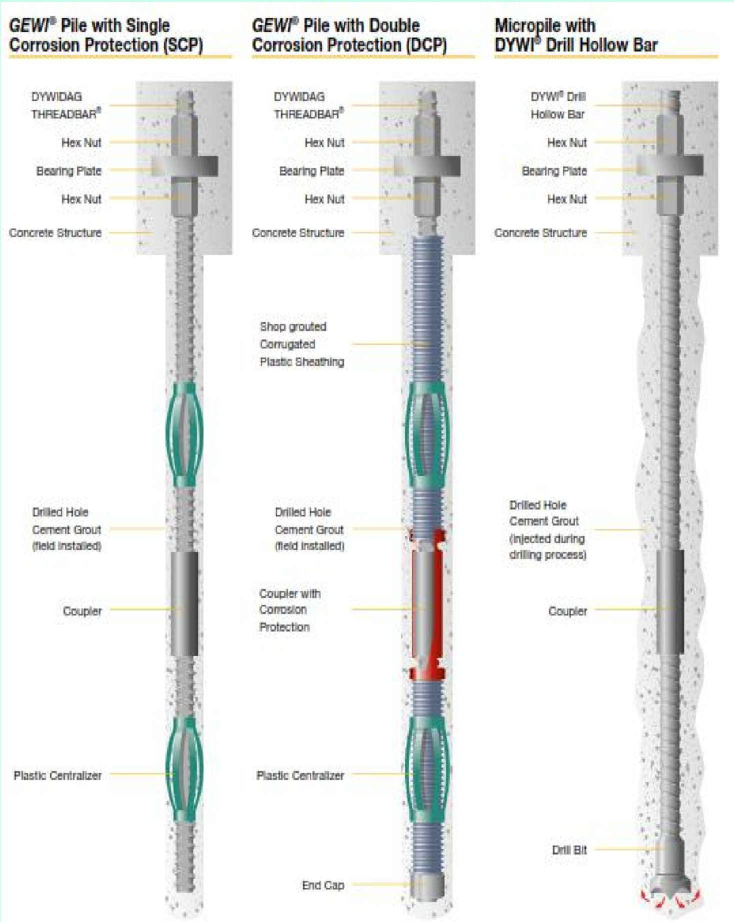


www.bladeoffshore.com/our-company/blade-offshore-remote-drilling#gallery[as]/2/

- Buoyant float-out hybrid structure concept
- Foundation base or mooring point template.
- GRP /reinforced concrete base configured to support tripods, jackets or GBS or:
- Pre-installed templates for inclined or vertical (TLP)taut or slack catenary mooring lines
- Steel /concrete edge skirts and suction caissons [SC] , or helical screws for differing soil types/thicknesses
- Tension resistance via pressure grouted rock anchors installed below upper support casing.
- Installed from an ROV operated marinised drilling unit via vessel launched LARS.
- External GRP, concrete or steel mudmats and/or integral plastic anti-scour frond mats/mattresses.
- Configuration has considerable lateral seabed resistance and tension uplift capacity.
- Design preceded by high quality shallow geophysical investigation of seabed surface and upper layering
- Confirmatory "pilot hole soil/rock coring by same ROV drilling unit used to install the anchors.
- Proof-loading of 5-10% to twice working load.

