Selecting the Optimal Location for Substations in Floating Wind Projects

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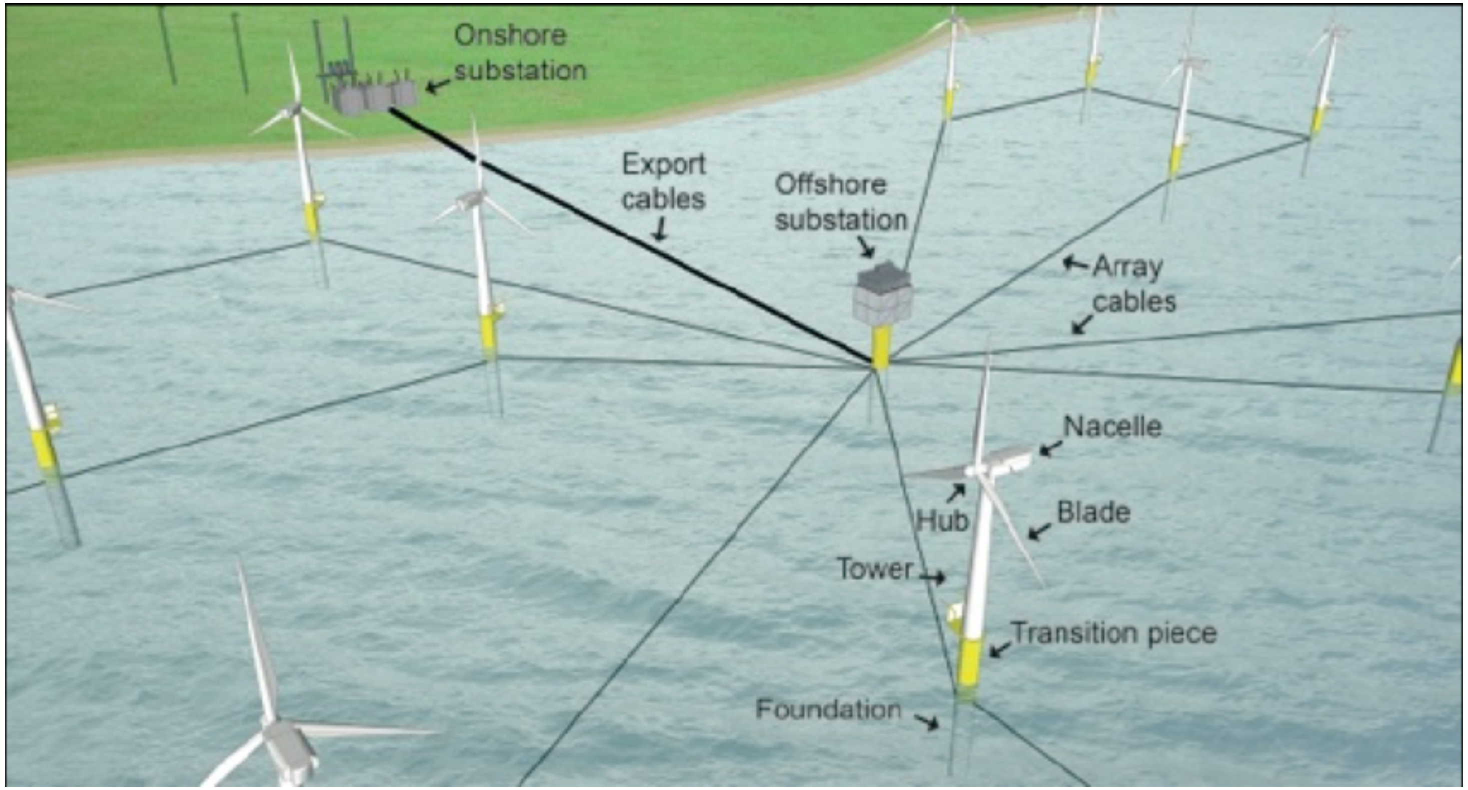
Export (Offshore Transmission) Systems

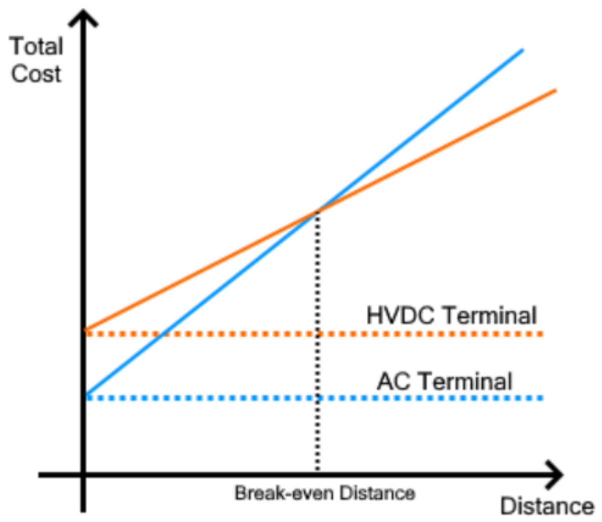
- Numerous Wind turbine generators (WTGs) in a field (an array)
- Array cables to string together WTGs at medium voltage AC
- Strings deliver MV AC power to offshore substation (OSS)
- OSS steps up voltage to transmission
- OSS delivers power to onshore substation (OnSS)
- OnSS delivers power to metered point of interconnection (POI)

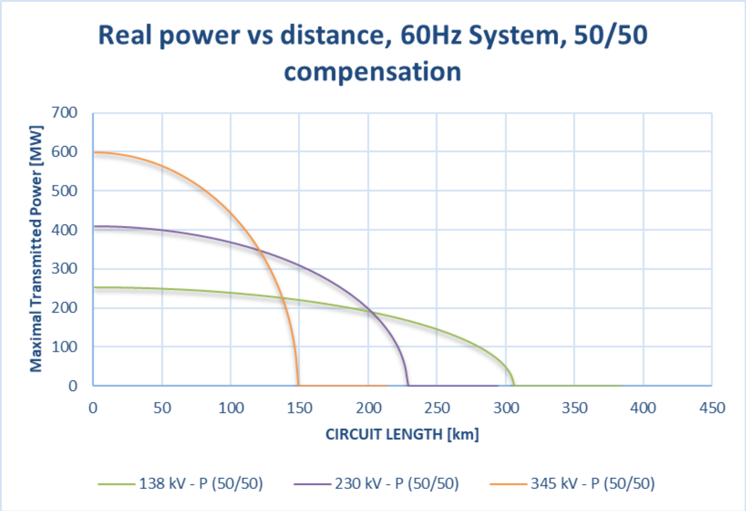


D'Amico, F., Mogre, R., Clarke, S., Lindgreen, A. and Hingley, M., 2015. How purchasing and supply management practices affect the key success factors of an industry: the case of the offshore-wind supply chain, Hull University Business School.

