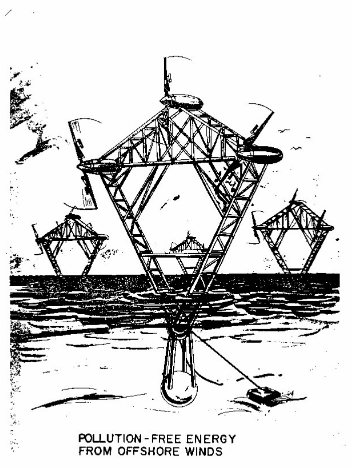
Anchoring & Mooring for Floating Offshore Wind

8th November 2017 Future Offshore Foundations, Brussels

Dr. Chris Golightly GO-ELS Ltd.

Geotechnical & Engineering Geology Consultant

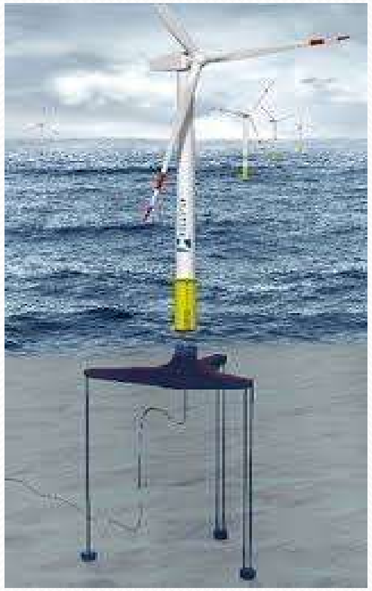


Source: Univ. Mass. 1974

SPAR - HYWIND

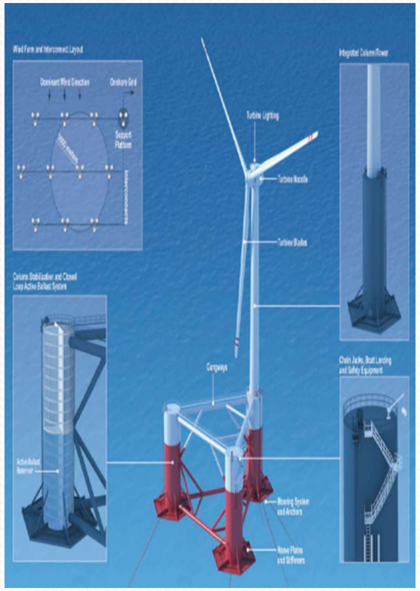
Source: Statoil

TLP - PELASTAR

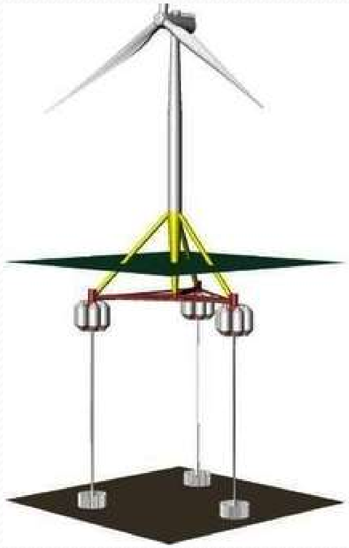


Source: Glosten Associates

SEMI SUB WINDFLOAT



Source: WINDFLOAT



Summary - Anchoring & Mooring Systems For Floating OW

PART 1 FLOATING WIND LCOE

Global Temperature Predictions	[World Bank 2012]
Global Offshore Wind Kinetic Energy	[PNAS 2017, NREL 2012]
Floating Wind – Potential Offshore Resource	[Open Ocean, Statoil]
Offshore Wind Turbine Fixed "Foundation"	[NGI]
European OW Fixed Bottom Structure Costs	[Carbon Trust, NREL]
North Sea/Atlantic Offshore Wind Resource	[Carbon Trust, UK Eval. Group]
Why is Floating Wind Necessary?	[Atkins 2017]
Examples of Floating Wind Structures	[Various]
Active European Floating Wind Projects	[Inducomm*, 2017]*
Offshore Wind LCOE Reduction Potential	[U DoE EERE, LBNL 2016]
Fixed Vs Floating: Reducing OW LCOE	[LBNL]
Fixed Vs Floating: OW LCOE Predictions	[Lazard, 2016, LBNL 2016]
Fixed North Sea Vs NREL Floating California	[NREL]
Floating Vertical Axis – Sandia Labs [FVAWTs]	[SANDIA LABS]

Summary - Anchoring & Mooring Systems For Floating OW

PART 2 – ANCHORING AND MOORING

Offshore Anchor Types

The Four Conventional Anchoring Solutions

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

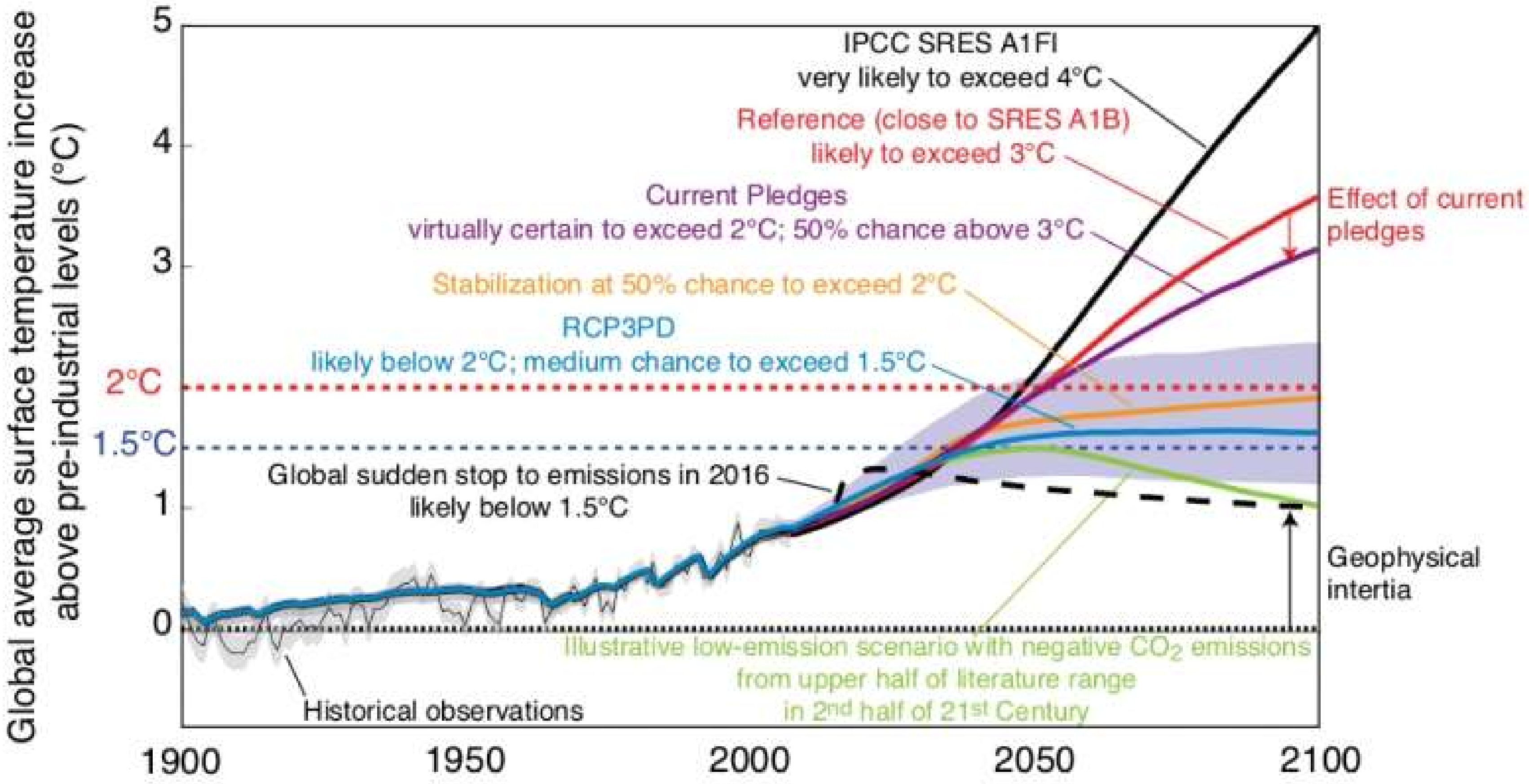
Innovations
- 1: Nylon Rope and Gravity Anchor Bags [TTI]
- 2: Submerged Taut Moored Substructure [SBM]
- 3: Dynamic Tether: Elastomer/Spring [TFI]
- 4: First Subsea "Ballgrab" Platform Mooring Connectors
- 5: McLaughlin & Harvey Drilled Anchors
- 6: Seabed Anchored Foundation Template [SAFT]