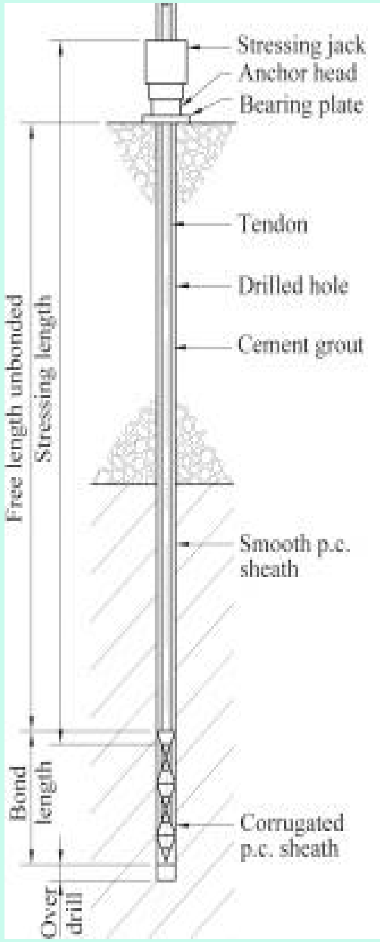
Micropiles Vs Tension Anchors

Micropiles



Source: DSI - DYWIDAG GEWI Micropiles

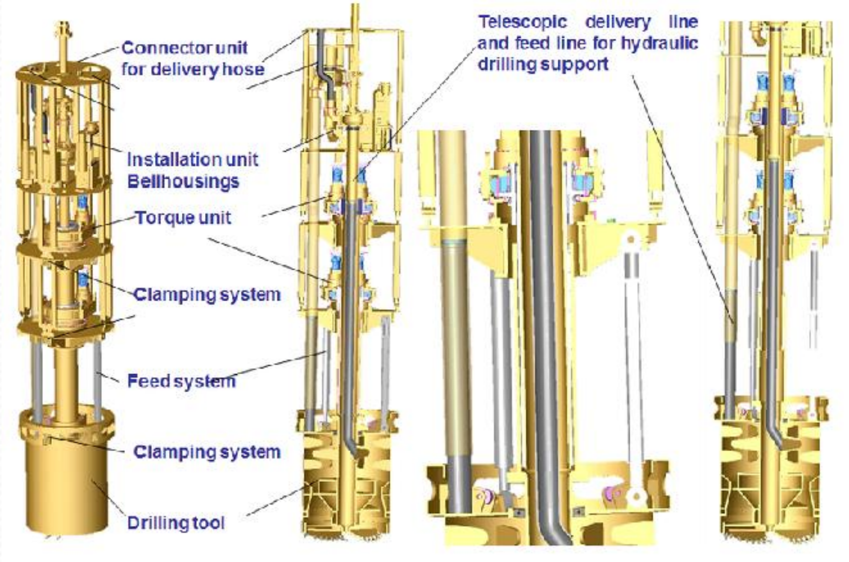
Post-Tensioned (Pre-Stressed) Anchors



Source: Brown, E.T (2015), "Rock Engineering Design of Post-Tensioned Anchors for Dams - A Review". J. Rock Mechs & Geotech. Eng., Vol. 7 (2015) pp. 1-13.

Source: BAM-Ritchies. Loch Arklet Dam Anchor Heads

Bauer Monopile/Jacket Pile Installation Methods



Dive-Drill. 2-3 m Dia. Jacket Piles. Source: Bauer Renewables. Spagnoli, G. & Weixler,L. (2013), New Technologies Offshore Pile Installation". 11th Offshore Med. Conf. & Exhibition Ravenna, Italy, March 20-22, 2013

Fly-Drill 5500 Barrow Wind Farm. Source: Bauer Renewables

BSD 3000 11 m Monopiles Vouth Tidal Turbines Orkney. Source: Bauer

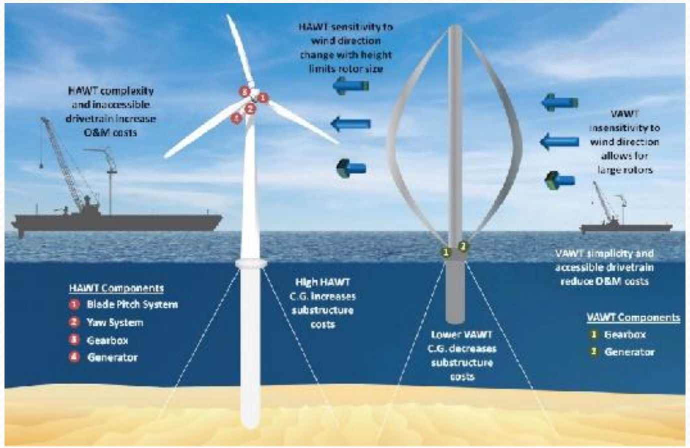
Floating Vertical Axis [FVAWTs] Sandia Labs (Ref. 4)

"Offshore Floating Vertical-Axis Wind Turbine Project Identifies Promising Platform Design", US Dept.of Energy EERE, 17th October 2017.