Export (Offshore Transmission) Systems

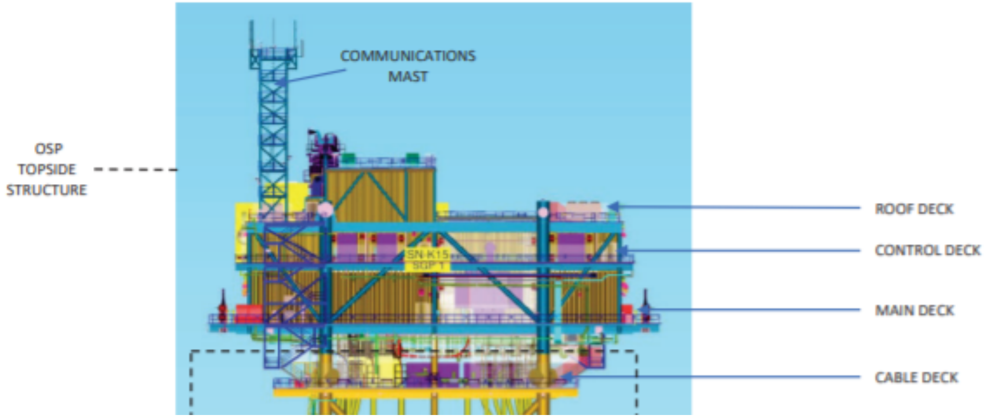
	HVAC	HVDC
Capacity constraint	Reactive power limits transmission capacity	No reactive power – not applicable
Cable system	One three-core subsea export cable per circuit offshore e.g. 1800 mm2 @ 275 kV (plus three single-core cables per circuit onshore)	• Symmetrical monopole: Two single-core cables, e.g. 1600 mm2 @ ± 320 kV • Bipole: Two single-core cables plus one Direct Metallic Return (DMR) cable, e.g 2x 1600 mm2 + 1200 mm2 (DMR)
Voltage range	110 (prior) – 345 kV (nowadays)	±320 - 525 kV
Losses	AC has active and reactive power losses. Losses depend on voltage, size, distance of the cable. Losses associated with onshore equipment (transformers, reactors, harmonic filters).	Only active power transmission, low cable losses compared to AC. No losses in conductor, sheath, armoring. Converter has losses (~1% per converter)





Offshore Substations

- OSS (or OSP) is used to collect power, convert to high voltage for long-distance high-capacity transmission to the onshore grid interconnection
- OSS contains:
  - Oil-insulated equipment (e.g. transformers and reactors) – there are ester oil and mineral oil designs
  - HV, MV switchgears with their control and protection
  - HV, MV, LV cables and routing
  - Non-electrical infrastructure like cranes, tanks, navigation and bunkering system
- Typical weights/dimensions of OSS with references:
  - HVAC export solution – weight up to 5000 MT and size 52x35x20 m for 1,14 GW - Seagreen 1 bottom-fixed)
  - HVDC export solution - weight up to 9000 MT and size 65x40x40 m for 1,24 GW (Dogger Bank A bottom-fixed)