Conclusions

References & Links

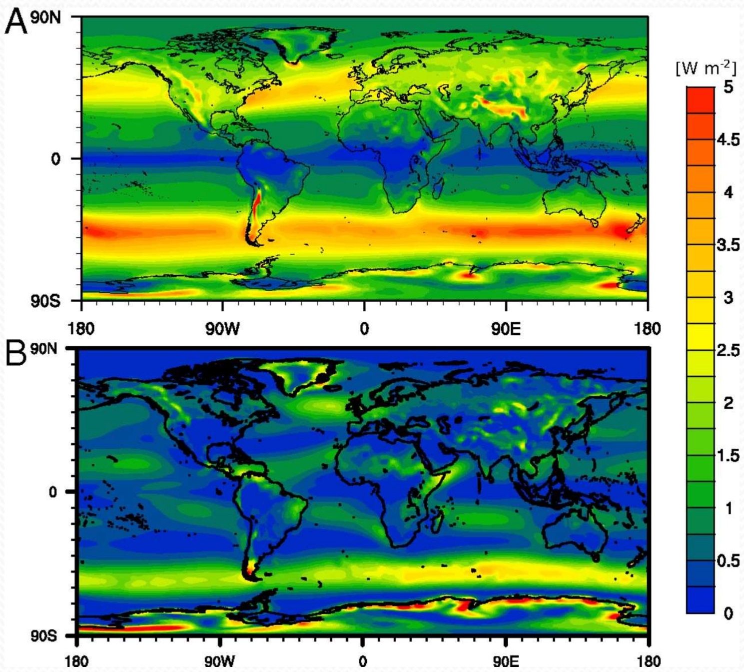
Contact Details

Global Temperature Predictions [World Bank 2012]

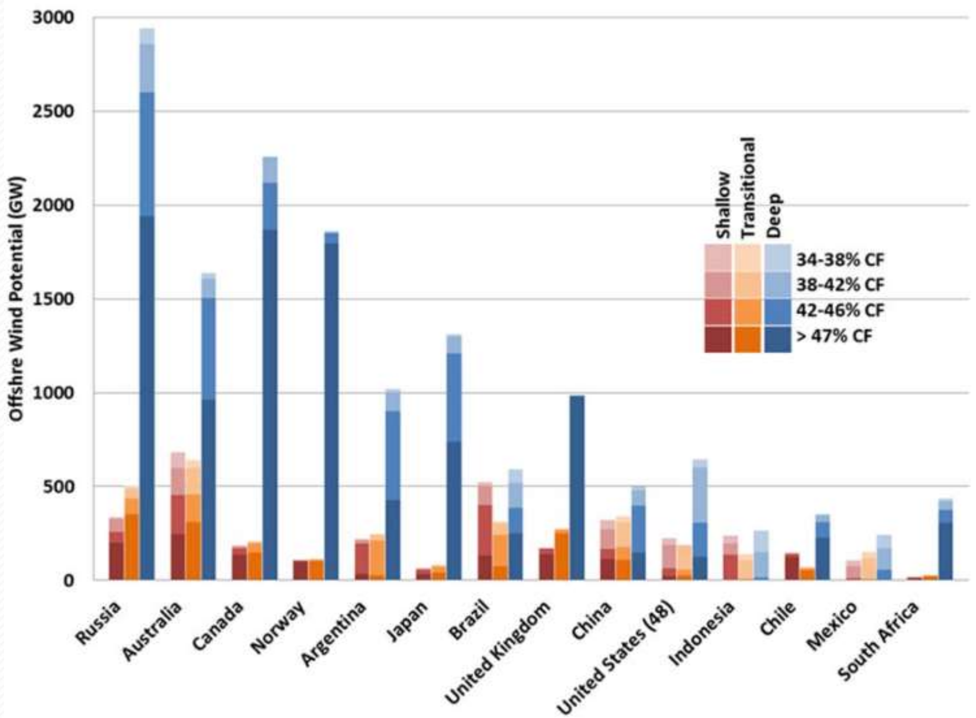


Source: World Bank/Potsdam Institute November 2012

Global Offshore Wind Kinetic Energy



Source: Possner & Caldera [PNAS] 2017



Source: NREL 2012

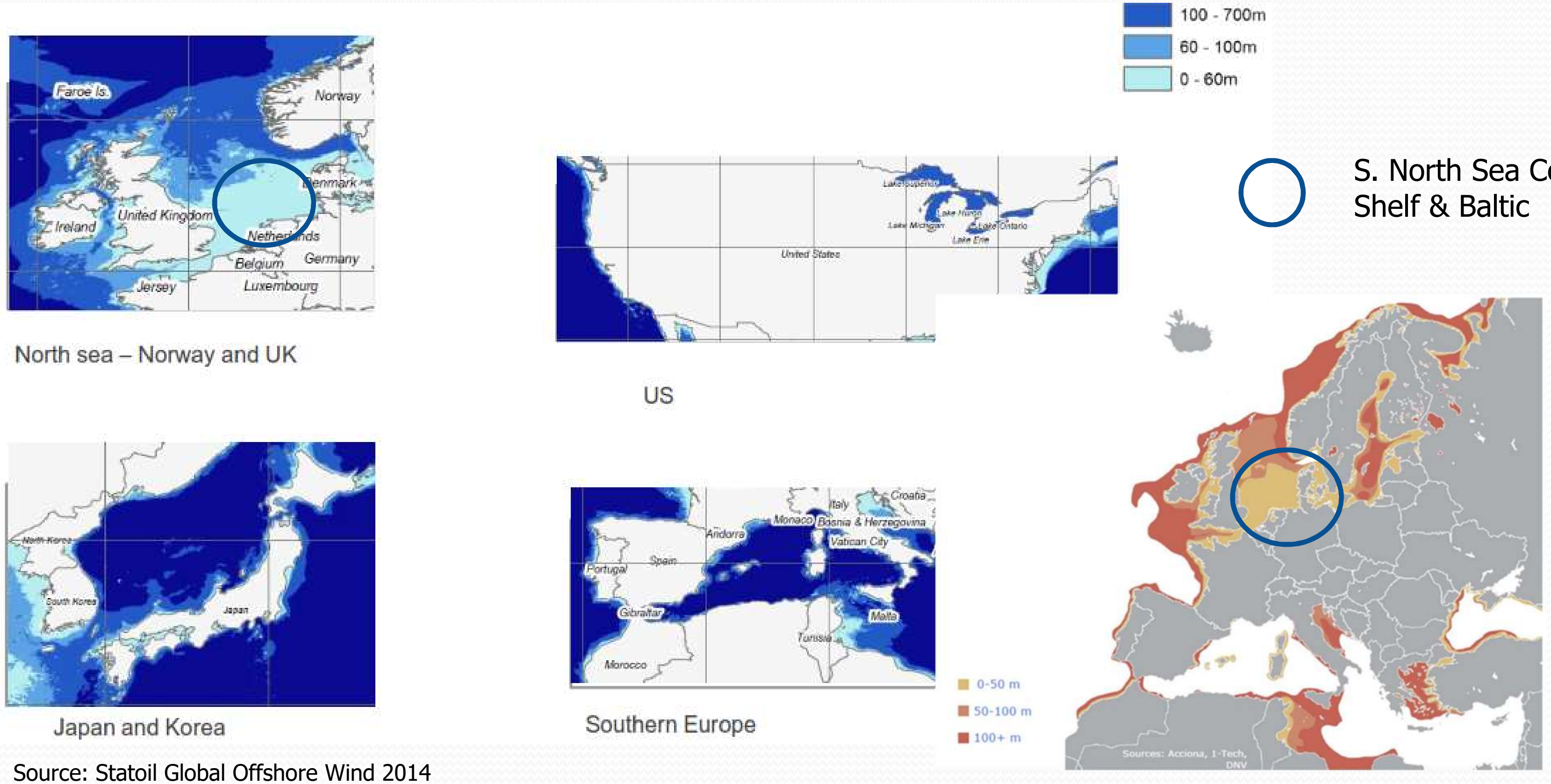
A: Climatology of Kinetic Energy Extraction (KEE) B: Annual Mean Kinetic Energy (KE) Dissipation into Boundary Layer.

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

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.