- Floating VAWT platform design may enable US developers to access the country's vast deep-water OW resource.
- Study by Sandia National Laboratories & Stress Engineering Services identified a VAWT platform design that may decrease the LCOE of offshore wind.
- Floating VAWT TLP meets operational conditions. Six designs capture floating stability mechanisms: deep-draft ballasting, buoyancy, waterplane & tension mooring.
- A TLP with a multi-cylindrical column hull most promising from cost perspective.
- TLP mooring scheme offers performance benefits resulting from reduced platform motions and smaller mooring anchor footprint.
- VAWT TLP challenges trends in commercial floating HAWT platforms, which favour semisubmersibles and spars.
- Shorter mooring cables & lower installation costs.
- Towed offshore with rotor installed.
- LCOE values of 15−20 cents per kWhr.

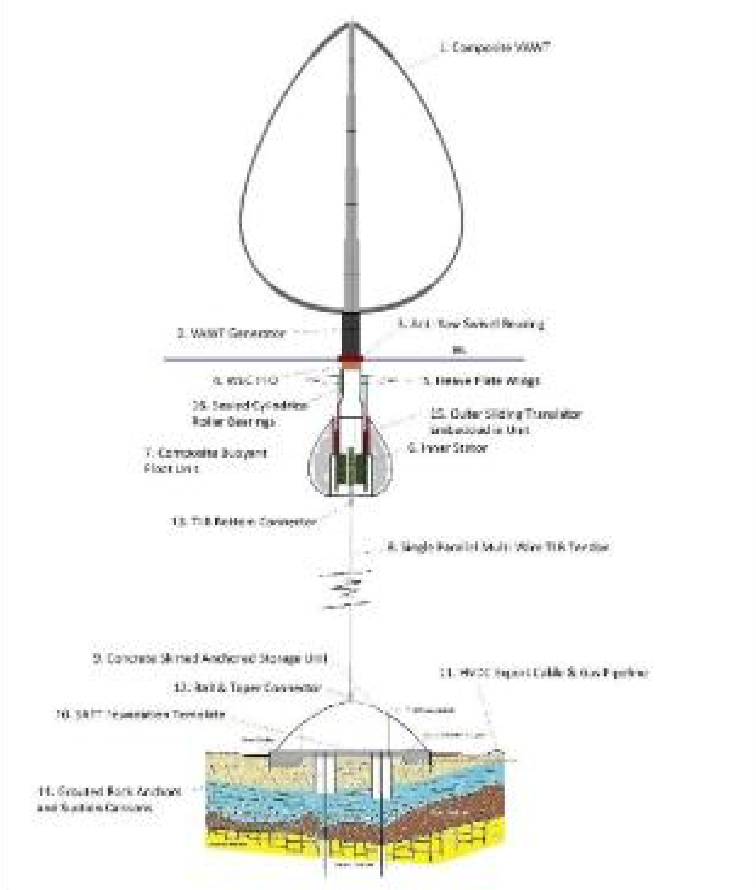
"VAWT TLPs benefit from small roll and pitch motions, such as increased energy capture and reduced inertial loading on tower & blades."

"Combined with favourable LCOE, this concept may merit further investigation for floating wind platforms."



BLACKBIRD VAWT on Tension Leg Buoy [F-VAWT-TLB]

No.	Component	TRL	Comments
1	Composite VAWT:	4	Carbon fibre lade configuration and design according to DeepWind Project 2011- 2014 and Sandia Labs 2016.
2	VAWT Conductor Generator:	4	Horizontal pseudo permanent magnet direct drive, possibly Superconductor
3	Anti-Yaw Bearing	5	Allows VAWT "weather-vaning" with bearing between VAWT and WEC/ floating structure
4	WEC PTO	3	Simpler electrical direct drive PTO, with no steps between primary interface and electrical machine
5	Heave Plate Wings	4	External heave plate "wings" to reduce vertical wave action response through viscous damping
6	Inner Stator Coils	2	Stator integral to central column, connected to tether line. Power via outer translator movement.
7	Composite Buoyant Float Unit	1	Submerged FRC composite floating USTLB tethered with single damped steel tension line
8	Single Multi-Wire Tendon-Tether	9	Damped high capacity multi strand steel tendon linking USTLB base to pumped storage unit
9	GRP Concrete Anchored Storage Unit	2	Flattened concrete dome subsea pumped CAES and electrical storage unit
10	SAFT Foundation Template	2	Skirted seabed anchored foundation template [SAFT], tied down by suction caissons and tendon rock anchors
11	HVDC Export Cable & Gas Pipeline	3	Electrical power and hydrogen exported via combined High Voltage DC export cable plus hydrogen pipeline
12	Ball & Taper Connector	9	Plug-in ball-and-taper connectors to storage unit.
13	USTLB Bottom Connector	9	Plug-in ball-and-taper connectors to floater underside.
14	Grouted Rock Anchors & Suction Caissons	8	SAFT suction caissons and pressure grouted tendon rock anchors by ROV deployed by LARS.
15	Outer Sliding Magnet Translator	2	Basic linear generator concept. Translator with alternating polarity directly coupled to USTLB