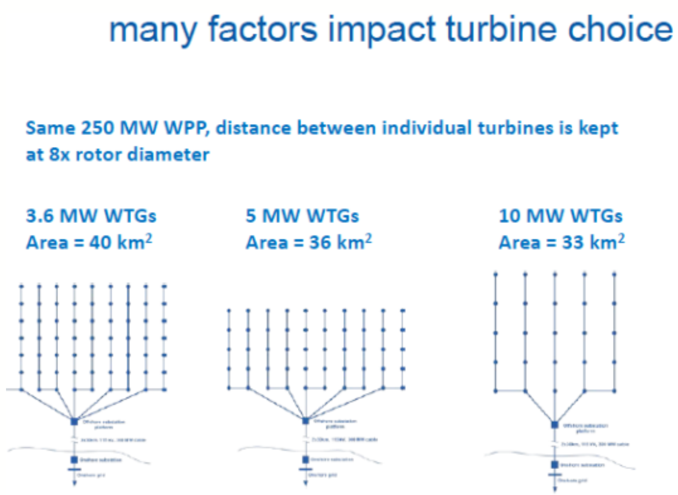


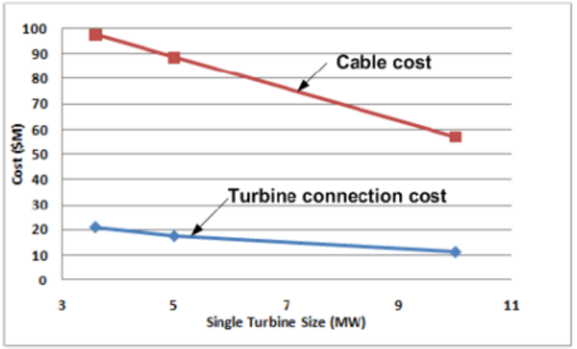
Seegreen phase 1 development, 2020

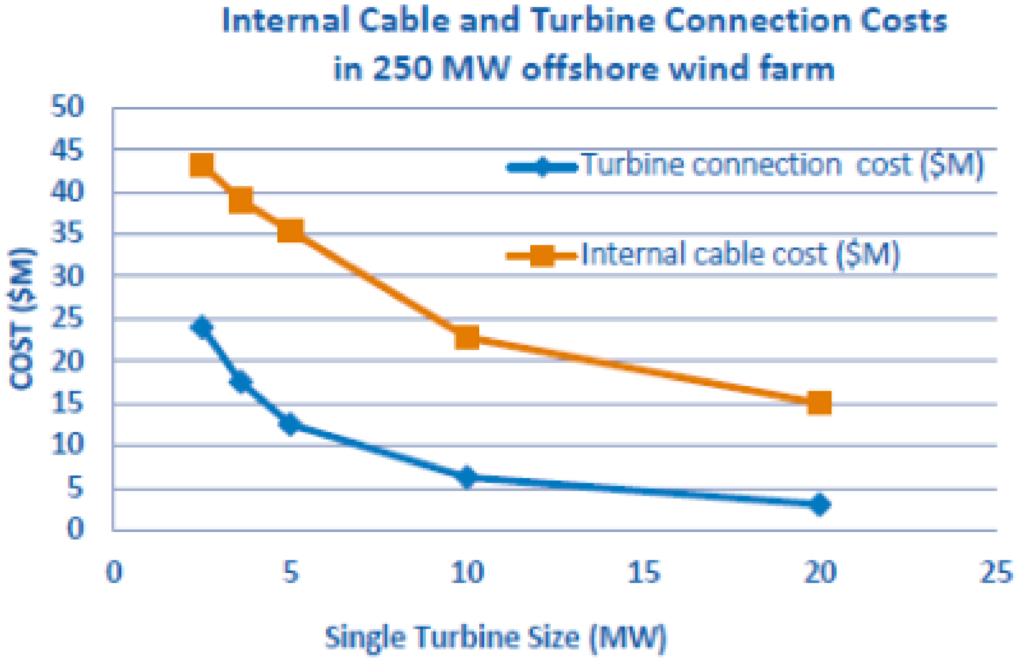
Array Systems

- Array cables AC, 33(34.5) kV or 66(69) kV radial, radial branched, or ring (looped).

- In recent years this is most commonly, 66-69kV array cables arranged radially with one substation exporting via 220-230 kV export cable(s).