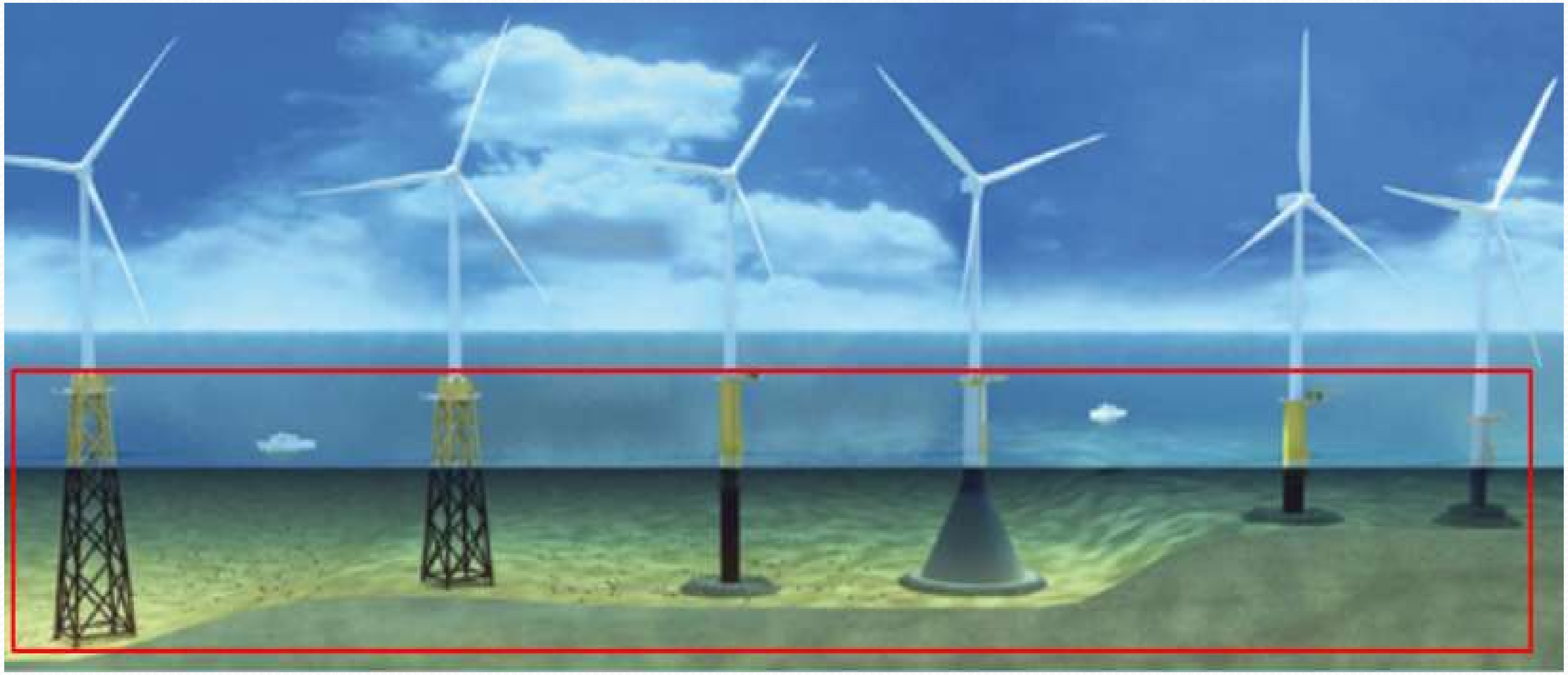
Not globally representative. Most coastal areas are steep, rocky, with thin (< 5 to 10 m) soil cover. Piling is costly for fixed or floating structures. Soils insufficient for drag or suction caisson anchoring.



Source: Statoil Global Offshore Wind 2014

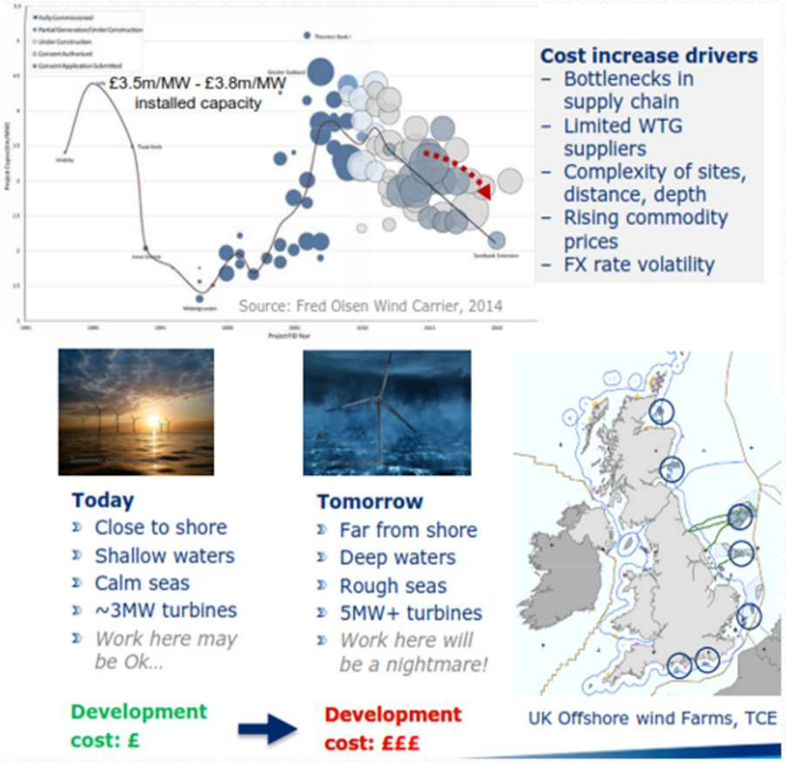
Offshore Wind Turbine Fixed "Foundation" Definition

