HARNESSING OFFSHORE MOORING EXPERIENCE AND ANCHORING TECHNOLOGY FOR THE FLOATING RENEWABLE ENERGY SYSTEMS

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Contents

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Introduction

- Vryhof is a mooring and anchoring company founded in 1972, headquartered near Rotterdam, The Netherlands. www.vryhof.com

- Since then invented designs like; Stevin®, Stevpris®, Stevshark®, Stevmanta®, Stevtensioner®, Stevtrack® and supplied 10400 anchors to the industry….

- Today we
  - design, manufacture and supply High Holding Power (HHP) anchors, suction piles, dynamically embedded anchors, gravity anchors, and tensioning equipment
  - Design and supply mooring systems
  - Provide offshore Installation assistance
  - Carry out FEED studies and other Engineering services

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Many of the offshore structures are floating and moored

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Upstream and Downstream activities in Oil and Gas Sector

Offshore drilling activities: MODUs, drillships

Offshore production activities: FPU, FPS, etc.

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Upstream and Downstream activities in Oil and Gas Sector

Offshore storage/offloading: FSO, FPOS, FSRU, etc.

Offshore terminal systems: SPM/CALM, CBM, etc.

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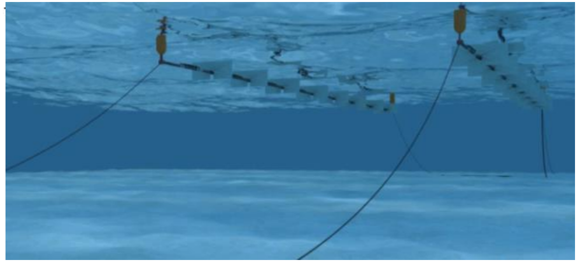
AND Renewable energy systems:
floating wind, wave, tidal, current, and OTEC devices



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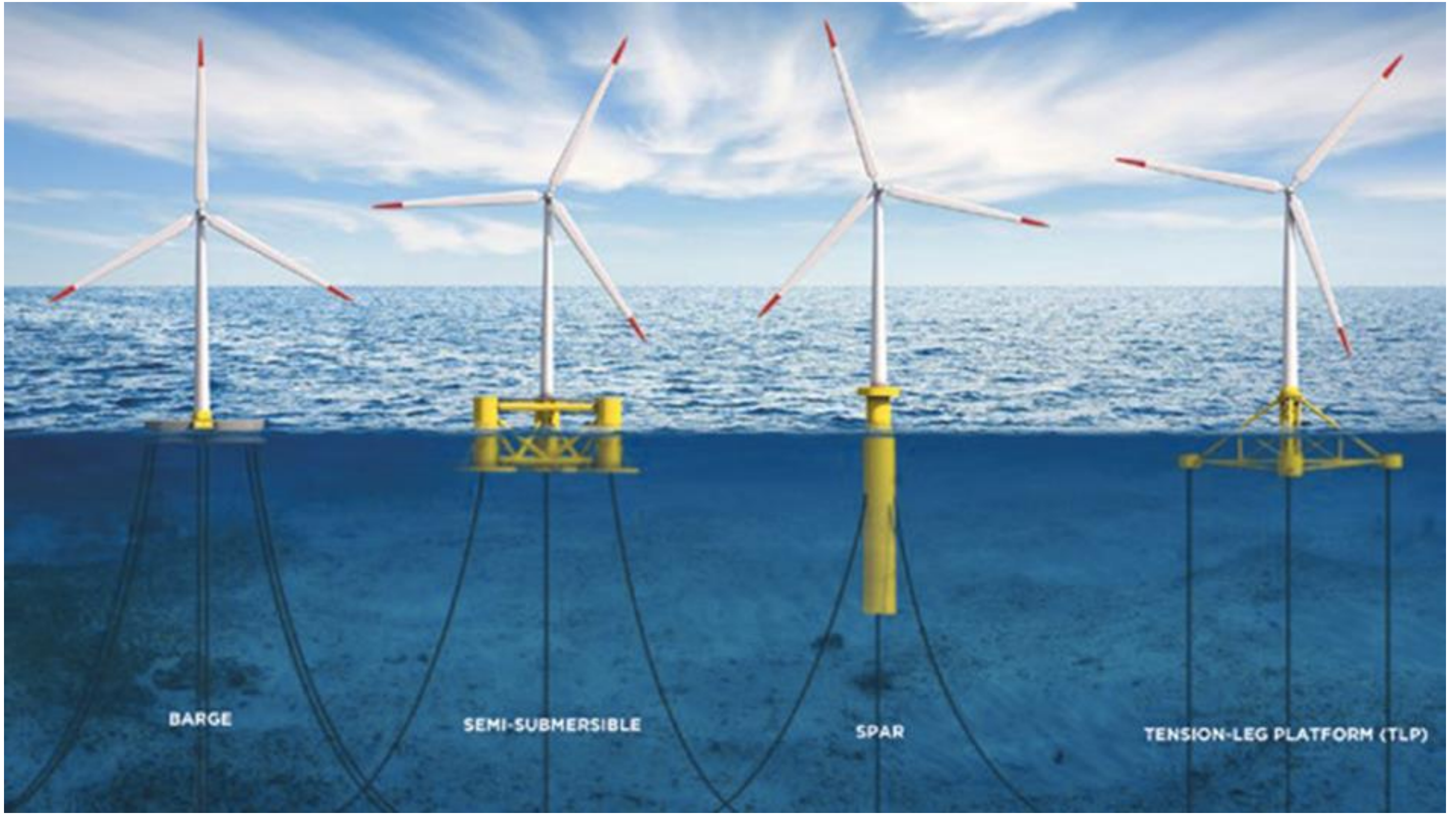
How are these floating units kept in position



Source: WindEurope 2017

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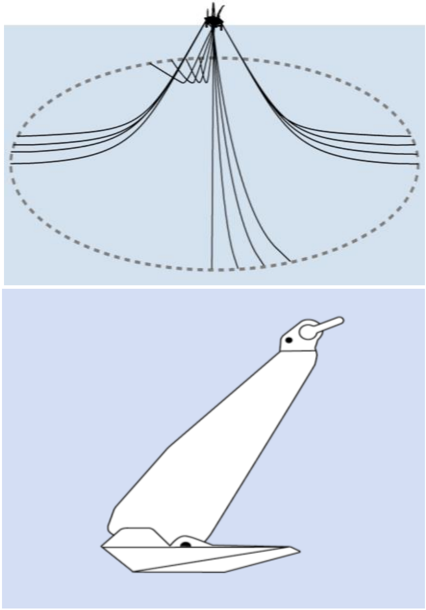
Moring systems in general

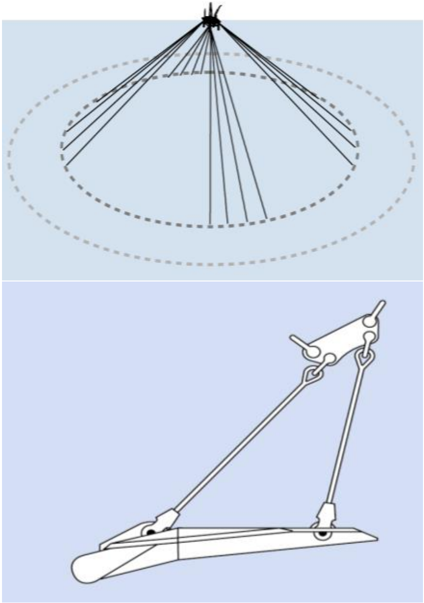
Catenary Mooring

- chain
- wire rope
- drag embedment anchor



Taut and Semi-taut Mooring

- synthetic rope
- wire rope
- vertical loaded anchor (VLA)