Notes: TRL = Technology Readiness Level [publications.europa.eu/en/publication-detail/-/publication/1da3324e-e6d0-11e7-9749-01aa75ed71a1/language-en/format-PDF/source-61073523]

VAWT = Vertical Axis Wind Turbine; WEC = Wave Energy Convertor; PTO = Power Take-Off; USTLB = Uniaxial Submerged Tension Leg Buoy; GRP = Glass Reinforced Polymer; LARS = Launch & Recovery System; SAFT = Seabed Anchored Foundation Template; CAES = Compressed Air Energy Storage; HVDC = High Voltage Direct Current.

Floating Wave and Tidal Energy

“Wave and Tidal Current Energy – A Review of the Current State of Research Beyond Technology”

Andreas Uihlein and Davide Magagna European Commission, Joint Research Centre (JRC), Institute for Energy and Transport (IET), P.O. Box 2, 1755 ZG Petten, The Netherlands. Renewable and Sustainable Energy Reviews 58 (2016) 1070–1081.

[core.ac.uk/download/pdf/82310982.pdf]

“Workshop on Identification of Future Emerging Technologies in the Ocean Energy Sector”, 27th March 2018, Ispra, Italy.

Magagna D., Margheritini L., Alessi A., Bannon E., Boelman E., Bould D., Coy V., De Marchi E., Frigaard P., Guedes Soares C., Golightly C., Hals Todalshaug J., Heward M., Hofmann M., Holmes B., Johnstone C., Kamizuru Y., Lewis T., Macadre L.M., Maisondieu C., Martini M., Moro A., Nielsen K., Reis V., Robertson S., Schild P., Soede M., Taylor N., Viola I., Wallet N., Wadbled X. and Yeats B., Workshop on identification of future emerging technologies in the ocean energy sector - 27th March 2018, Ispra, Italy, EUR 29315 EN, European Commission, Luxembourg, 2018, ISBN 978-92-79-92587-0, doi:10.2760/23207, JRC112635

[ec.europa.eu/jrc/en/publication/workshop-identification-future-emerging-technologies-ocean-energy-sector]

Wave Energy: Ocean Power Technologies PB3 Powerbuoy (US):

www.oceanpowertechnologies.com/product

Tidal Energy: NEDO-IHI Corp. (Japan):

www.nedo.go.jp/english/news/AA5en_100269.html

Non-Renewables Floating Structures

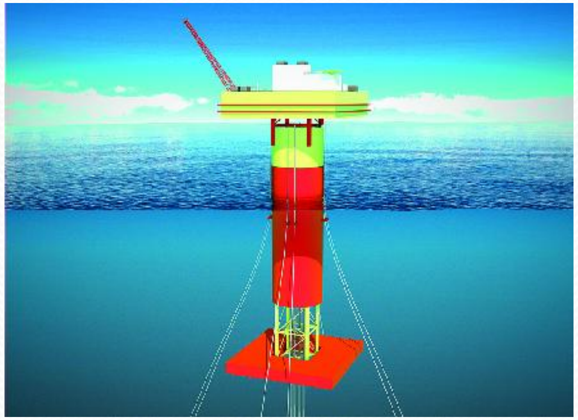
FLOATING STEEL CONCRETE

- Liquefied natural gas (LNG) import terminals
- Fossil fuel storage facilities
- Oil & gas exploration & production platforms
- Lake & ocean Solar PV farms
- Remote marine energy plant transmission facilities.
- Coastal airport runway expansions
- Bridges, highways & submerged tunnels
- Fish farms
- Cruise terminal quay structures
- City beach structures
- Housing and car parking facilities.