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

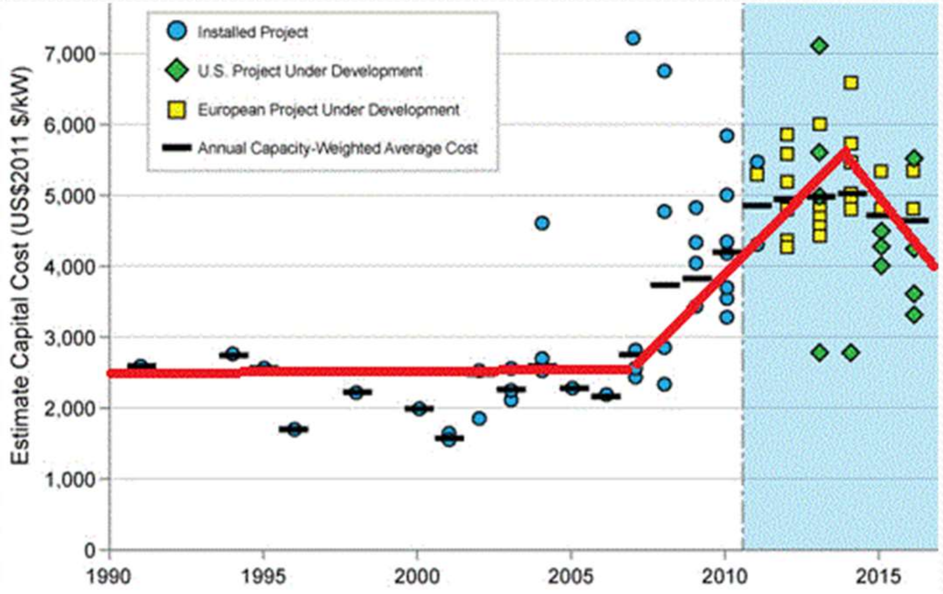


Source: Norwegian Geotechnical Institute

European Offshore Fixed Bottom Structure Costs



Source: Carbon Trust 2015

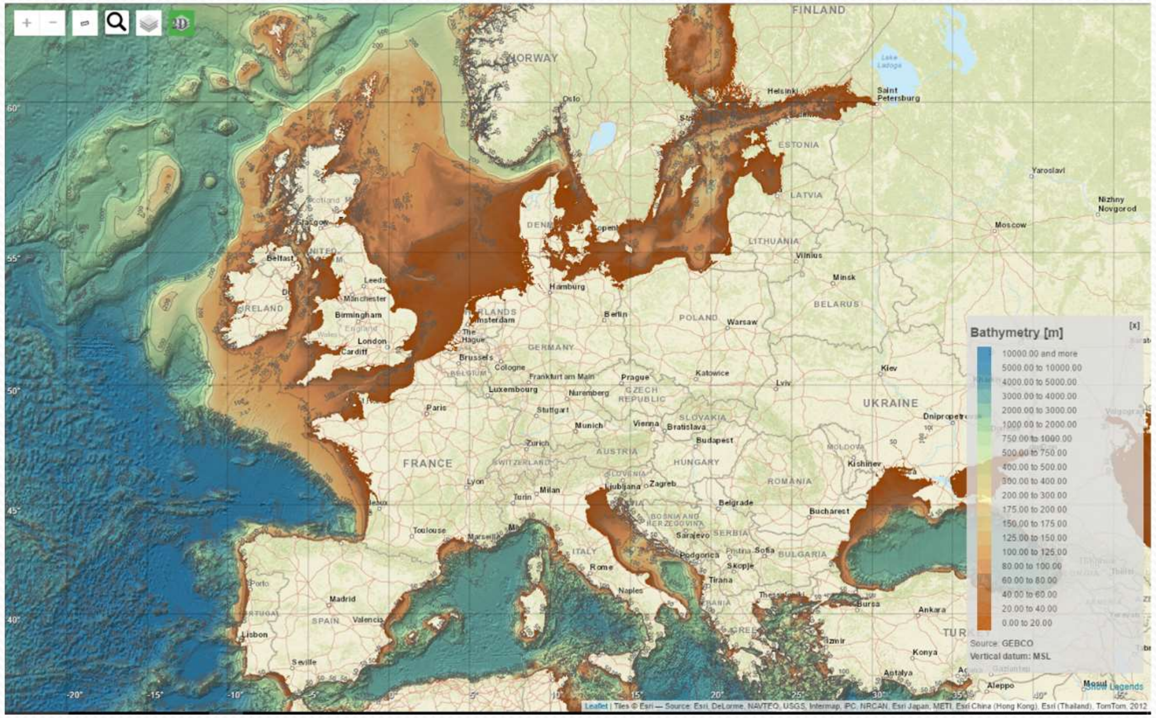


Source: US NREL Database

- Monopile costs per kW flat-lining 1991 – 2008
- Post-2008 increases: installation & high commodities costs (mainly steel)

- Heavier & longer over-designed “monopiles” [in reality very thin walled steel shells]
- Extensive & costly equipment and surface vessel spreads
- High levels of expensive downtime/weather standby
- Insistence on “known technology” reduced innovation, risk aversion, conservatism.
- Early days: Lack of developer experience; general skills shortage in a new industry.

North Sea/Atlantic Offshore Wind Resource



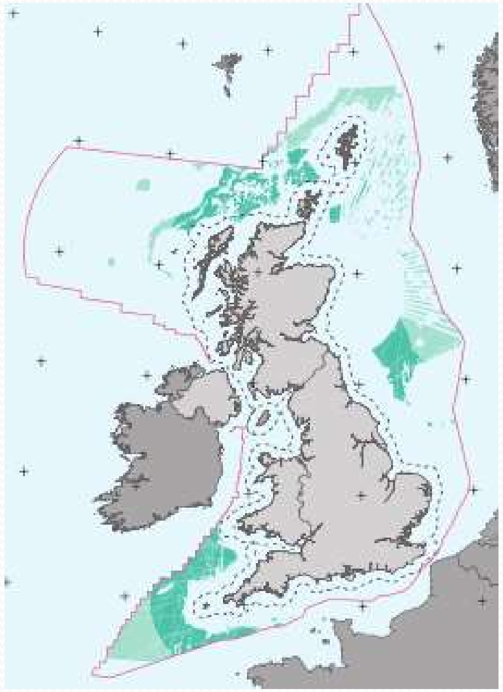
Source: www.openocean.fr 2017

"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)

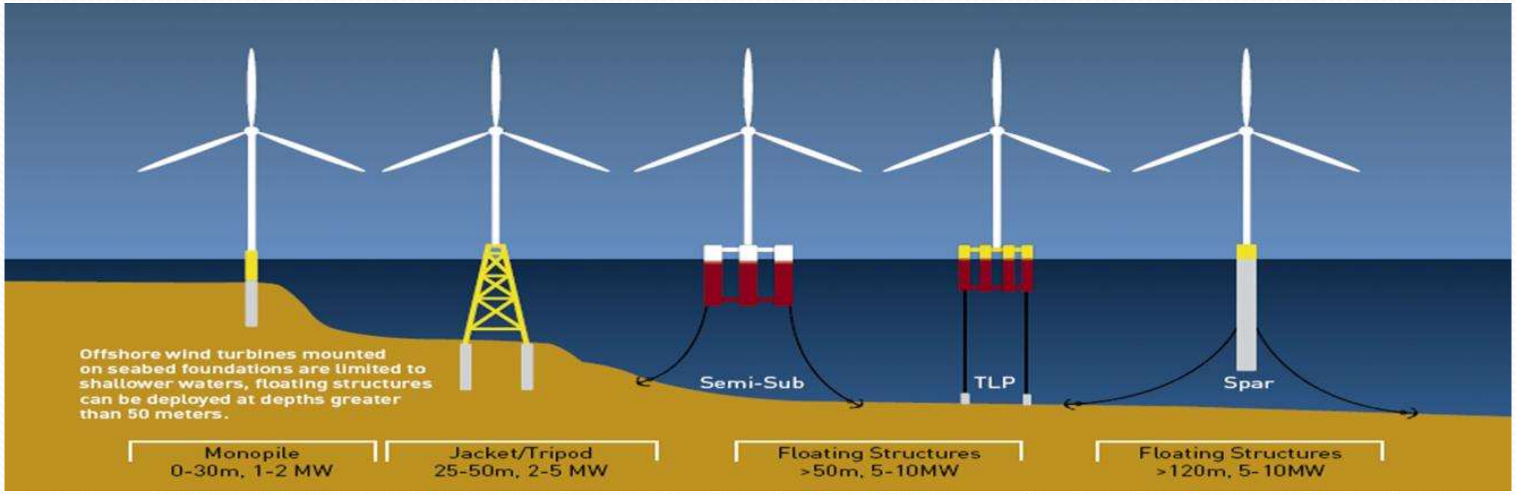
A UK ETI study found that with appropriate foundation technology for suitable sites, coupled with ongoing technology and supply chain innovation in other areas could deliver LCoE of less than ***Euro 100/MWh from the mid 2020's [USD 120]***

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



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



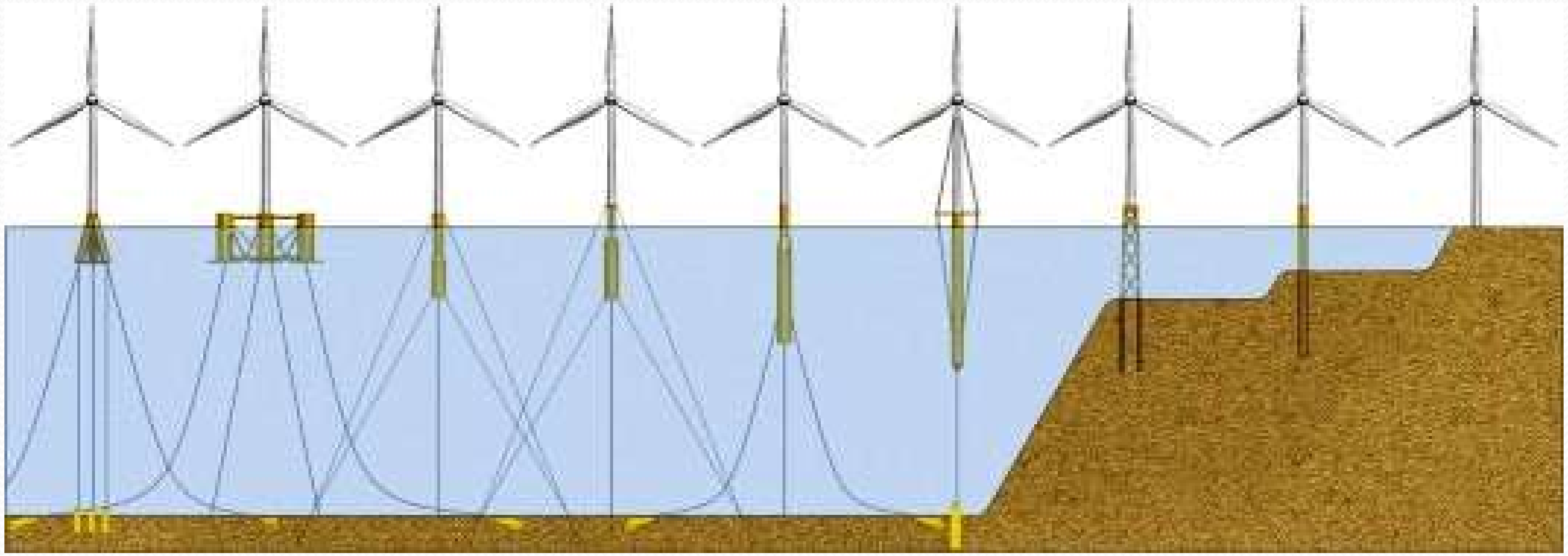
Source: Roddier & Weinstein, 2010

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 *Design & Installation of Support Structures*



Source: Myhr et al, 2014.