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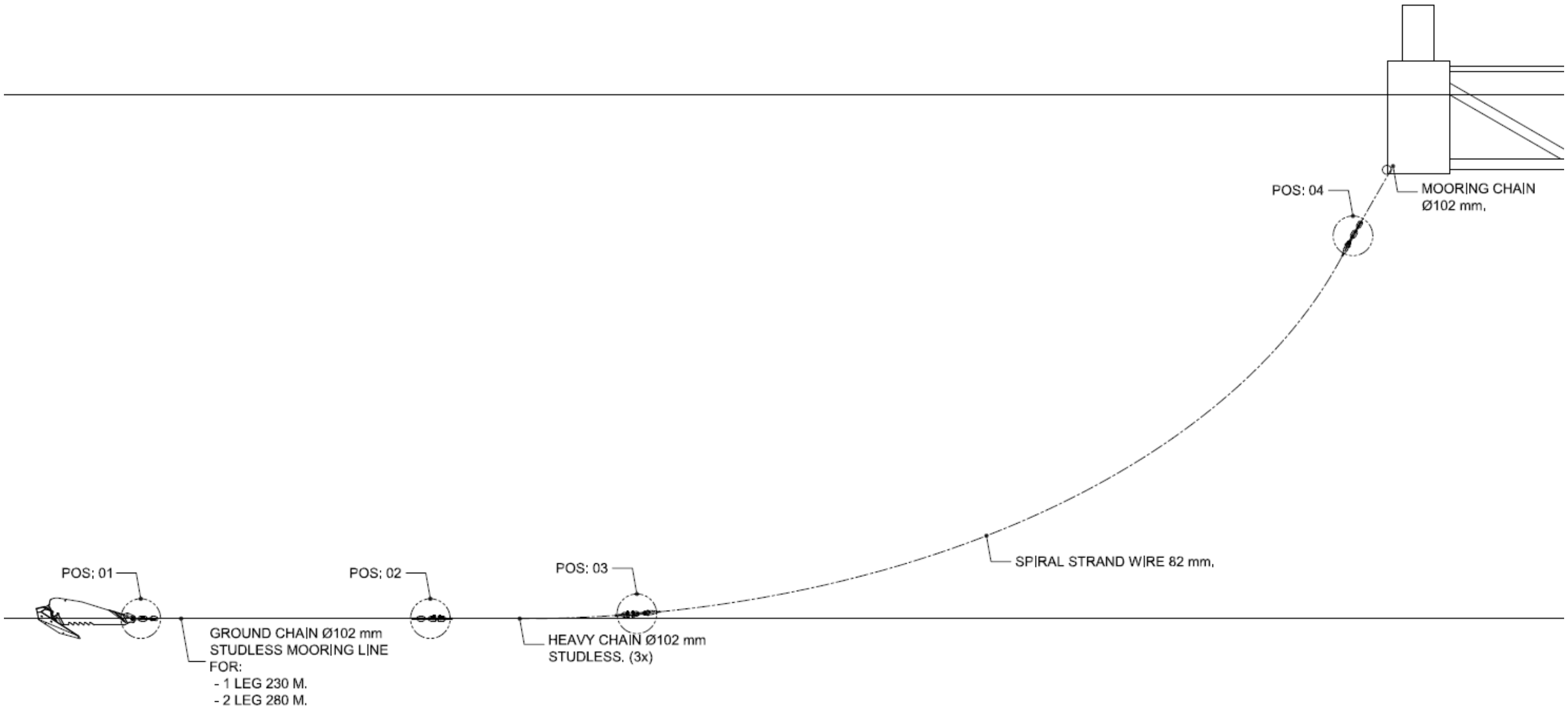
Moring system elements



Mooring arrangements

- Multitude of anchoring layouts are possible
- So far in renewable mooring systems the commonly used or analysed layouts
  - 3–leg systems
  - 4-leg systems
  - 6-leg systems
  - 9-leg systems
- Interesting scenarios to analyse:
  - Material cost versus installation time and cost
  - Size of system versus ability to handle and service
  - Permit area vs targeted production

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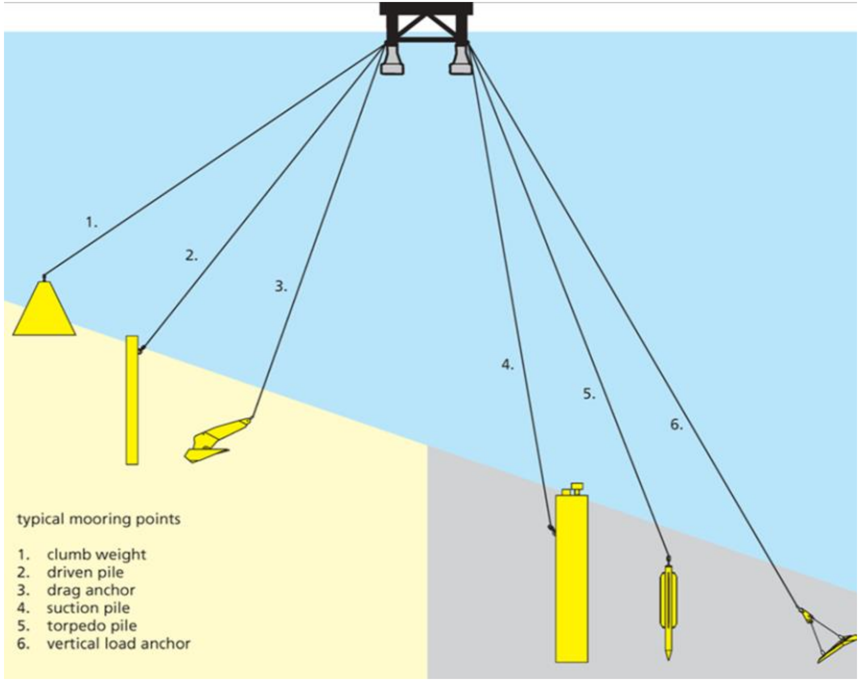
Anchoring options



- Gravity base anchor
- Anchor pile
- Drag embedment anchor
- Suction pile
- Dynamically installed anchors (DEPLA and DPA)
- Vertical load anchor

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Anchors

- Market leader in Ultra HHP anchors
- In-house developed and patented designs
- More than 10,400 units delivered, 2000 of which for permanent systems
- The **STEVPRIS®** anchor is the most applied anchor in the offshore industry
- The most applied anchoring technology in the floating MRE Industry
- Anchor types to serve different soils, water depths and load directions / applications

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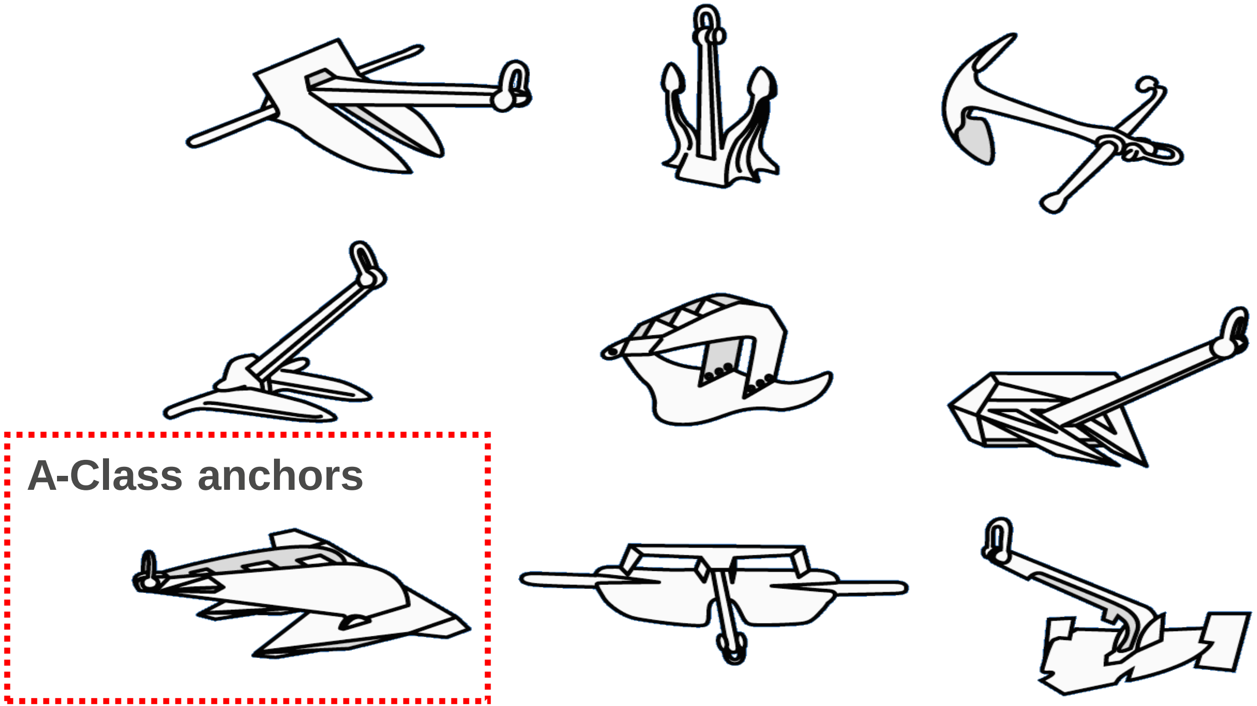
DEA

A drag embedment anchor is pulled in (dragged in) to the subseabed.
The capacity and performance is a function of anchor type/size and the in-situ geotechical conditions.