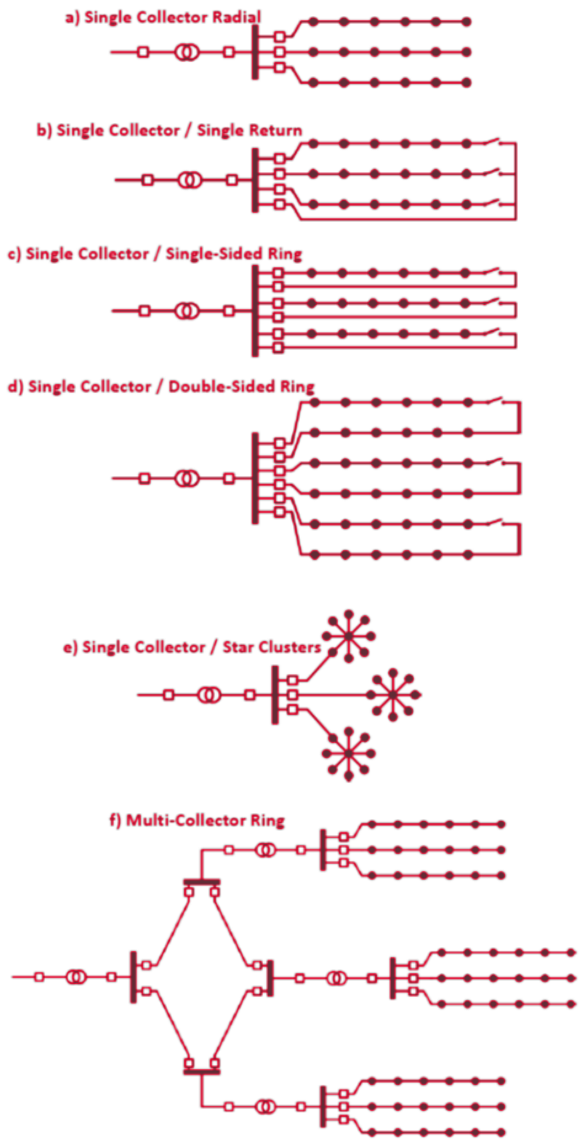




All images from NREL, 2014

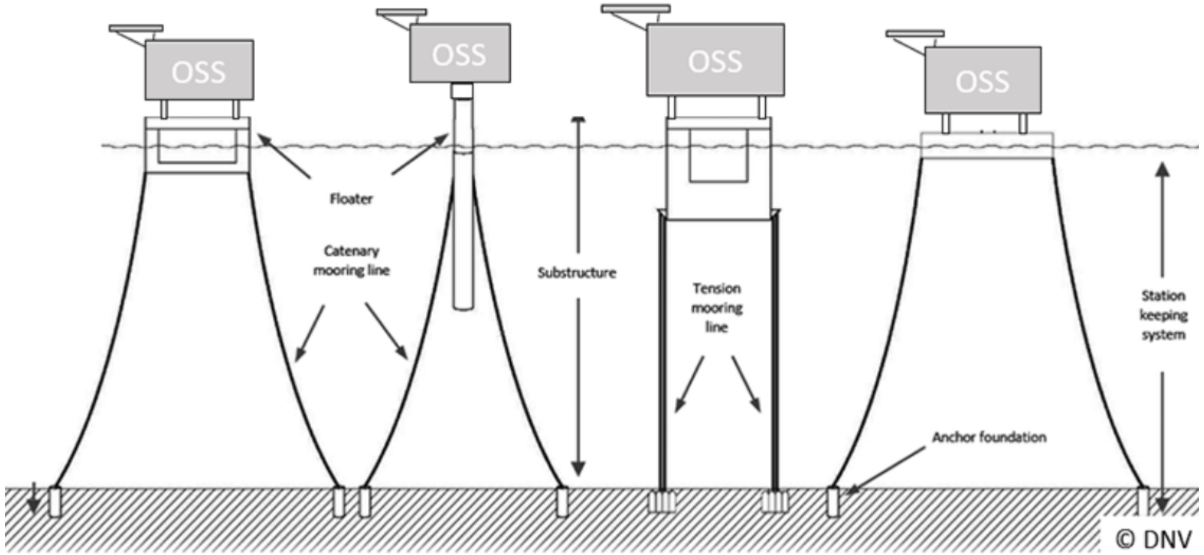
Array Systems

- Layout options:
  - Radial (i.e. daisychain)
  - Radial branched
  - Loop (i.e. ring)
  - Loop-on-loop
  - Others (mostly in academic type studies only)
- Considerations for array cable failure:
  - WTG auxiliary power supply (to run HVAC system, SCADA)
    - Has previously required mobilization of portable diesel generators to WTGs under outage
  - Ability to export power (lost energy due to outage)
- Radial has been most typical in industry so far with a few exceptions only
  - New WTG technology anticipated to provide own auxiliary power in event of outage will strengthen this position for conventional wind farms
- Floating WTGs must consider also the mooring line or ballast failure
  - This could tip the balance in favor of looped arrangements

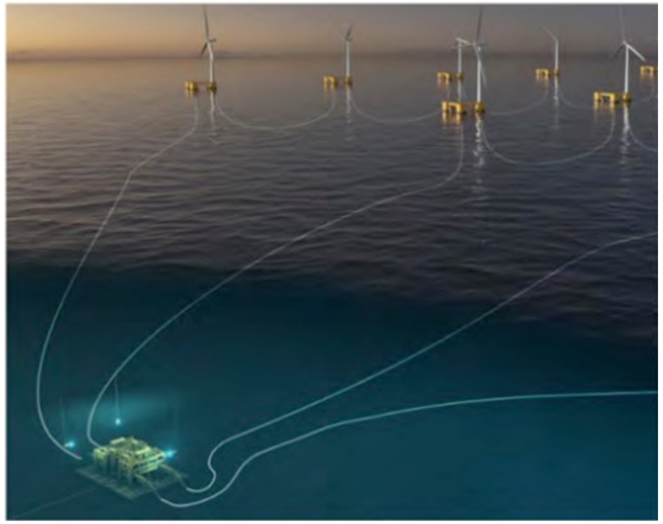


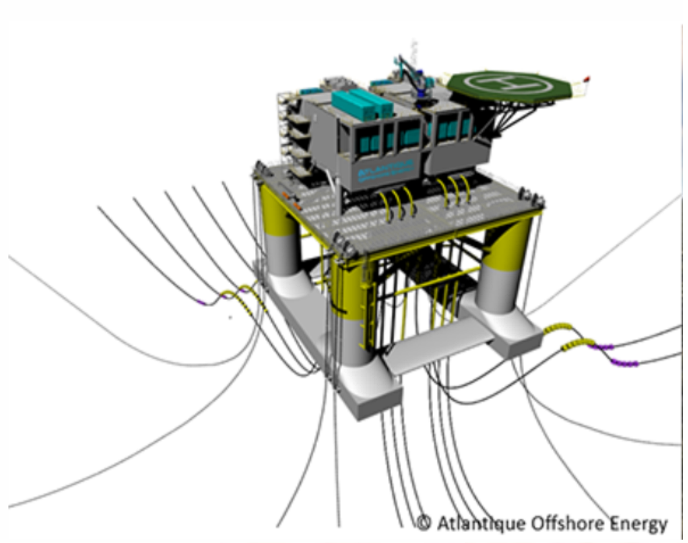
OSS Foundation Options

- Fixed
- Floating
- Subsea



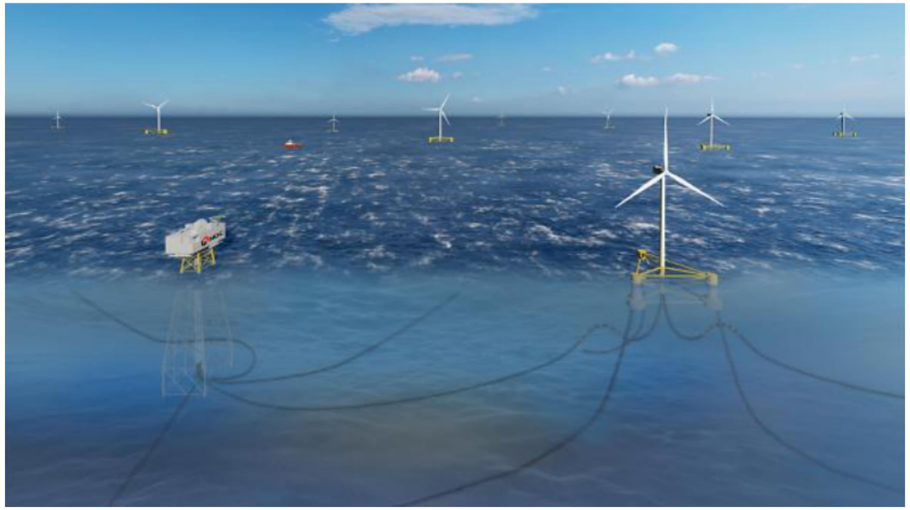
- Ref DnV





Large Type OSS (Multiple Transformers)

- Conservative / conventional solution
  - Feasible for up to 100 m water depth, various types of foundation
  - Would work where water depths for turbines is in similar water depth so array cables length would not be large
    - Example 200 MW Donghae 1 demo farm off Ulsan
  - 1 OSS preferable for deep water (1 foundation only) - minimize foundation costs
  - Multi-approach solutions available with consideration of quantity of circuits, transformers, reactors, additional ancillary equipment



Wikinger offshore substation, Industrias FERRI, 2016

Small type OSS (single transformer)