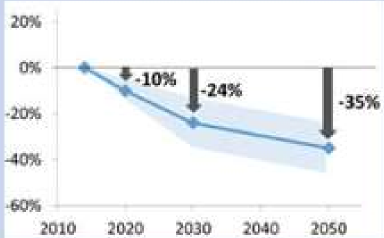
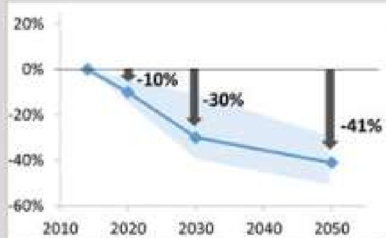
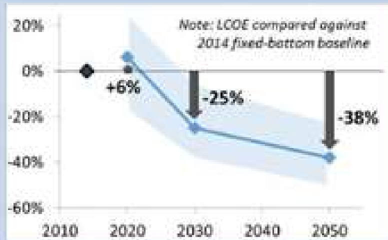
Active European Floating Wind Projects

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

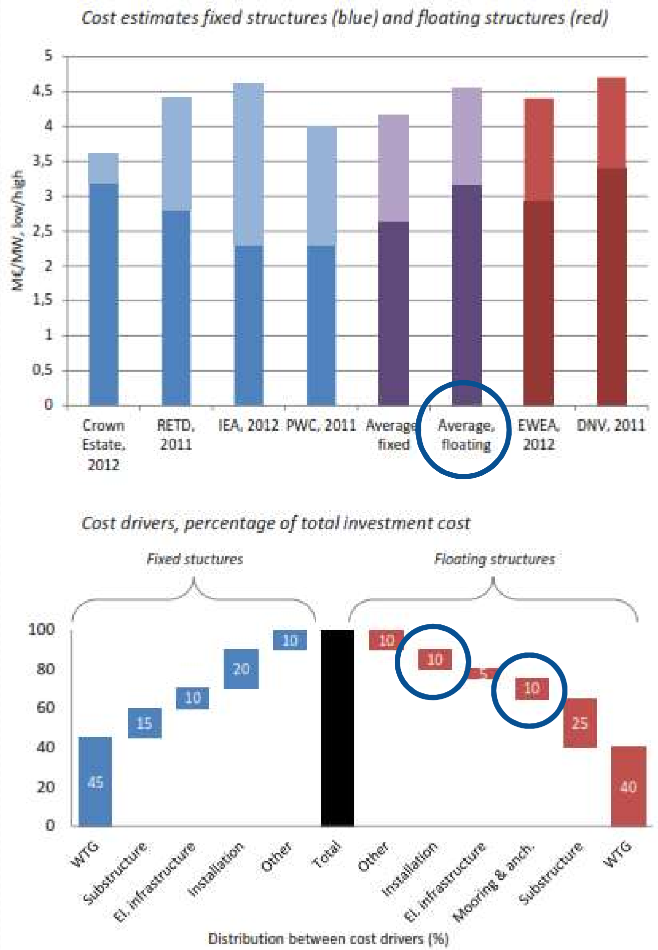
Offshore Wind LCOE Reduction Potential

Predicted Reduction: 25 to 30% by 2030

	ONSHORE (LAND-BASED)	FIXED-BOTTOM OFFSHORE	FLOATING OFFSHORE
LEVELIZED COST OF ENERGY (median estimates for median scenario & 1st-3rd quartile range)			
DRIVERS FOR COST REDUCTION IN 2030 (median estimates; median scenario)	Capacity factor: +10% Project life: +10% CapEx: -12% OpEx: -9% WACC: no Δ	Capacity factor: +4% Project life: +15% CapEx: -14% OpEx: -9% WACC: -10%	Capacity factor: +9% Project life: +25% CapEx: -5% OpEx: -8% WACC: -5%
TURBINE SIZE IN 2030 (typical projects)	 3.25 MW 115 m hub height 135 m rotor diameter	 11 MW 125 m hub height 190 m rotor diameter	 9 MW 125 m hub height 190 m rotor diameter
TOP-FIVE IMPACT CATEGORIES	• Larger rotors, reduced specific power • Rotor design advancements • Taller towers • Reduced financing costs • Component durability / reliability	• Larger turbine capacity • Foundation / support structure design • Reduced financing costs • Economies of scale via project size • Component durability / reliability	• Foundation / support structure design • Installation process efficiencies • Foundation / support manufacturing • Economies of scale via project size • Installation / transport equipment

Source: US DoE EERE/Lawrence Berkeley National Laboratory June 2016

Fixed Vs Floating: Reducing Offshore Wind LCOE
Support Structure, Installation, Mooring & Anchoring ~ 20%



Source: Wiser et al [LBNL] 2016

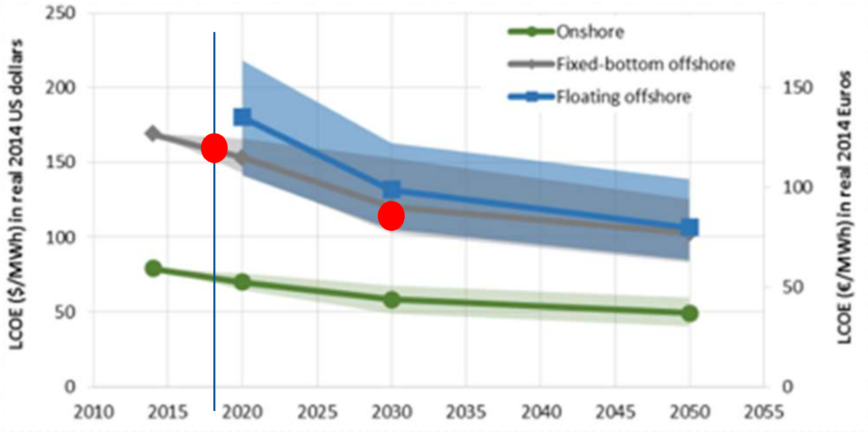
Expected Impact of Wind Technology, Market, and Other Changes on Reducing LCOE of Floating Offshore Wind Projects by 2030

Wind Technology, Market or Other Change	% Rating as "Large Impact"	Mean Rating [3 Large:0 None]
Foundation and Support Structure Design Advances	80	2.8
Installation Process Efficiencies	78	2.7
Foundation and Support Structure Manufacturing Standardisation, Efficiencies and Volume	68	2.6
Economies of Scale Through Increased Project Size	65	2.6
Installation and Transportation Equipment Advances	63	2.5
Increased Turbine Capacity & Rotor Diameter	59	2.4
Reduced Financing Costs & Project Contingencies	58	2.5
Increased Competition Between Component Suppliers, Turbines, Balance of Plant, Installations, O & M.	46	2.3
Rotor Design Advances	46	2.2

Source: Wiser et al [LBNL] 2016

Fixed Vs Floating: Offshore Wind LCOE Predictions

Subsidy Independence Using 8 – 15 MW Floating HAWTs?



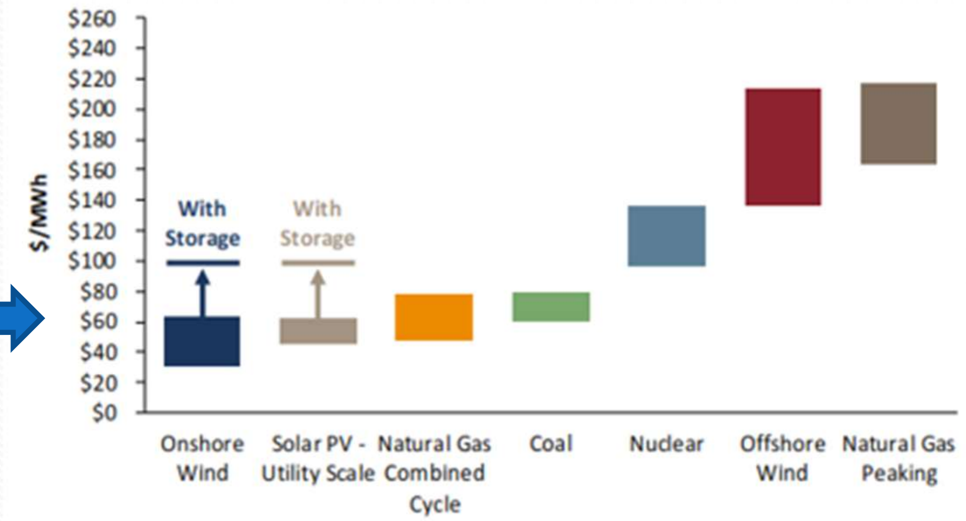
Expert Estimates of Median-Scenario LCOE for Three Wind Applications
Source: Wiser et al [LBNL] 2016