Only a special category of drag embedment anchors is suitable for offshore use



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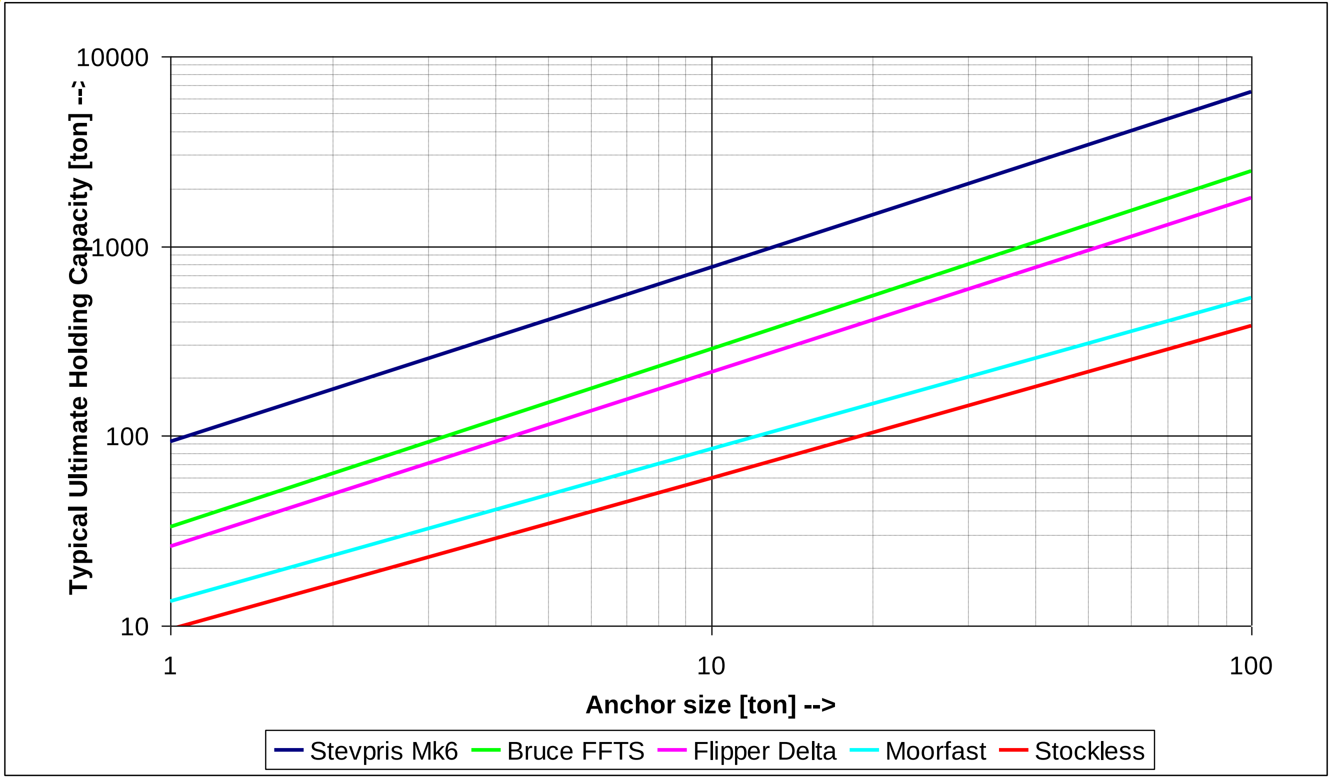
Anchor holding capacity in medium dense silica SAND



DESIGN AND ANCHOR ANALYSIS

Mooring / metocean conditions
Type of mooring system
- Spread or single point
- Catenary or taut or semi-taut

Type of moored object
- Permanent (FPSO, FSO, FPI, FOWT)
- Temporary (MODU, barge, etc)

Mooring line characteristics
Anchor loads (quasi-static / dynamic)
- intact
- damaged
- transient

Specifications and applicable codes

Site conditions
- Location (maps)
- Bathymetry
- Geophysical data
- Geohazards
- Geological data
- Geotechnical data

- **Suitable anchor type & size**
- **fluke/shank angle setting**
- **Drag + Penetration**
- **Inverse catenary of forerunner**
- **Installation requirements**
- **Installation performance**
- **Long term performance**

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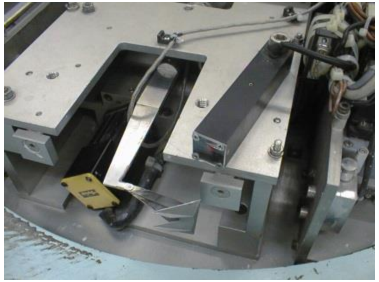
It takes many years of research and testing to design and build stable and High Holding Capacity anchors



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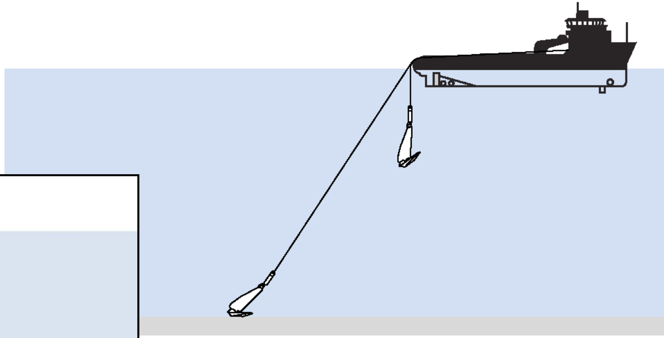
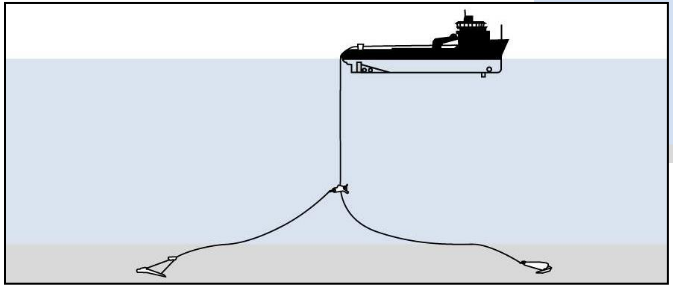
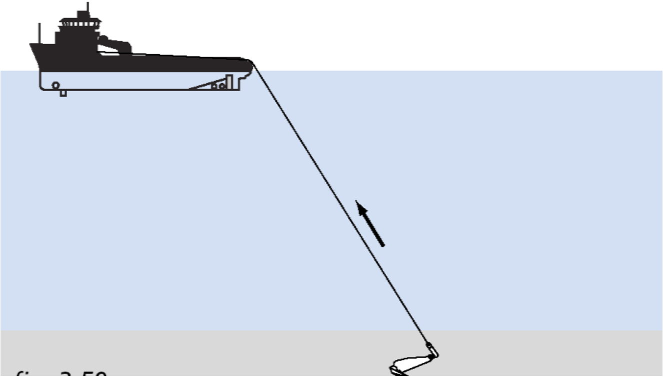
Easy and cost effective installation and recovery methods readily available:







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Lessons learned from completed demo projects:

from mooring systems, anchors and offshore installation perspective

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Vryhof is heavily involved in Floating Renewable Energy Systems (FRES)

We have supplied to the following projects in the world

- Hywind - Statoil - Norway
- Windfloat - Principal Power - Portugal
- University of Maine - VolturnUS - USA
- Fukushima Kizuna – IHI/JMU - Japan
- Fukushima Mirai – Mitsui - Japan
- Fukushima Shimpuu – Mitsubishi - Japan
- SKWID – Modec - Japan
- Wave and current devices - Worldwide
- And NEW ongoing Projects

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Hywind – Statoil - Norway

- Turbine 2.3 MW
- WD: 186-204 m
- Soil: soft clay – side loads
- Catenary chain + wire mooring
- 3 x Vryhof Stevshark®
  - Catenary = vertical movement of the floater
  - Stiffness - clump weight mounted on the line
- Installation: AHV
- Installed in 2009

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Hywind - Installation

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WindFloat – Principal Power, Aguçadoura Portugal

- Turbine: 2 MW
- WD: 45 m
- Soil:
  - Limited soil data
  - Combination of sand, gravel, clays
  - layered soils
- Catenary chain + wire mooring
- 4 x Vryhof Stevshark® with ballast and special cutter points
- Installation: AHV + Stevtensioner
- Installed in 2011

WindFloat – offshore installation

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VolturnUS 1:8 - University of Maine – USA

- Turbine: 0.02 MW
- WD: 60 m
- Soil:
  - Sandy, shells, bedrock
- Catenary chain
- 3 x Vryhof Stevshark®
- Installation: Maine Maritime Academy
  - Tugboat and construction Barge
- Installed in 2013

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Fukushima Forward – JMU (former IHI)
Fukushima Kizuna

- Substation
- WD: 120 m
- Soil:
  - Soft rock, mudstone/siltstone
- Catenary all chain
- 4 x Vryhof Stevshark® with ballast and special cutter points
- Installation:
  - AHV and construction barge with chain tensioner
- Installed in: July 2013

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Fukushima Forward – MITSUI
Fukushima Mirai

- Turbine: 2MW
- WD: 122-123 m
- Soil:
  - Soft rock, mudstone/siltstone
- Catenary all chain
- 6 x Vryhof Stevshark® with ballast and special cutter points
- Installation:
  - AHV and construction barge with chain tensioner
- Installed in: November 2013

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Fukushima Forward – Mitsubishi Fukushima Shimpuu

- Turbine: 7 MW
- WD: 125 m
- Soil:
  – Soft rock, mudstone/siltstone
- Catenary all chain
- 8 x Vryhof Stevshark® with ballast and special cutter points
- Installation:
  – AHV and construction barge with chain tensioner
- Anchors installed in: July 2014,
  – hook-up in July 2015

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Fukushima Forward – offshore installation