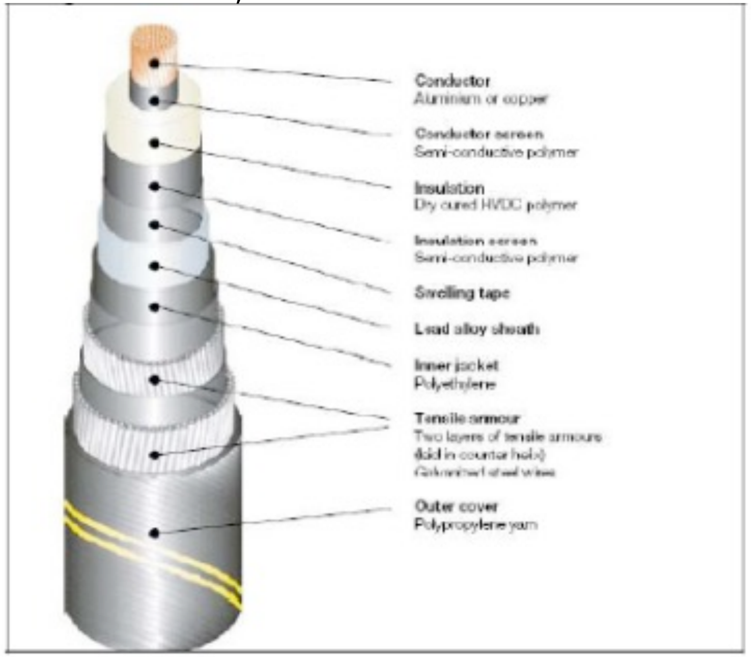
- Smaller modular single transformer OSS
  - Optimized and compact solution
  - Power transfer limited to one transformer (~430 MVA)
  - Quick performance of fabrication
  - Use similar foundation as the WTG
  - Possible to install offshore using the same WTG assembly vessels
  - Favorable for multi-stage OWF developments, assuming 250-400 MW in each

Beatrice offshore wind farm, 2018

Beatrice offshore wind farm, 2018

Floating Substation Options and Challenges

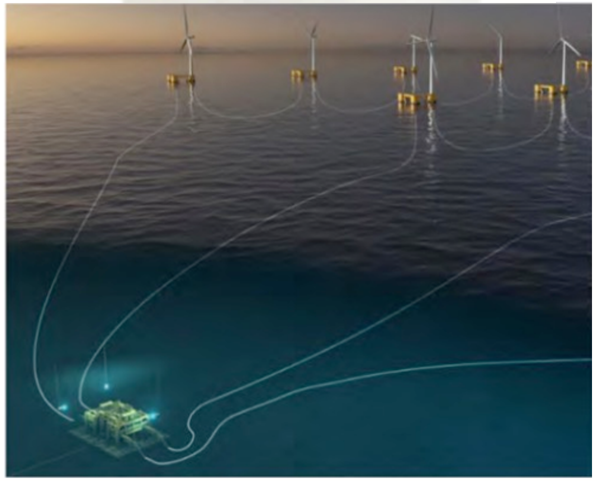
Hitachi ABB, 2021



- Floating Platforms: semisub, barge, spar and TLP (last two are better for cable fatigue).
- Attention to single mode failure.
- Dynamic cable constraints (fatigue of lead sheaths used in HV cables)
  - High voltage export cable currently limited to 72.5 kV class which is too small for commercial wind farm where 110-275 kV AC or 150-525 kV DC likely required.
- Because of no high-power deployments of floating wind over 300-500 MW, Siemens OTM solution is still attractive option emphasizing its power limitation to one transformer and ~430 MVA
- Floating OSS may be completed at quayside then towed towards offshore minimizing any offshore integration and commissioning work.
- Design of transformers and HV GIS for repeated motions and sloshing:
  - Hitachi ABB has lunched transformer portfolio for floating recently

Subsea Substation (HVAC) and Challenges

(ref Eidsvik & Bekhouche OTC Paper)



- Eliminates need for dynamic export cables. 20-25 years maintenance free design required.
- Can be modular and installed separately after quayside integration and commissioning testing. Transformer dry-mated to export cable.
- Components include:
  - Subsea transformer (reactor ?) with double water barrier.
  - Subsea connectors (commercially-available 132 kV qualified to 1100 m water depth. No wet-mate connectors available above 45 kV.
  - Subsea switchgear – currently limited to 36 kV and 125 Amps.
  - Subsea junction boxes can be used to reduce no. of cables coming into substation.

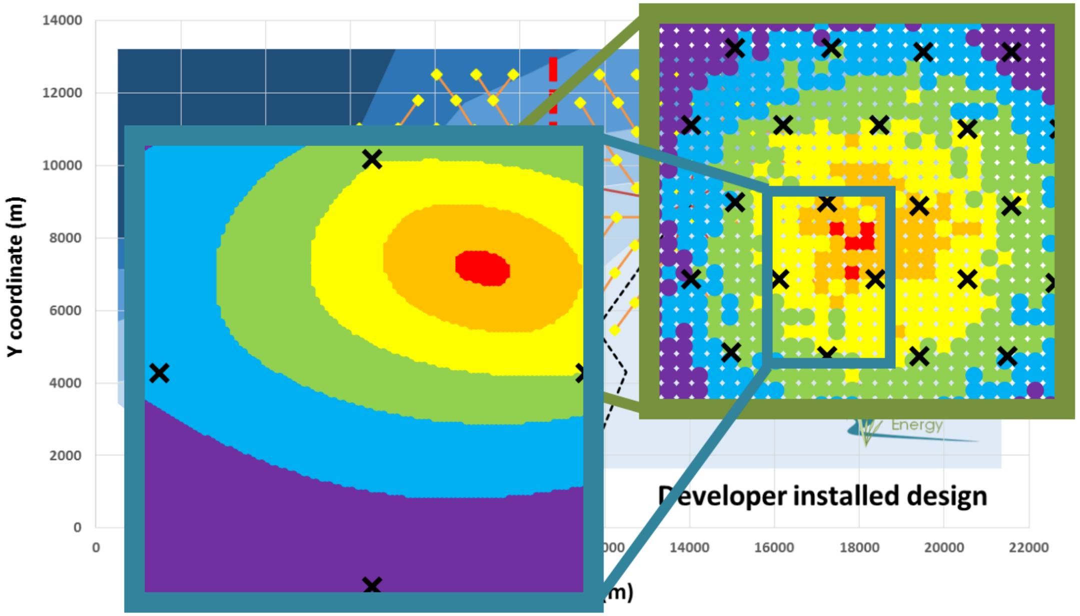
Subsea Substation (HVAC) and Challenges

- No technology gaps up to 33/132 kV transformers, 160 MVA substation
- No technology gaps for 66 kV or 132 kV switchgear, this has to be dry mated
    - No wet mating technology available. HV switchgear equipped with C&P equipment on seabed.
- Technology gap is the dynamic HV cable > 66 kV.
- Subsea reactive power not done to date but should be feasible (similar to transformer)
- Important to increase penetrations / dry terminations to > 132 kV to enable higher export rating
- Remote voltage control challenges
- Maintenance and HSE challenges.