$160 (2017) >> $110 (2030)
Euros 135 to 90 by 2030

"The competition is with solar, onshore wind and fixed wind. ***Floating wind will not be given equal time****" – SBM: FOWT 2017 Marseilles*

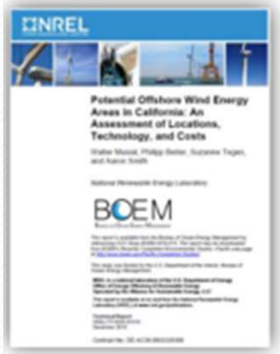
Unsubsidized LCOE in the US by Source
Source: Lazard, IJGGC, IEA on 31/12/2016

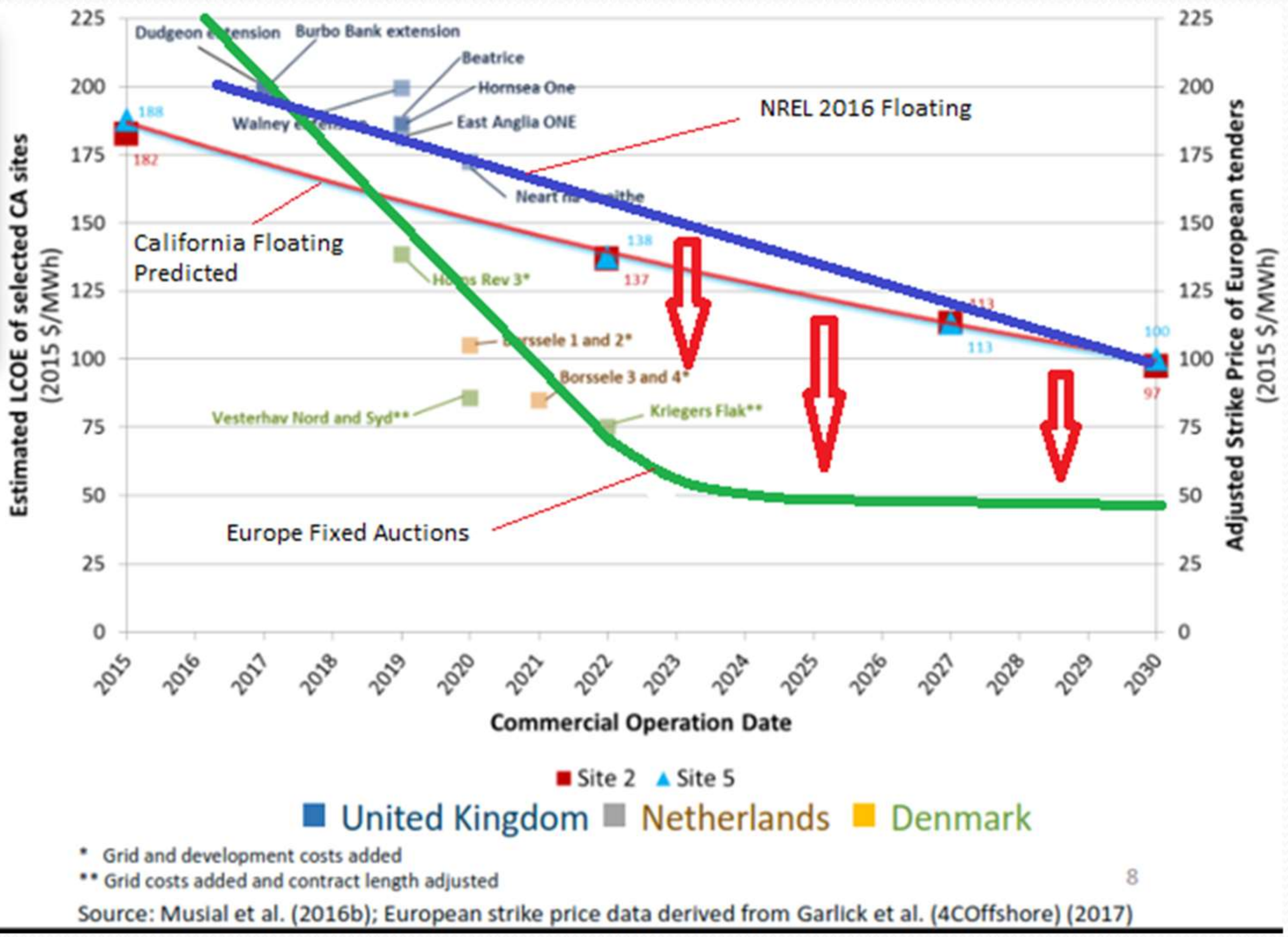
Offshore Wind Needs to go to Euros 50 MWh
To become Subsidy Independent
Achieved Using 8 – 15 MW Floating HAWTs?



Fixed North Sea Vs NREL Floating California

"Investor Confidence Gap" Fixed Vs Floating ?





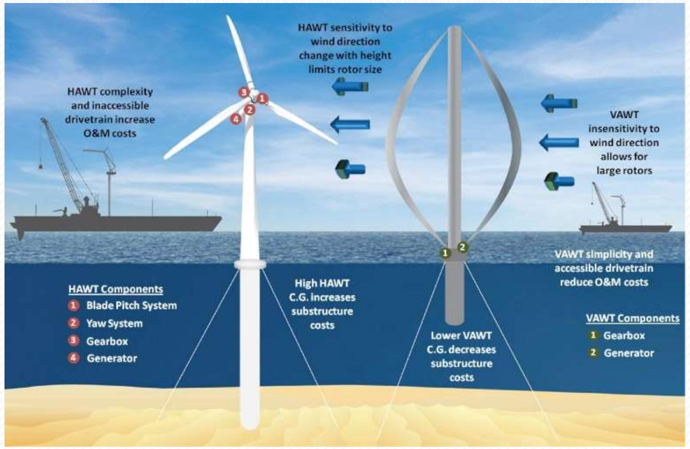
Floating Vertical Axis [FVAWTs] Sandia Labs (Ref. 16)

"Offshore Floating Vertical-Axis Wind Turbine Project Identifies Promising Platform Design", US Dept.of Energy EERE, 17th October 2017 (Ref. 13).

- 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.

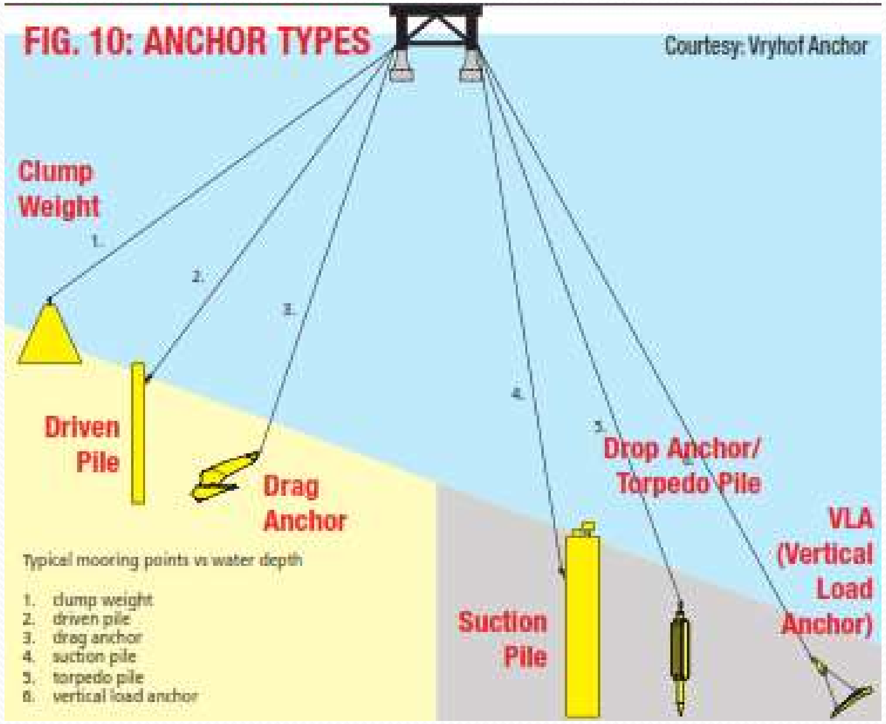
"VAWT TLPs benefit from small roll and pitch motions, such as increased energy capture and reduced inertial loading on tower & blades."