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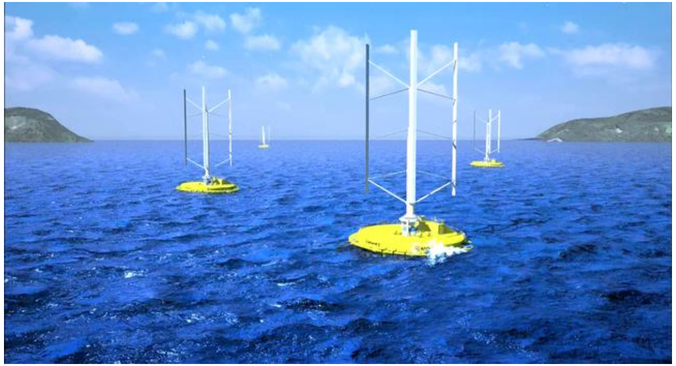
Fukushima Forward – offshore installation

MODEC – SKWID: near Kabe island, Karatsu, Saga Prefecture - Japan



- Turbine: 500kW hybrid wind/current
- WD: 53 m
- Soil:
  - Gravelly sand overlaying bedrock
- Catenary all chain
- 4 x Vryhof Stevshark® with ballast and special cutter points
- Installation:
  - AHV and construction barge with chain tensioner
- Anchors installed in: September 2013,
  - hook-up in 2014-2015

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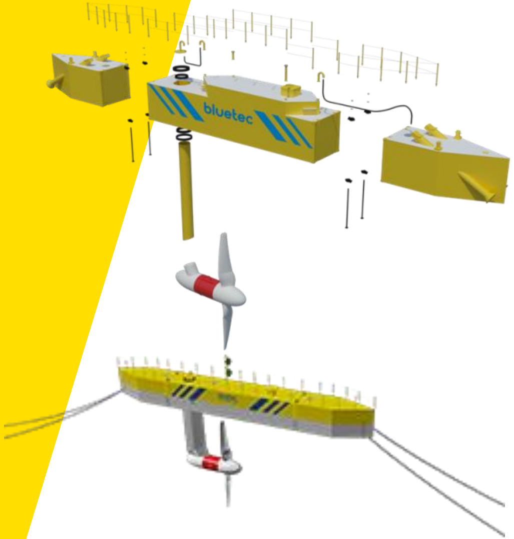
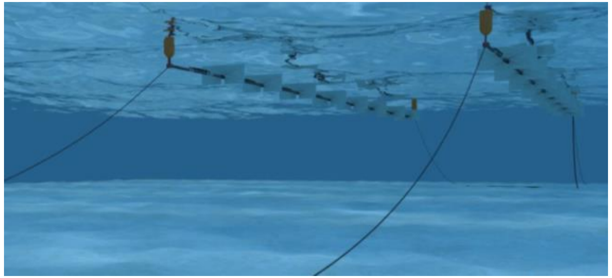
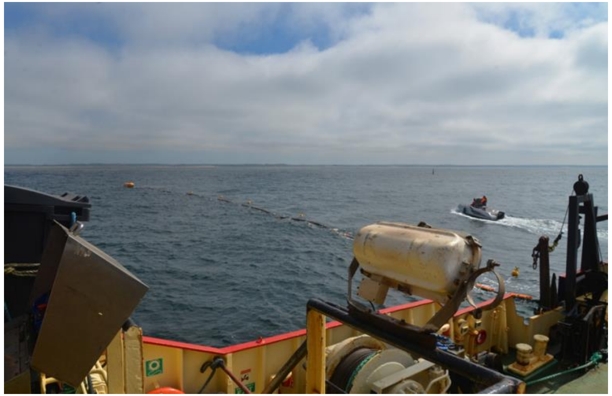
Bluetec–Netherlands, Wavepiston–Denmark, Oceantec-Spain







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Lessons Learned

Demo units have shown us that:

- The floating WTG technology is proven successful
- For moorings; the designs, materials, and installation means are now available
- For mooring systems there is room to optimize the technology and reduce the costs
- The mooring design and offshore installation should consider local circumstances
- The offshore installation interface is required early in design phase
- Industrialization and R&D efforts should run in parallel

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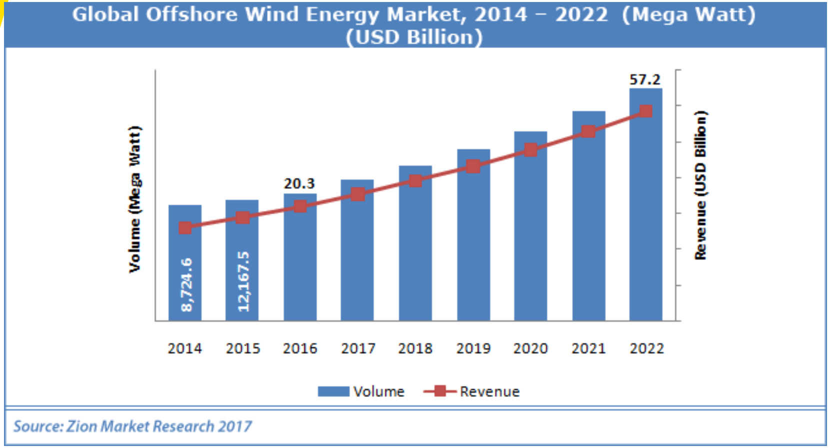
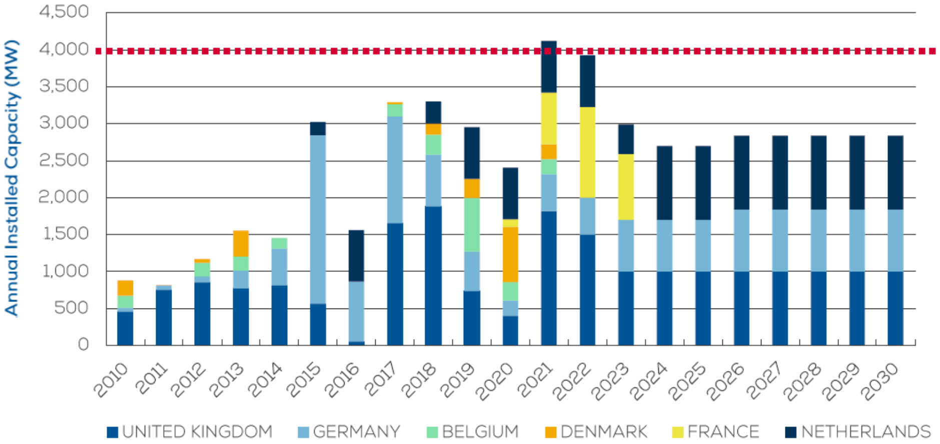
Demands, potential and Trends

- Demand for energy is increasing worldwide.
- Estimated need for Europe is at least 4GW/yr offshore wind industry investment

Global offshore wind energy market was valued at USD 20.3 billion in 2016 and is expected to reach USD 57.2 billion in 2022



Source: Zion Market Research



Source: WindEurope

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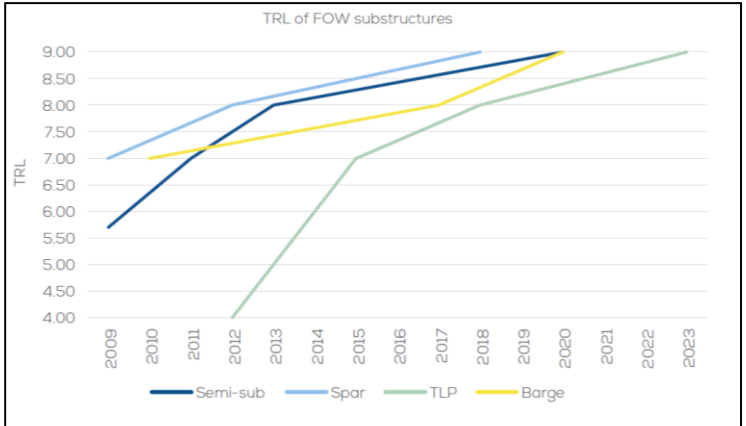
Demands, potential and Trends

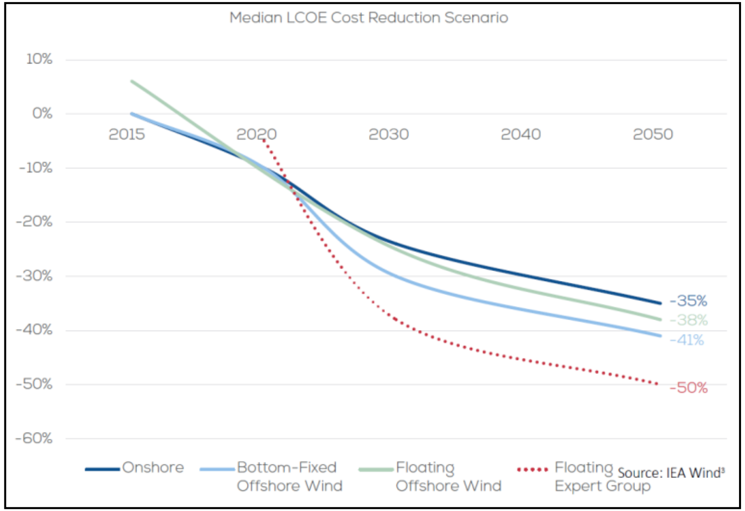
- Potential for floating wind is huge
- TRL for floating technology is increasing
- Costs are coming down more rapidly