OSS Positioning (1) – Introduction

- OSP positioning is a cost-benefit exercise with many considerations:

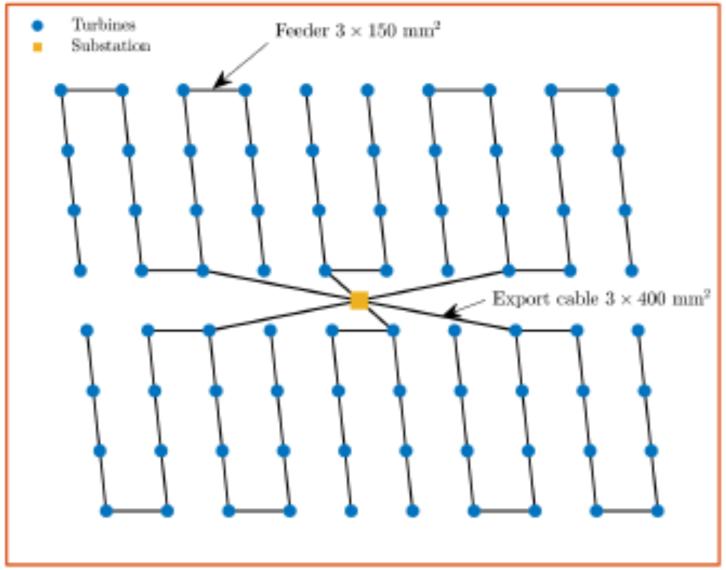
  1. Array vs export cable CAPEX and OPEX
  2. Ground conditions and water depth
  3. Cable routing and moorings

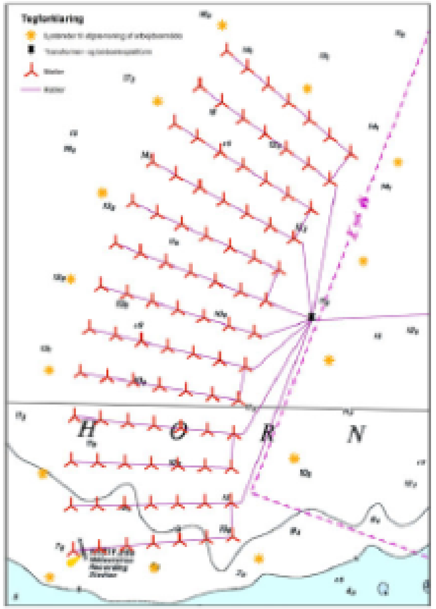


Kinewell Energy, 2021

OSS Positioning (2) – Array vs Export

- Array cable vs export cable
  - Distance to shore
  - Capex
  - Electrical losses
  - Unavailability
- Export cable length considerations
  - Cable thermal limits
    - MW transfer capacity decreases with distance for AC systems because of reactive power
    - Length does not affect DC systems other than increasing losses (increases sending end power)
  - WTG dynamic stability and Fault Ride Through performance
    - WTG dynamic stability influenced by impedance between WTG and grid
    - Export cable length influences this – AC only – study needed to see if shorter or longer is better (shorter export = longer array and vice versa)





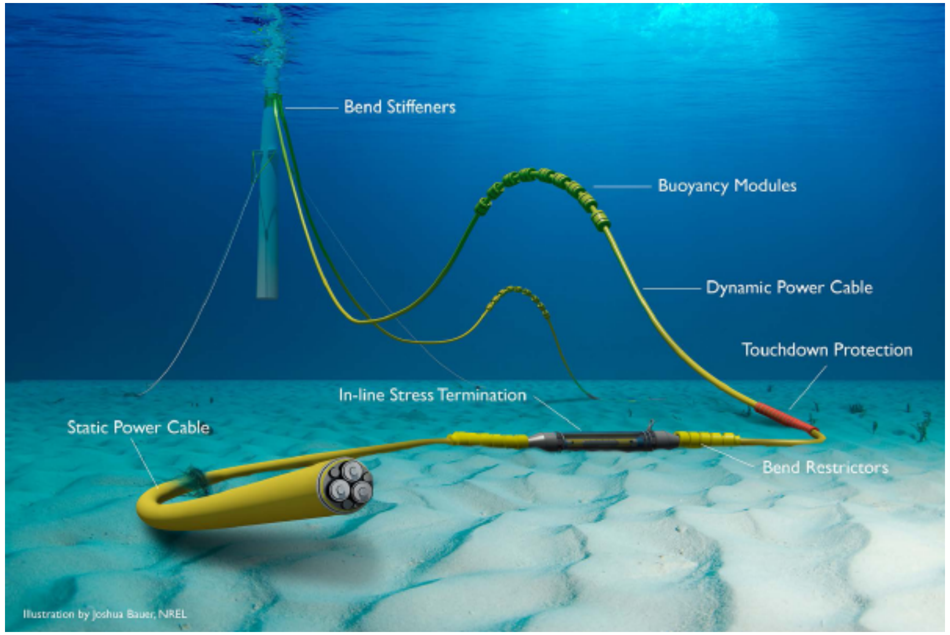
Horns Rev 2

OSS Positioning (3) – Ground conditions and water depth

- Align with selected export cable survey corridors
- May be limited to pre-defined grid positions within the array
- Ground conditions for moorings (floating) or piled (fixed) OSS
  - Substation hull could be governed by heave and excursion performance favoring spars and TLPs (certain soil conditions required for latter). Neither option offers good quayside integration.
- Deeper water has harsher conditions, could affect OSS mooring design and also cable design, mooring cost (think 1000 m WD)
- Cable installation – sand waves, UXO areas, steep slopes, etc.
- Weather conditions are harsher in deeper water – HSE and OEM risks – e.g. during maintenance access and evacuation from floater