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



Offshore Anchor Types

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



The Four Conventional Anchoring Solutions

Gravity Anchors

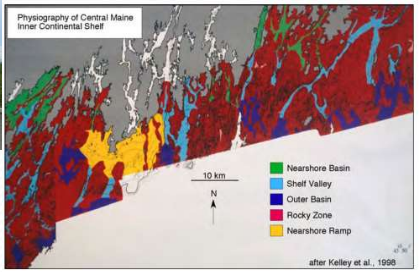
Needs Hard Seabeds for Sliding, Settlement

Suction Caissons

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

Drag Embedment Anchors

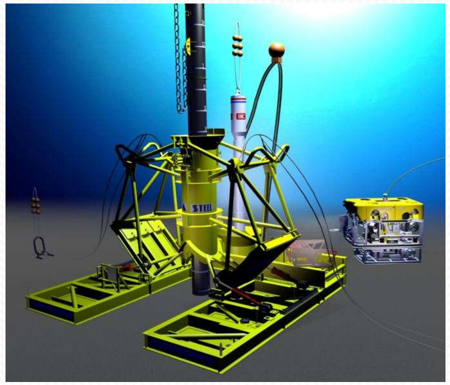
Needs Adequate Soil Layering/Depth



Recommended: Intermoor Mooring Chart 2013

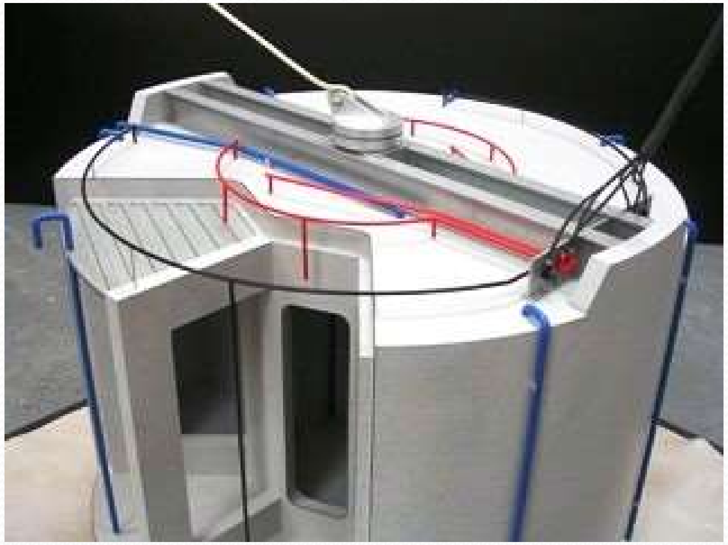
Anchor Piles

Steel Driven/Drilled & Grouted



Case Study - Gravity Anchors – Oregon WEC OPT

Gael Force Sea Limpet



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

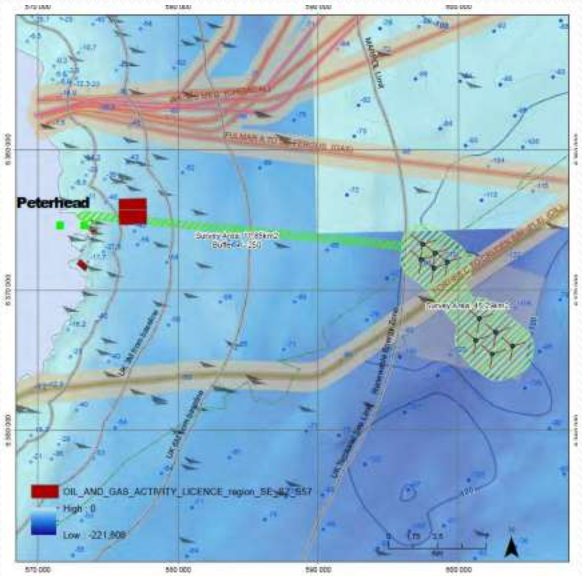
Designer: Gael Force Inverness
Client: US Ocean Power Technologies
Initial 3 No. 460-tonne Patented Sea Limpet
Flooded Compartment Ballast Tanks
Fabricated on Quayside

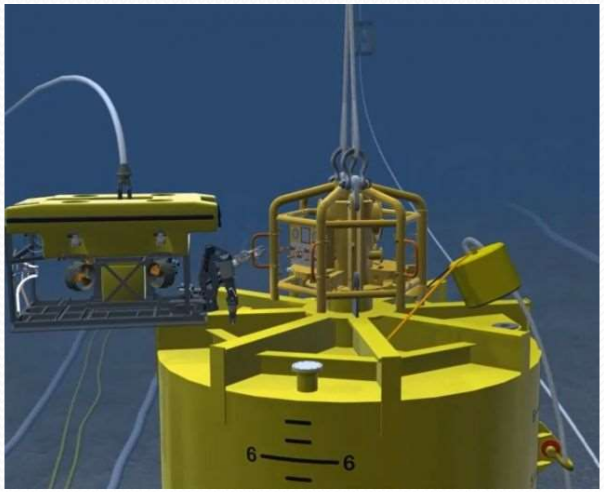
Triple Line Taut Moored WEC
OPT PowerBuoy WEC
Oregon - Contract $1.48 million)
Cross Beam Stiffened
Floated Out and Towed

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 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.





Case Study - Drag Embedment Anchors – Principle Power (Ref. 19)

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®

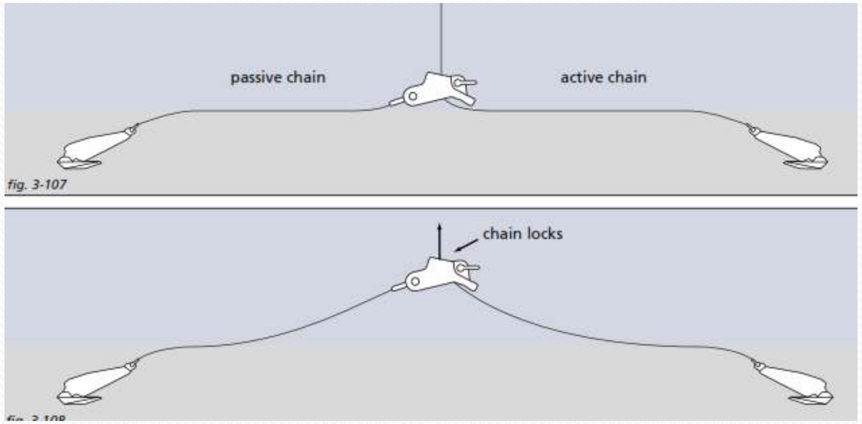
Anchoring & Mooring: ~ 20% costs.

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. 7)

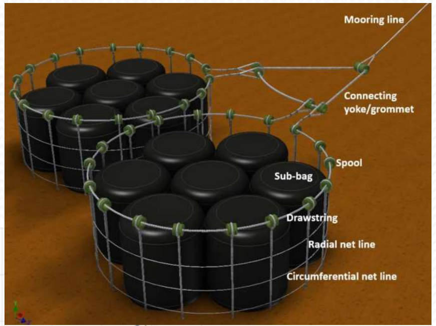
IDEOL SEM-REV Windfloat & Bluewater Texel NL Tidal Floater

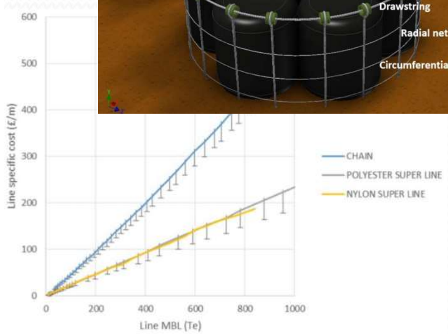
Innovate UK, Scottish Govt., Carbon Trust Project

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.