COUNTRY / REGION	SHARE OF OFFSHORE WIND RESOURCE IN +60m DEPTH	POTENTIAL FOR FLOATING WIND CAPACITY
Europe	80%	4,000 GW
USA	60%	2,450 GW
Japan	80%	500 GW
Taiwan	-	90 GW

Sources: MOFA and Carbon Trust[2]



Source: The Crown Estate[1] and WindEurope



Source: IEA Wind[3]

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New enabling tools and technologies for moorings

- New anchors for challenging ground conditions
- Installation tools to reduce costs and offshore time (*for renewables the offshore installation cost and vessel availability are critical factors*)
- Tools to facilitate easy and cheap connection-disconnection and pre-tensioning
- Tracking tools

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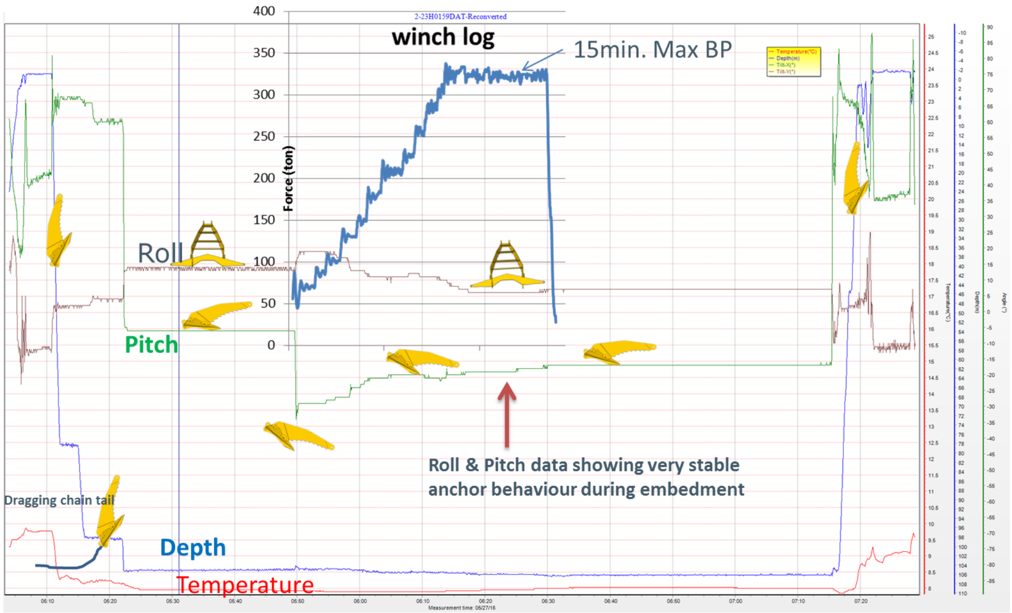
New anchors for challenging ground conditions

- **Stevshark®REX designed, developed and field tested; enabling anchoring in hard ground conditions found commonly at FOWT locations**



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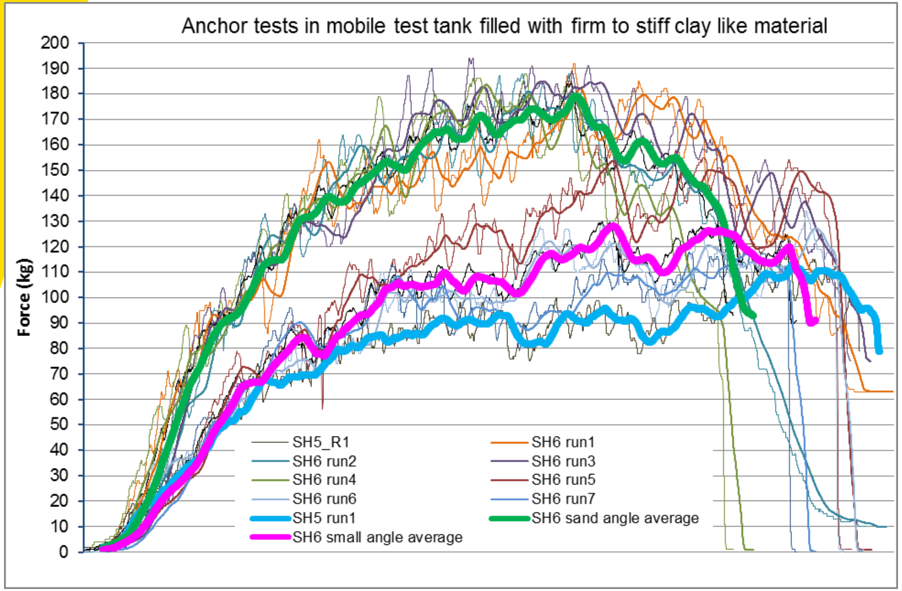
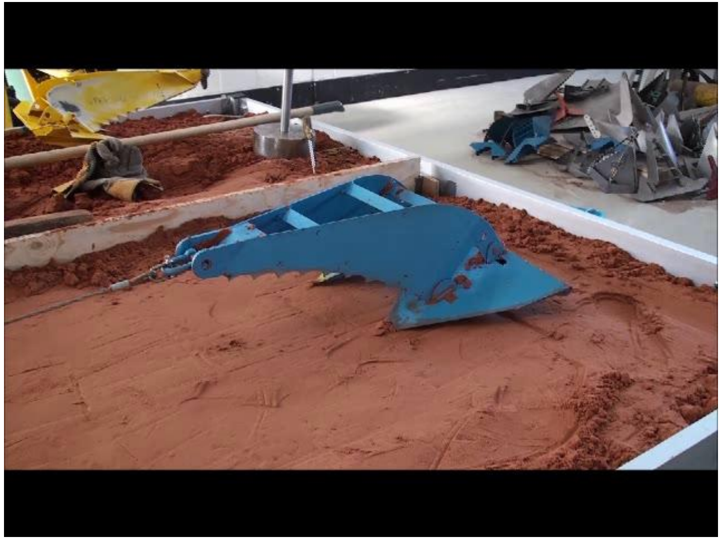
Lab test results in hard soil Stevshark®REX versus Stevshark® Mk5

7 kg Stevshark®REX anchor has higher holding capacity and shorter drag than 7 kg Stevshark®Mk5 anchor

- **64% higher capacity in stiff soil**
- **High capacity developed with shorter drag**





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Comparative field scale tests in North Sea: Krafla and Aksja locations: 7 mT Stevshark®REX versus 7 mT Stevshark® Mk5

- On hard soil locations selected by a major oil operator
- Testing with AHVs (Bollard Pull 338 and 350 tons)
- Tension, anchor position, anchor orientation measurements
- ROV observations
- Witnessed by Class Society

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Comparative tests:
7 mT Stevshark®REX versus 7 mT Stevshark® Mk5

- Two different oil fields and two different AHVs
- Water depths: 104-107 m
- Anchor line: all chain
- 15 test runs at the selected test locations (Selected test locations are known with anchoring problems (normally large anchors and piggy-back systems are needed)

First test campaign: 14 – 15 March 2016
Normand Prosper (338t BP) w/24h WROV

Second test campaign: 27 May 2016
Scandi Vega (350 t BP) w/24h WROV

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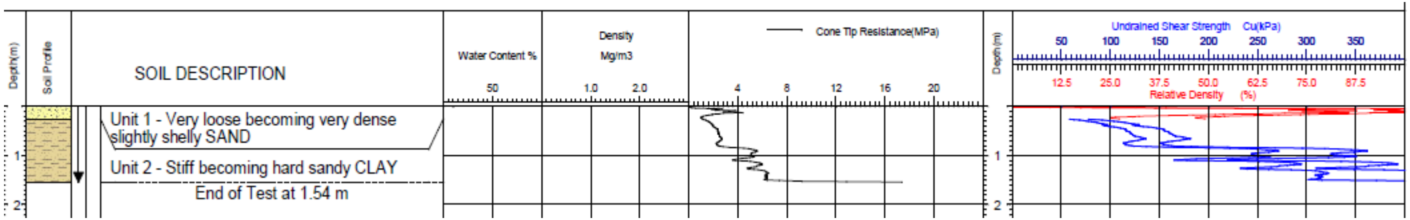
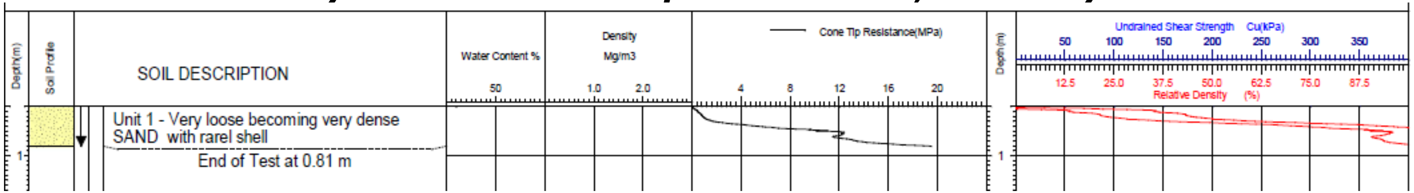
Krafla and Aksja locations are characterized by very dense sands and hard clays: previously anchoring problems – piggy-back anchors