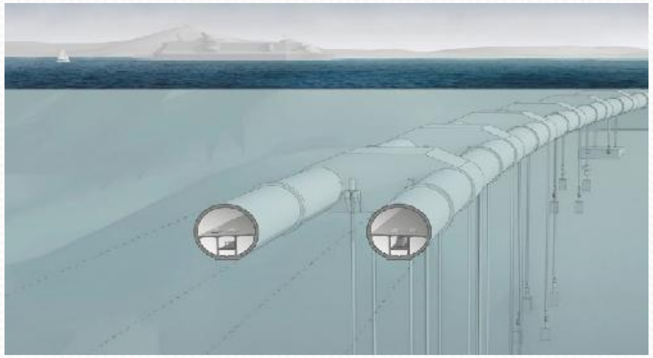
VERY LARGE FLOATING [VLFs]

- Airports (e.g. Osaka Bay, Japan)
- Floating port & harbour facilities
- Modular housing (e.g. Seasteading)
- Hotels, restaurants & heliports
- Performance spaces (e.g. Marina Bay)

Jackson G (2018)
Delivering Urban Energy and Transport Links Using Offshore Structures.
Proceedings of the Institution of Civil Engineers – Civil Engineering 171(6): 39–44.



Tistel, J., Grimstad, G. & Eiksund, G. (2017), "Testing & Modelling of Cyclically Loaded Rock Anchors", J. Rock Mechanics and Geotechnical Engineering Vol. 9 (2017), p. 1010-1030



SMD-BORD JV (2012) [Dissolved] - Patented Concept

Conclusions - Offshore Floating Wind

1. European OW has been North & Baltic Seas shallow water oriented, adopting monopiles, piled tripods/tripiles & jackets. CAPEX rose between 2008 (2.5 M/MW) & 2015 (5.5M/MW), but has fallen since (~USD 4 M/MW) (USD$ 2011 prices).
2. Fixed Foundation Risks: Grouted connections, env. piling noise, long & heavy pile design, pile tip buckling, drilling out/re-driving, excessive corrosion, tilting /settlements.
3. Fixed costs have reduced and "subsidy free" is possible post 2020. Innovative step-changes essential. Predicted Reduction for Fixed & Floating: 25 to 30% by 2030.
4. OW could deliver LCoE of less than Euro 100/MwHr by mid 2020s. "Comparable position to that of the nascent UK oil and gas companies in the 1970s".
5. Deep water OW is untapped. Potential is huge. Development of Floating alternatives in WD > 50 m 2 Semi Subs (IDEOL & WINDFLOAT) & Spar (HYWIND) lead the race.
6. North Sea fixed structure low bids means "Investor Confidence Gap" between Fixed Vs Floating. Floating needs big LCOE reduction, thus technology gamechanger.
7. VAWT TLP offers interesting performance benefits such as increased energy capture and reduced loads on the tower and blades. Favourable LCOE estimates suggest further investigation and consideration is merited.

Conclusions - Seabed ROV Geotechnical Investigations & Micropile/Tension Anchor Installation

1. Floating projects will encounter many subsea bedrock sites of varying geomorphology and complexity around the world. Development of a fast effective subsea ROV template drilling system for multiple rock anchor installation is essential.
2. For difficult rocky, irregular seabeds in deeper water, innovative and creative thinking will be needed, particularly if TLP-VAWT develops, as is expected. Anchoring in soft soils will likely be via suction caissons, in hard soils & bedrocks mostly drilled anchors.
3. Ground Engineering Technical Note: "The New Grouted Anchor Testing Standard EN ISO 22477- 5:2018 8th October, 2018".

Idealised Floating Array Scale Investigations

1. Essential: Detailed geological and historical survey data desk study.
2. Same Vessel: High quality shallow (20-30 m) area-wide geophysical survey plus Preliminary Geotechnical Seabed ROV investigation.
3. Final Geotechnical Investigation per location: single pair parallel continuous PCPT plus sonic core or 100 m Dia. Sampling BH, depending on overburden type. Rock coring from "fresh bedrock" level. Shallo VCs for index tests/grading.
4. Followed by (same mobilisation, same vessel, same ROV unit): Installation of either micropiles or grouted tension anchors through skirted well slotted seabed template.