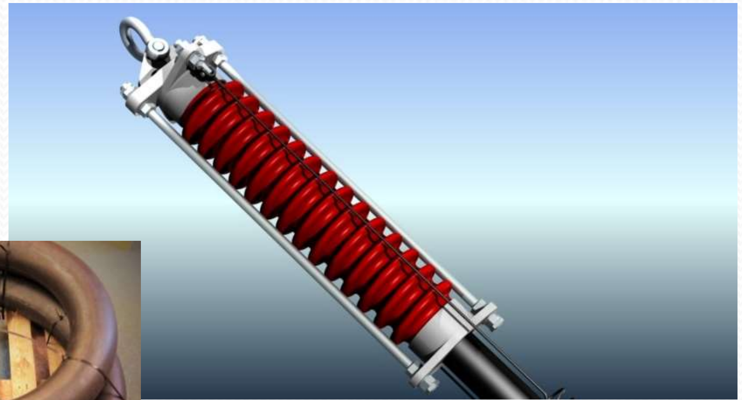
Innovation 2: SBM Taut Moored Submerged Modular Frame Structure (Ref. 17)

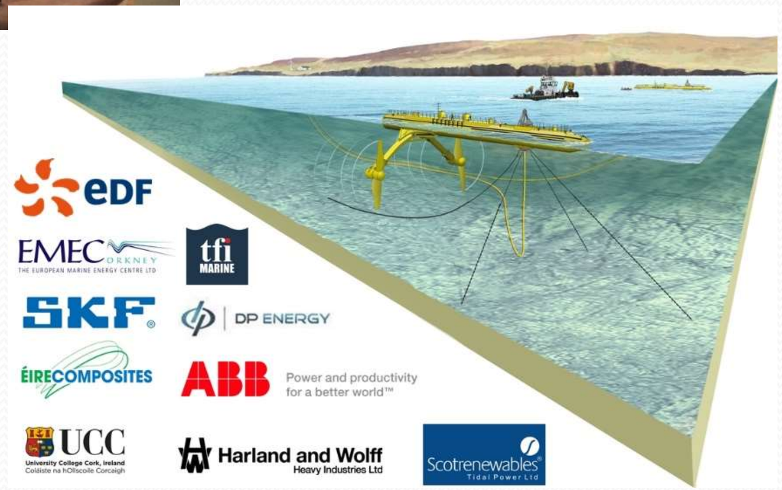
- SBM-EDF-IFP-Siemens
- Light, relatively cheap, small nacelle motions with catenary cable installation.
- Field proven components. No active ballast.
- Mass ratio decreases with larger WTGs
- Small draft for WTG installation @quay, with conventional Wet Tow
- Modularity and low complexity components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

Innovation 3: TFI Dynamic Tether: Elastomer Line /Spring (Ref. 18)

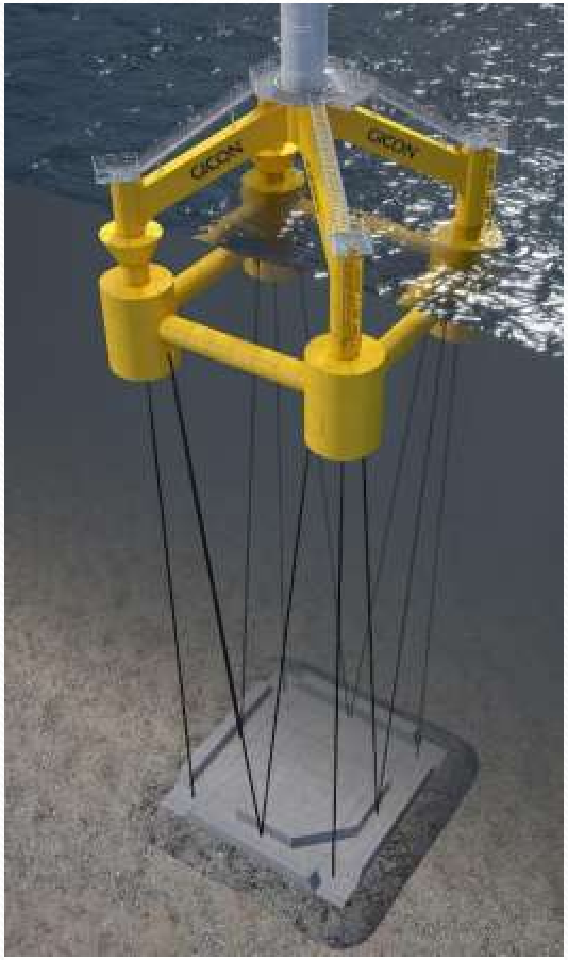
- Significantly reduces peak loads by up to 70%
- Eliminates snatch loads
- Scalable to 300 Tonnes load capacity
- Stabilises floating structure more effectively
- May be installed alongside existing mooring system
- Lower operational costs
- Smaller footprint
- Reduced seabed scour

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





Innovation 4: First Subsea "Ballgrab" Platform Mooring Connectors (Ref. 6)



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 Source: First Subsea

TLP Top Connector

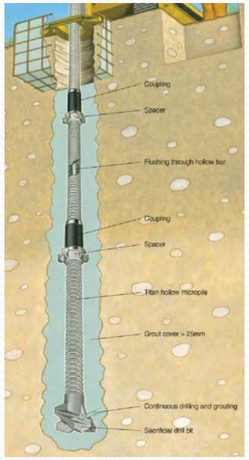
- Automatic connection
- Removes need for expensive chain jacks & fairleads
- Low pretension installation
- Adjustable mooring line length/tension
- Simplifies, speeds up and standardises installation
- No ROV intervention required
- Eliminates the need for divers
- Cost Effective. High load Capacity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

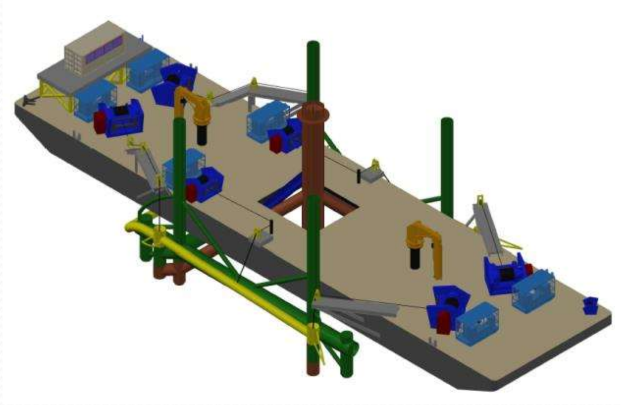
Innovation 5: McLaughlin and Harvey Subsea Drilled Anchors (Ref.3)

Mooring spread for ScotRenewables SR2000 floating Tidal Turbine at EMEC Orkney.

Almost completely bare rocky seabed swept by strong tidal currents.

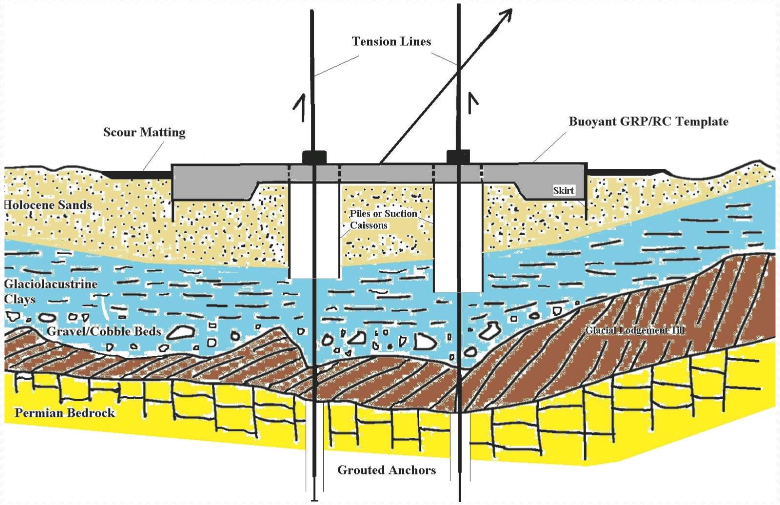
Anchor options: (1) Floating & Modular gravity; (2) **Drilled and Grouted**





- 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.

Innovation 6: Seabed Anchored Foundation Template [SAFT] (Ref.8)



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.

Conclusions [1] Offshore Wind Fixed Vx Floating LCOE

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 such that "subsidence free", may be possible post 2020. Further 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. However, recent low bids for North Sea fixed structure OW suggest an **"Investor Confidence Gap"** between Fixed Vs Floating. Floating wind needs substantial reduction in LCOE requiring a considerable technology gamechager.

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 [2] Anchoring and Mooring

1. 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 be via suction caissons, in hard soils and bedrocks mostly drilled anchors.

2. 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.

3. 4 Conventional Anchoring Solutions - Case Studies

Gravity Anchors	- Oregon WEC OPT
Suction Caissons	- HYWIND Buchan Deep
Drag Anchors	- Principle Power Portugal

4. Innovation Examples

1: Nylon Rope and Gravity Anchor Bags	[TTI];
2: Submerged Taut Moored Substructure	[SBM];
3: Dynamic Tether: Elastomer/Spring	[TFI];
4: “Ballgrab” Platform Mooring Connectors	[First Subsea]
5: Drilled Anchors	[McL&H];
6: Seabed Anchored Foundation Template	[SAFT]

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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*

Contact Details

Dr. C.R. Golightly, BSc, MSc, PhD, MICE, FGS.
Geotechnical and Engineering Geology Consultant
Rue Marc Brison 10G, 1300 Limal, Belgium
Tel. +32 10 41 95 25
Mobile: +32 478 086394
Email: chris.golightly@hotmail.com
skype: chrisgolightly
Linked In: linkedin.com/pub/5/4b5/469
Twitter: @CRGolightly
Academia.edu: https://independent.academia.edu/ChristopherGolightly

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

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

"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.