Very dense sands (Dr>100%) or hard clays (Su>500 kPa) at or close to seabed

Test location 1
20cm loose to very dense sand on top underlined by stiff becoming hard sandy clay (350 kPa clay at 1m) – CPT refusal



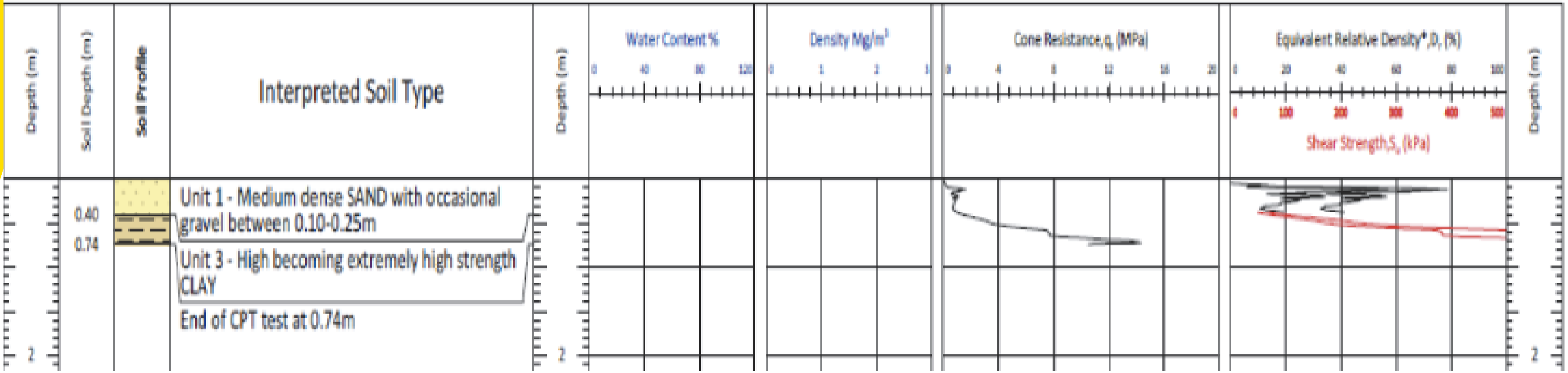
Test location 2
0.8m loose to very dense sand on top. Below sand, hard clay – CPT refusal



Krafla and Aksja locations are characterized by very dense sands and hard clays: previously anchoring problems – piggy-back anchors

Very dense sands (Dr>100%) or hard clays (Su>500 kPa) at or close to seabed

Test location 3
30cm layer of sand on top. Extremely high strength clay (500 kPa at 0.5m) – CPT refusal



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Offshore test results Norway

Test location 1

Stevshark®REX anchor > 338 tons, Max BP reached - AHV stops
Stevshark® Mk5 anchor slips or breaks out max. at 230-320 tons

Test location 2

Stevshark®REX anchor > 338 tons, Max BP reached - AHV stops
Stevshark® Mk5 anchor slips or breaks out max. at 275-290 tons

Test location 3

Stevshark®REX anchor > 350 tons, Max BP reached - AHV stops
Stevshark® Mk5 slips or breaks out max. at 290 tons

In field tests: Stevshark®REX anchor has generated 22%-47% higher capacity than Stevshark®Mk5 anchor

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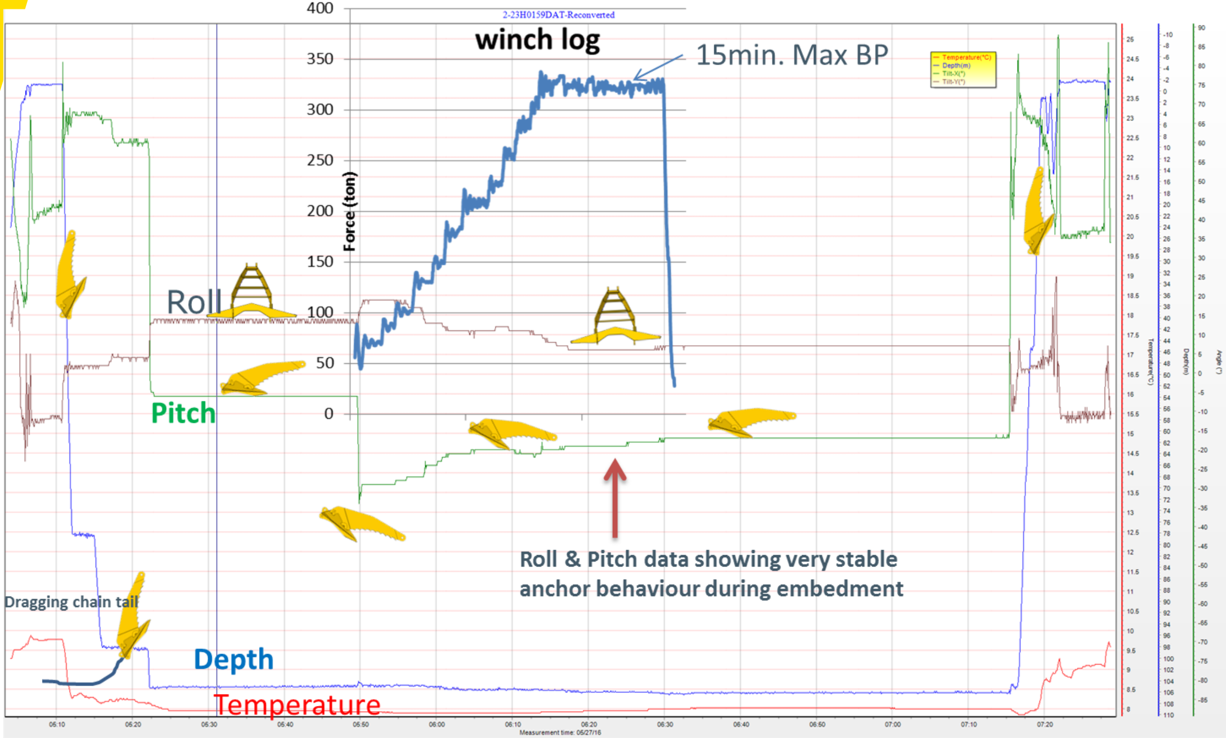
Offshore test results Norway

Tension and orientation data: Stevshark®REX anchor very stable & fully penetrated



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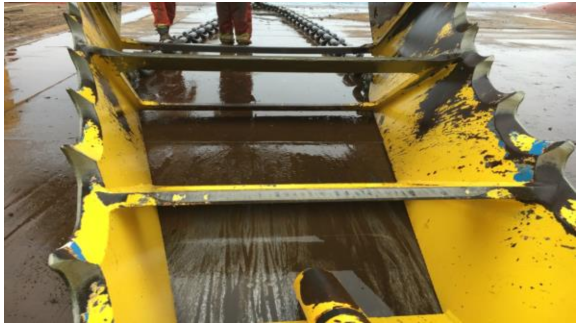
Offshore test results Norway



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2 x 18 mT anchors built: one of them is shipped for tests in NWA, the other one is shipped for tests in UAE with a Rock Suction Cutter Dredger