References

Offshore Floating Wind, Mooring And Anchoring

1. First Subsea (2013), "Getting to Grips with Offshore Handling and Assembly of Wind, Wave and Tidal Devices", All Energy 2013, Aberdeen, 22nd -23rd May 2013 p.17.
2. Flory, J. F., Banfield, S. J., Ridge, I. M. L., Yeats, B., Mackay, T., Wang, P. and Foxton, P. (2016), "Mooring Systems for Marine Energy Converters". In J. Zande, & B. Kirkwood (Eds.), OCEANS 2016 MTS/IEEE Monterey, OCE 2016.
3. Golightly, C.R. (2013), "Efficient Anchored Template Foundations for Offshore Wind Turbines [OWT]", Proc. EWEA 2013, Ref. Paper No. 377, p.1.
4. US Dept.of Energy EERE (2017)"Offshore Floating Vertical-Axis Wind Turbine Project Identifies Promising Platform Design", 17th October 2017.
5. BLACKBIRD F-VAWT-TLB: www.researchgate.net/project/Blackbird-Hybrid-Floating-VAWT-WEC

Sandia Floating VAWT Reports June 2018

www.slideshare.net/sandiaecis/todd-griffith-challenges-and-opportunities-for-large-scale-floating-offshore-vertical-axis-wind-turbines

sandia.gov/energy/renewable-energy/wind-power/offshore-wind/offshore-publications/

1. Brandon L. Ennis, D. Todd Griffith. System Levelized Cost of Energy Analysis for Floating Offshore Vertical-Axis Wind Turbines, SAND2018-9131.
2. Todd Griffith, M. Barone, J. Paquette, B. Owens, D. Bull, C. Simao-Ferriera, A. Goupee, and M. Fowler. Design Studies for Deep-Water Floating Offshore Vertical Axis Wind Turbines, SAND2018-7002.
3. Chad Searcy, Steve Perryman, Dilip Maniar, D. Todd Griffith, Brandon L. Ennis. Optimal Floating Vertical-Axis Wind Turbine Platform Identification, Design, and Cost Estimation, SAND2018-9085

Seabed ROV Geotechnical Investigations

1. Osborne, J., Yetginer, G., Halliday, T., and Tjelta, T. (2011), "The Future of Deepwater Investigation: Seabed Drilling Technology?", In: Gourvenec, S. and White, D. (Eds.), Proc. Int. Symp. Frontiers in Offshore Geotechnics II. ISFOG 2011. London: Taylor & Francis pp. 299-304.
2. Yetginer, G. and Tjelta, T. "Seabed Drilling vs. Surface Drilling – A Comparison", Frontiers in Offshore Geotechnics . " In Gourvenec & White (eds), Taylor & Francis Group, London, ISBN 978-0-415-58480-7. 2011

Recommended Links

EC Marine Knowledge 2020 Database:	ec.europa.eu/maritimeaffairs/policy/marine_knowledge_2020
IRENA Costs Database:	irena.org/costs
USA Offshore Wind Database:	offshorewind.net
UK Floating Wind:	thecrownestate.co.uk/media/428739/uk-floating-offshore-wind-power-report.pdf
4C Offshore Wind Database:	4coffshore.com

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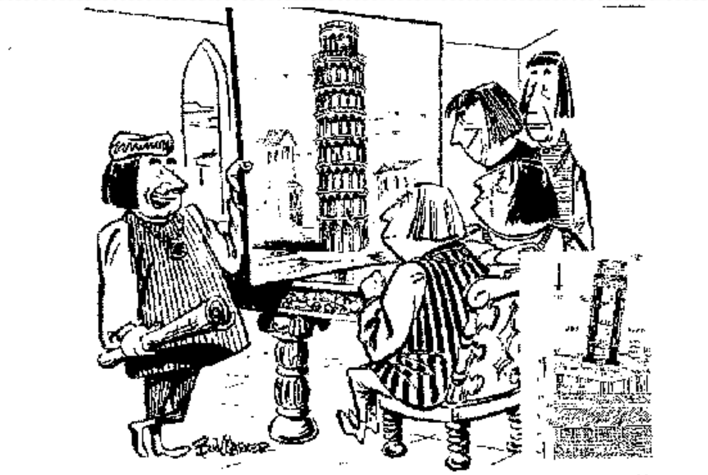
Twitter: @CRGolightly
Linked In: www.linkedin.com/in/chrisgolightly/
Academia.edu: https://independent.academia.edu/ChristopherGolightly



"...and we can save 770 lira by not taking soil tests"

"You Pay for a Site Investigation - Whether You do One or Not" – Cole et al, 1991.

"Ignore The Geology at Your Peril" – Prof. John Burland, Imperial College.

All my students know how to respond to the question "What happens when you use land-based technology in the ocean?" They learn from day one to answer in unison: "You die."

'The Silent War' – John Craven