OSS Positioning (4) – Cables and moorings

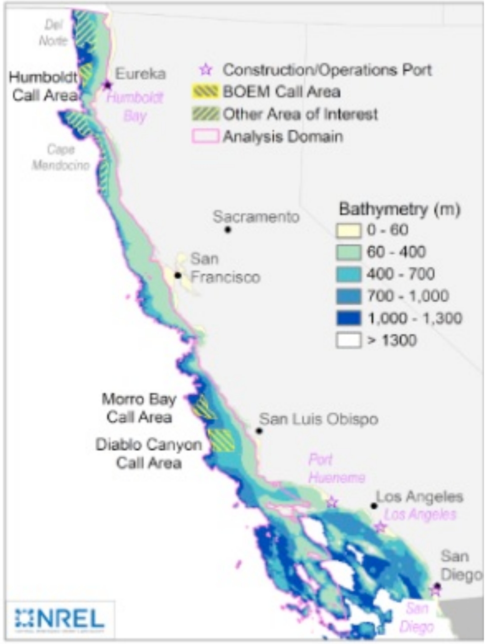
- Cable crossings – both array and export, follow on project phases, with other projects, etc.
- Combination of catenary and synthetic lines to eliminate uplift at anchor and reduce excursions / weight of mooring system
- Mooring line placement and the effect of excursions on array cable layout
- Mooring line layout in relation to array and export cables.
- Export cable constraints: Avoid hard bottom rock substrates, steep slopes or fault lines.



NREL

California

- California some located 20 miles from shore. Water depth > 600m at distances of 25-40 miles from interconnection point. Substation likely founded in similar water depth.
- For 450 MW farm, say 30 x 15 MW. Spacing 1,500-2000m to minimize wake affects and avoid clashes of mooring lines. Inter array cable length > 50 km.



Item	Unit	Site 1: Morro Bay	Site 2: Diablo Canyon	Site 3: Humboldt	Site 4: Cape Mendocino	Site 5: Del Norte
BOEM designation	N/A	Call Area	Call Area	Call Area	N/A	N/A
Size and nameplate capacity potential	mi²	311	557	207	800	850
	km²	806	1,441	536	2,072	2,202
	MW/km²	3	3	3	3	3
	MW	2,419	4,324	1,607	6,216	6,605
Area centroid	Latitude (decimal degrees)	35.56342	35.11532	40.95078	40.13330	41.69974
	Longitude (decimal degrees)	-121.77974	-121.39522	-124.63619	-124.73094	-124.76659
20-year mean wind speed at 150 m (centroid)	m/s	9.80	9.43	10.81	11.60	12.02
Significant wave height	m	2.47	2.47	2.61	2.60	2.61
Distance from site to cable landfall (export cable)	km	43.5	48.7	42.0	29.5	43.7
Assumed distance from cable landfall to point of interconnection	km	5.0	5.0	5.0	5.0	5.0
Construction, operations, and maintenance port	N/A	Port Hueneme	Port Hueneme	Humboldt Bay	Humboldt Bay	Humboldt Bay
Distance from site to port	km	317.7	247.5	55.5	122.4	122.2
Mean water depth	m	1,013	640	832	835	807