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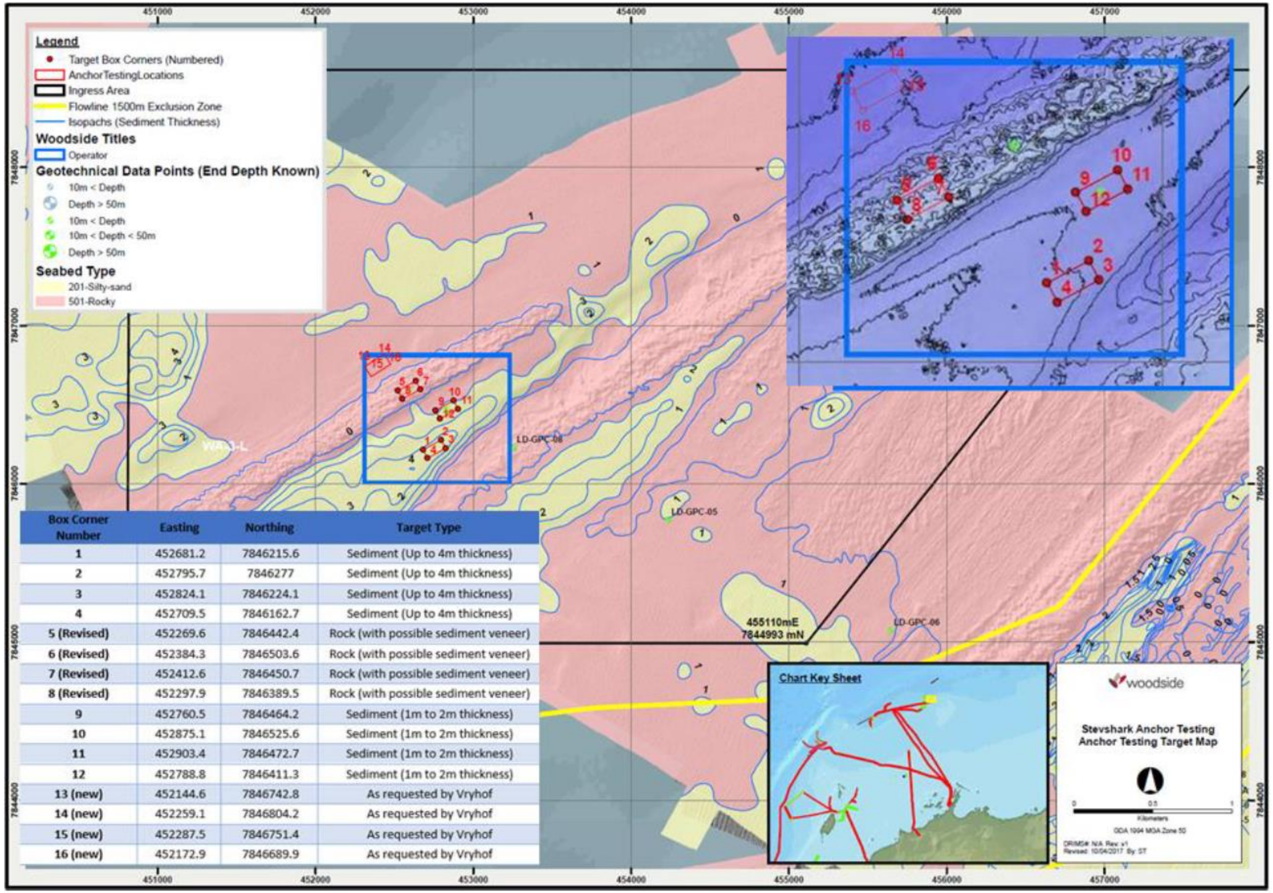
Full scale tests in Angel field NWA with 18 mT Stevshark®REX



Box Corner Number	Easting	Northing	Target Type
1	452681.2	7846215.6	Sediment (Up to 4m thickness)
2	452795.7	7846277	Sediment (Up to 4m thickness)
3	452824.1	7846224.1	Sediment (Up to 4m thickness)
4	452709.5	7846162.7	Sediment (Up to 4m thickness)
5 (Revised)	452269.6	7846442.4	Rock (with possible sediment veneer)
6 (Revised)	452384.3	7846503.6	Rock (with possible sediment veneer)
7 (Revised)	452412.6	7846450.7	Rock (with possible sediment veneer)
8 (Revised)	452297.9	7846389.5	Rock (with possible sediment veneer)
9	452760.5	7846464.2	Sediment (1m to 2m thickness)
10	452875.1	7846525.6	Sediment (1m to 2m thickness)
11	452903.4	7846472.7	Sediment (1m to 2m thickness)
12	452788.8	7846411.3	Sediment (1m to 2m thickness)
13 (new)	452144.6	7846742.8	As requested by Vryhof
14 (new)	452259.1	7846804.2	As requested by Vryhof
15 (new)	452287.5	7846751.4	As requested by Vryhof
16 (new)	452172.9	7846689.9	As requested by Vryhof

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Full scale tests in Angel field NWA with 18 mT Stevshark®REX

- Four test locations with a total of 7 test runs are performed
  - Location 1 is characterised by 3-4 meter thick carbonate sand underlined by calcarenite bedrock
  - Location 2 is characterized by 1-2 meter thick carbonate sand underlined by calcarenite bedrock
  - Location 3 is characterized by no sediment but with calcarenite bedrock of irregular and rough seabed topography
  - Location 4 is characterized by no sediment but with calcarenite bedrock of smooth seabed topography

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Full scale tests in Angel field NWA with 18 mT Stevshark®REX

- 7 tests in total at the maximum Bollard Pull (BP) of 235-250 tons (i.e. maximum capacity of AHV) held at least 15 minutes at each test
- At all locations the capacity of 18 mT Stevshark®REX is higher than the available BP of AHV.
- Depending on location the anchor drag lengths vary from 8 to 19 meters
- Previously the operator was using piles in this field. NOW Stevshark®REX offers cost effective foundation solution

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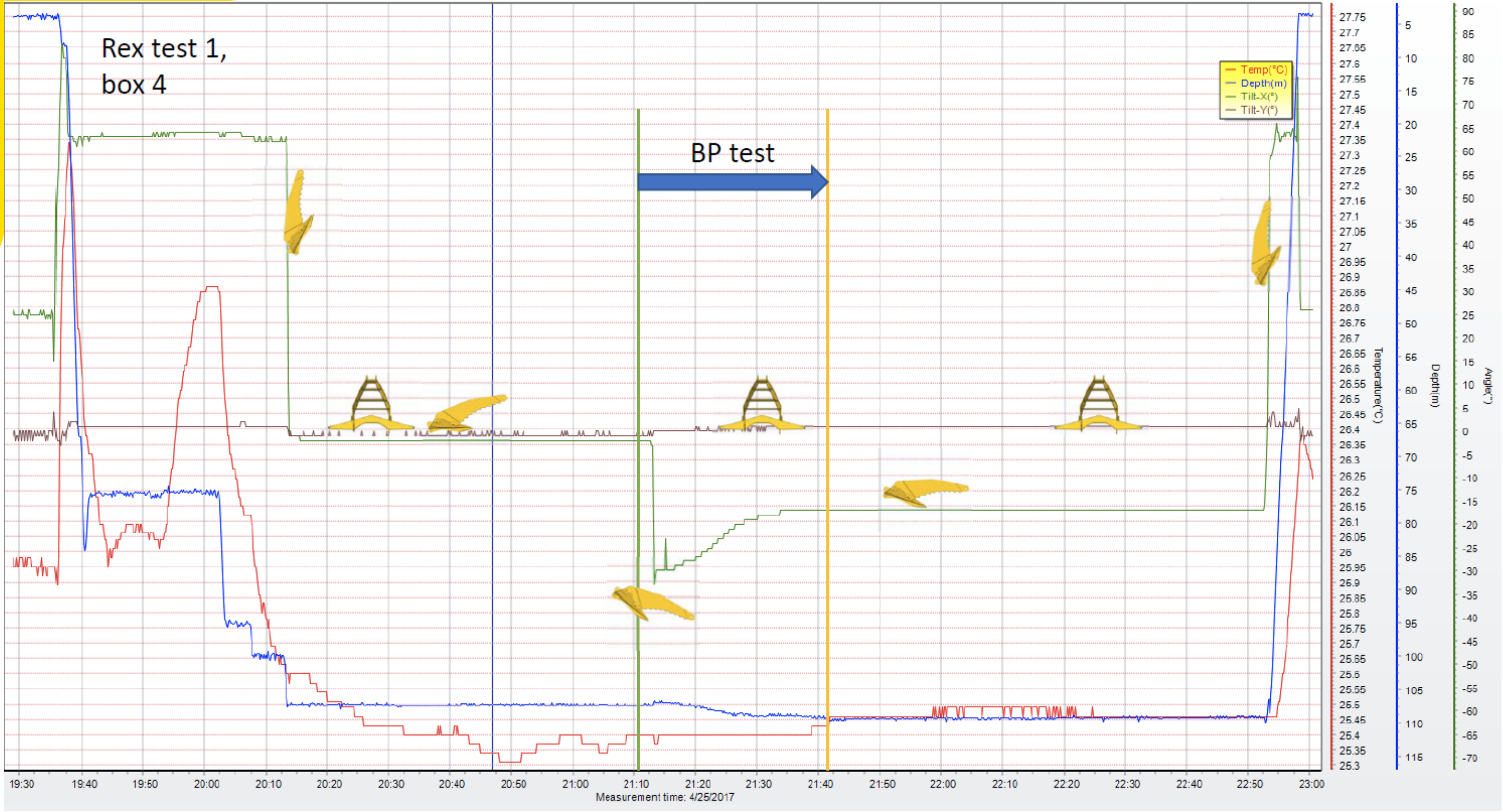
Full scale tests in Angel field NWA with 18 mT Stevshark®REX

Full scale tests in Angel field NWA with 18 mT Stevshark®REX



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18 mT Stevshark®REX anchor before and after the NWA tests

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Summary

- New anchor has expanded the suitability boundaries of DEAs
  - Harder soils and higher rock strengths
  - Complex soil stratigraphy, mass flow deposits, cobble/boulder inclusions
  - New anchor geometry
  - Increased penetration ability and holding capacity
  - Increased stability and strength

- Laboratory and field scale tests with Stevshark®REX anchor show 22% to 47% higher capacity than Stevshark® Mk5 anchor. New anchor has excellent stability.

- The penetration ability and the holding capacity of Stevshark®REX anchor in harder soils is significantly higher than older anchors (in lab tests 64% higher capacity than Stevshark® Mk5 anchor).