NREL 2020

California

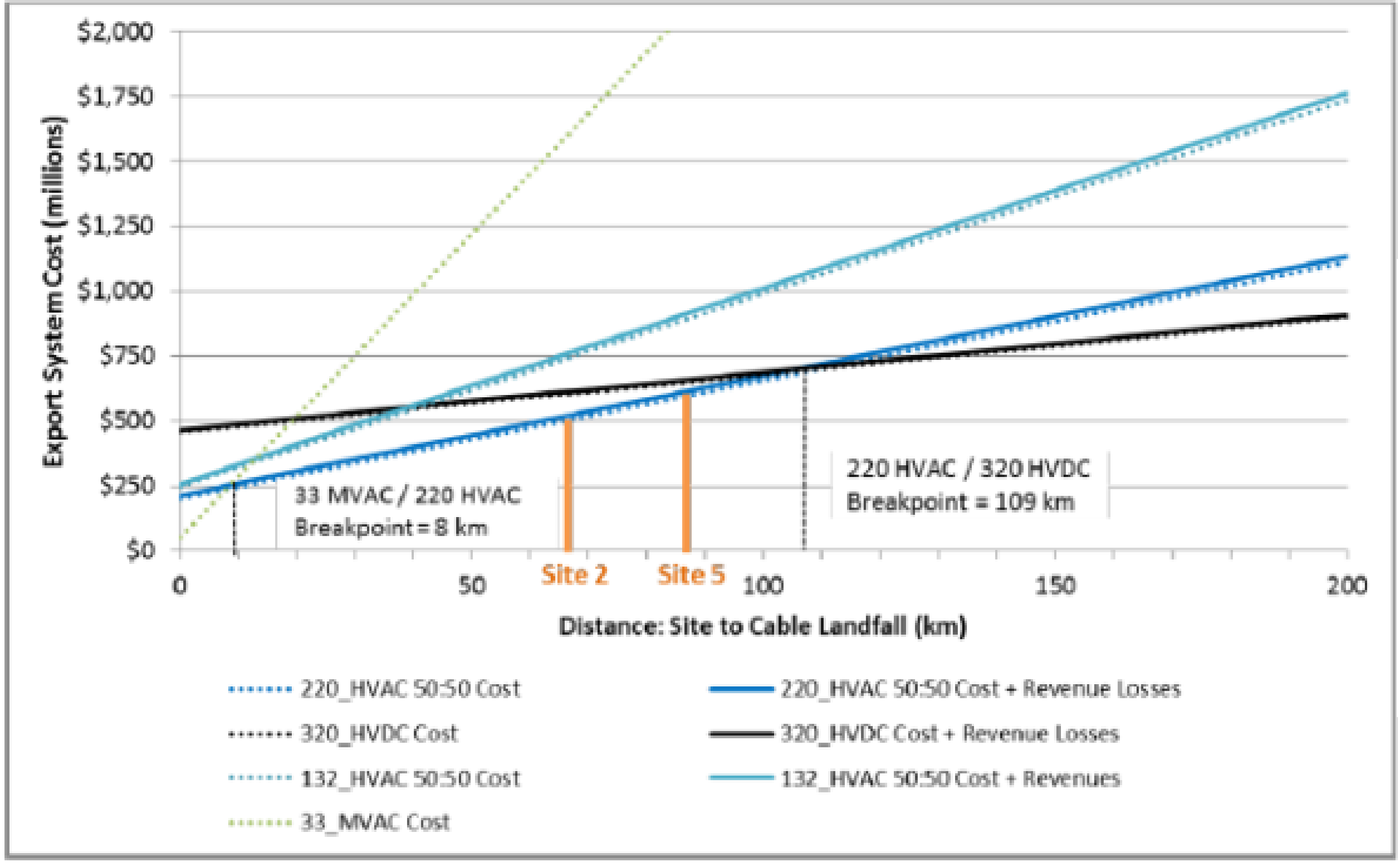


Figure 23. Summary of export system costs with distance from shore showing the two reference sites (Source: Adapted from Beiter et al. [2016])

NREL / BOEM 2016

Typical Array Electrical Cable Layout

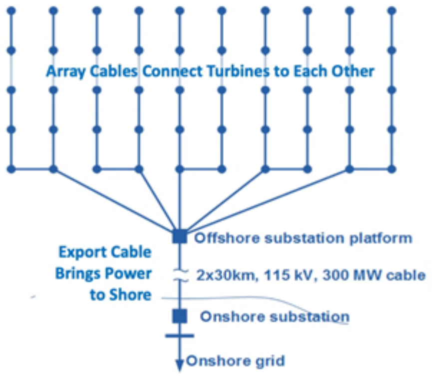


Figure credit: NREL

- Array voltage will soon increase to 66 kilovolts (kV) to lower cost
- Electrical array cable cost increases with turbine spacing but decrease with turbine size
- Exact turbine spacing is a trade-off between wake losses and array cable cost
- Other factors such as navigational safety may play a role

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California Issues with Grid Connection

- Impact on routing on export lines / onshore substation
- Export distances and interconnection present issues
  - Depends on which part of California
  - HVDC type technology likely to be required for most cases

Study Area	Point of Interconnection	Maximum Voltage
Diablo Canyon	Diablo Canyon substation (adjacent to Diablo Canyon power plant)	500 kV
Morro Bay	Morro Bay substation (adjacent to Morro Bay power plant)	230 kV
Cape Mendocino	Fort Bragg substation	60 kV
Humboldt	Humboldt Bay substation (adjacent to Humboldt Bay generating station)	115 kV
Del Norte	Substation in Crescent City	60 kV

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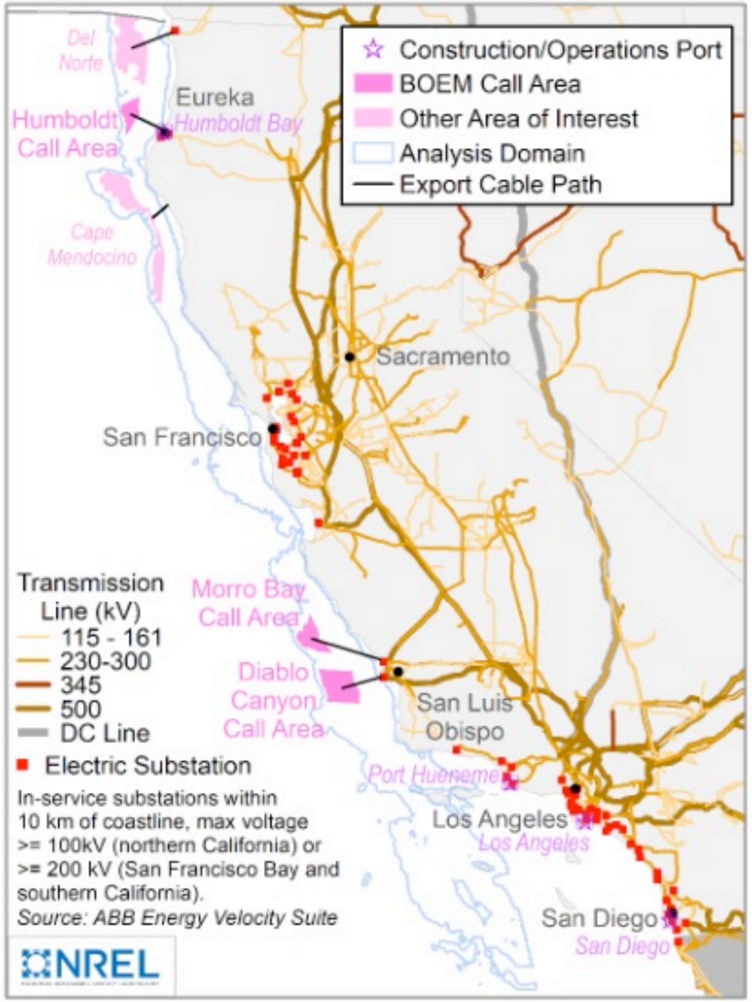

Capital and Installation Costs and Practical Challenges

- Cost of OSS increases with water depth (mooring system, designing for righter watch circle and compliance, weight of system increases weight on hull)
- Lower heave and smaller watch circles solutions cause anchor uplift (expensive to fabricate and install + does not work with all soil conditions)
- Certain types of soil do not lend themselves to drag embedment anchors
- Integration issues: Preference for quayside completion. Spar and likely TLP would require offshore installation with significant cost impact. TLP (depending on design) may not have sufficient stability to be completed before towing.