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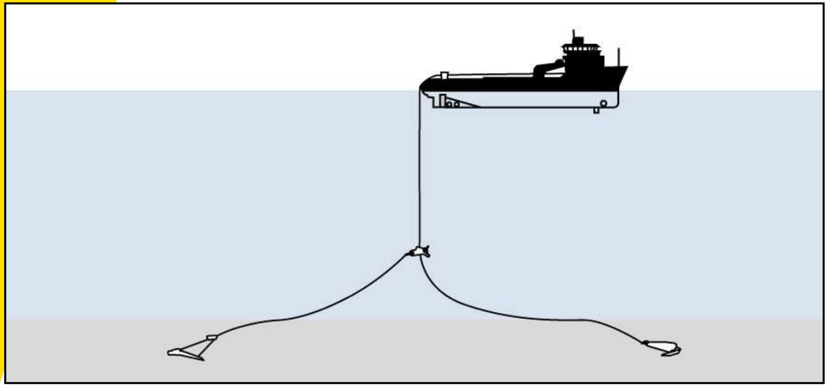
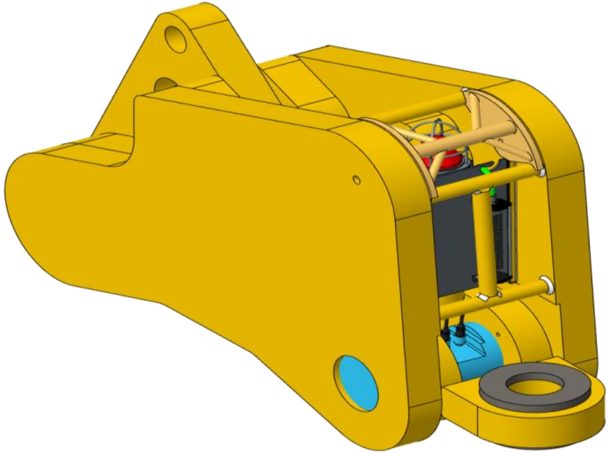
Installation tools reducing cost and time of offshore installation

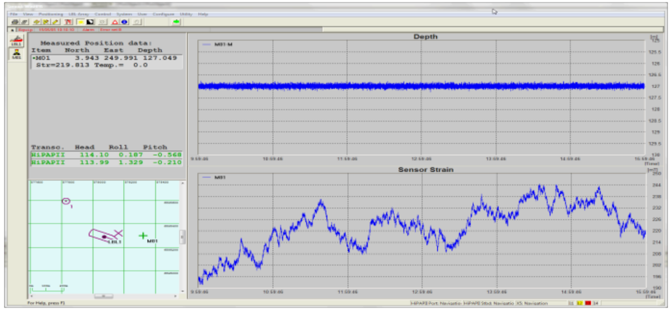
- **Stevtensioner®; allows installation of moorings using small AHTS or local barges**
- **developed and improved with acoustic communication and additional data display and storage systems**





<u>Data available:</u>
•Tension in horizontal line
•Position of STEVTENSIONER®
•Tilt of STEVTENSIONER®

<u>**All data available on vessel APOS screens through HiPAP**</u>



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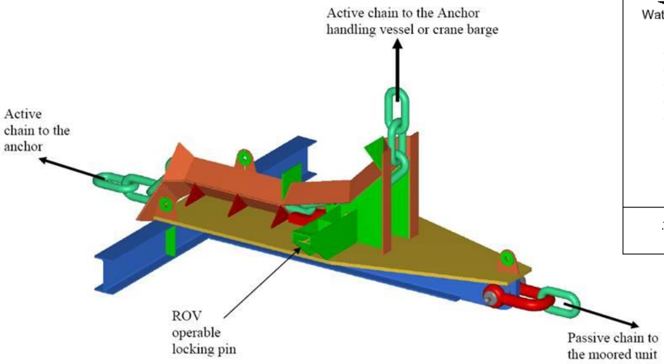
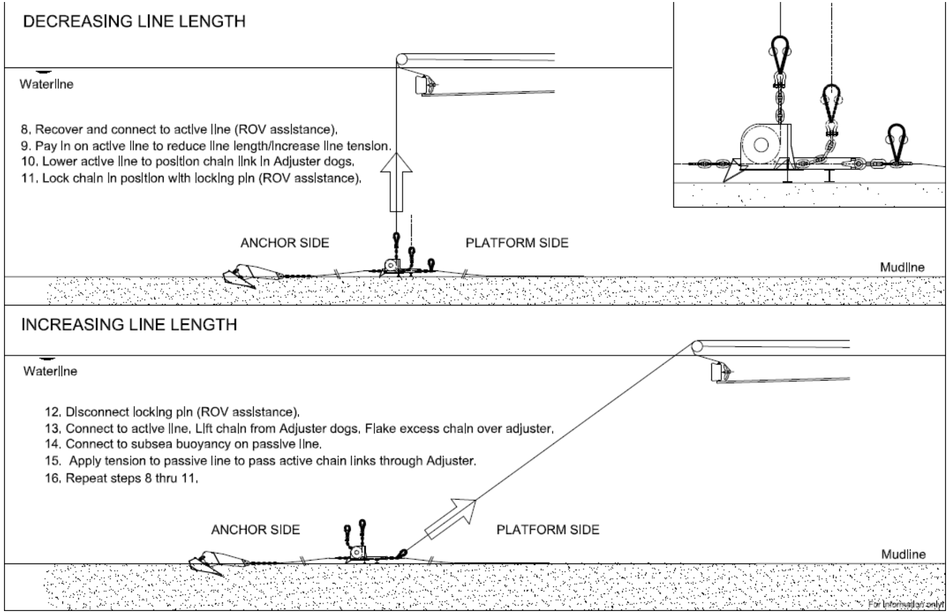
Tools to facilitate easy and cheap connection-disconnection and pre-tensioning

- **Stevadjuster® / inline pre-tensioner® allows winchless platforms reducing the offshore installation and platform/floater costs!! The tool is improved for long term use for line connection, disconnection, length adjustments and for line pre-tensioning**





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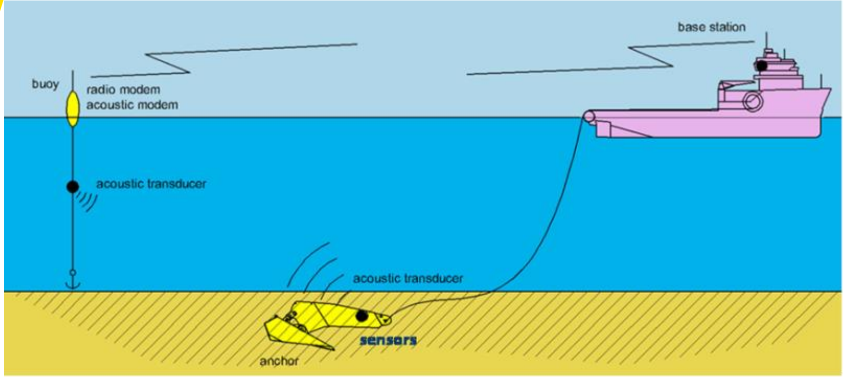
Tracking tools

- **Stevtrack® and ADAPS® developed for monitoring the anchor position and orientation as well as the tension at the anchor and anchor penetration-drag**



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Cost of moorings and offshore installations: from demos to farm scale developments

- The cost estimates for mooring system+offshore installation lie between 13% - 29% of the CAPEX+OPEX (e.g.Bearing Point, Carbon Trust, DNV)
- The cost of moorings and offshore installation from demo units may not be representative for the farm scale developments.
- Vessel availability, local circumstances, the requirement for special installation tools/aids makes big difference in total costs of offshore mooring installation
- In demo scale developments, depending on unit and location the cost of mooring system+offshore installation varies about 5% to 40% of the CAPEX

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Expected cost reductions in commercial scale developments

- Our studies show that for farm scale developments
  - Increasing the # of platforms (each 3 mooring legs) form 1 to 250 may allow possible cost reductions of 30% to 40% on the total anchor costs
  - Increasing the # of platforms (each 3 mooring legs) form 1 to 500 may allow possible cost reductions of 40% to 50% on the total anchor costs
  - The cost reductions of 5% to 20% is estimated on other mooring elements and offshore installation if the #of platforms increases from 1 to 250 units.
- Further undergoing studies on optimization and industrialization of mooring systems for floating wind by our joint research projects:
  - INFLOW (Industrialization Setup of a Floating Offshore Wind Turbine)
  - GOALI-Multi-Line Anchor System
  - New R&D and demonstrator proposals to EC Horizon 2020

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Conclusions

- Mooring systems for floating WTG technology is ready for farm scale commercial developments
- Moorings with Drag Embedment Anchors (DEAs) offer the most cost effective and easy to install systems
- There is always room for improvements and developments; R&D efforts should continue in parallel to industrialization process
- With increasing number of platforms there are significant cost reductions in the mooring system cost.
- With similar reductions in other cost drivers, the LCOE for floating wind is predicted to go further down

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Thank you for your attention

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