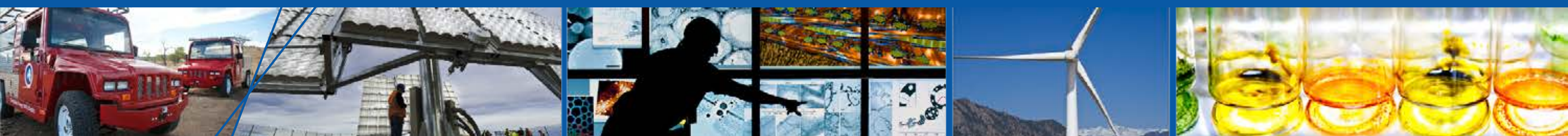
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Offshore Wind Plant Electrical Systems



BOEM Offshore Renewable Energy Workshop

Ian Baring-Gould

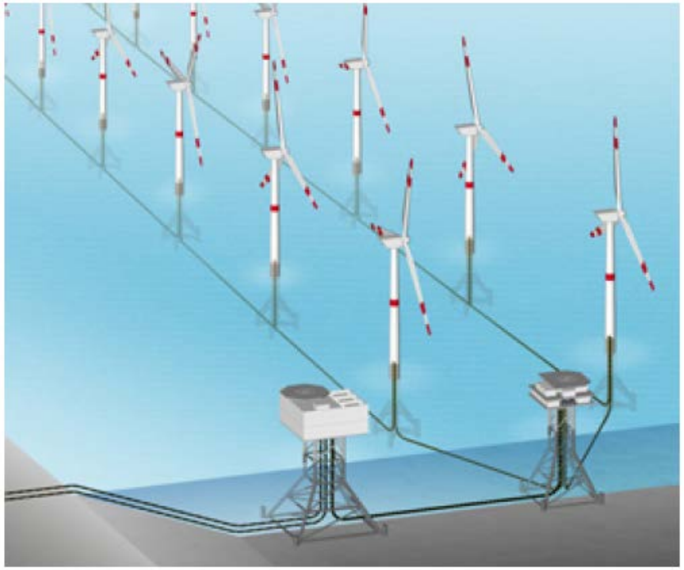
July 29-30, 2014

Major Offshore Wind Farm BOS Components

- Foundations
  - Grounded (monopile, gravity, tripod, etc.)
  - Floating (ballast, mooring, buoyancy stabilizations, etc.)

- Wind farm collector system
  - Inter-turbine Medium Voltage (MV) AC cables (typically 34.5 kV)
  - Substation platform with transformer and electrical equipment
  - Converter platform if High Voltage (HV) DC transmission is used

- Transmission to shore
  - HVAC or HVDC submarine cable
  - Cable landing
  - HVAC or HVDC land cable
  - On-shore converter station for HVDC
  - Onshore substation/interconnection


Source: NSW Submarine Power

BOS = Balance of System or Balance of Station

Key Principles of Electrical Systems

Maintaining a high level of power quality is driven by:

- Regulation / Grid codes
- Low voltage ride-through
- Active frequency and power control
- Reactive power control

Much depends on:

- Configuration
- Type and age of equipment
- System integration and control

Power System Basics:

- Power: Power = Volts * Amps (VA)
- Ohms Law: Volts = Amps * Resistance
- Resistance = electrical resistance * (length of run / area of cable)

Standard AC Transmission Voltage Ratings

	Overhead		Submarine cable technology
	US, (kV)	Europe, (kV)	
MV	34.5	33	Available
HV	69	66	
	115	110	
	230	220	
EHV	345	400	
	500		
	765	750	Not available
UHV	1100	1200	

Balance of Station Land-based – Offshore Differences

BOS technical and economic aspects of **land based wind farms** are well understood, but still need improvements. Optimization tools are available.

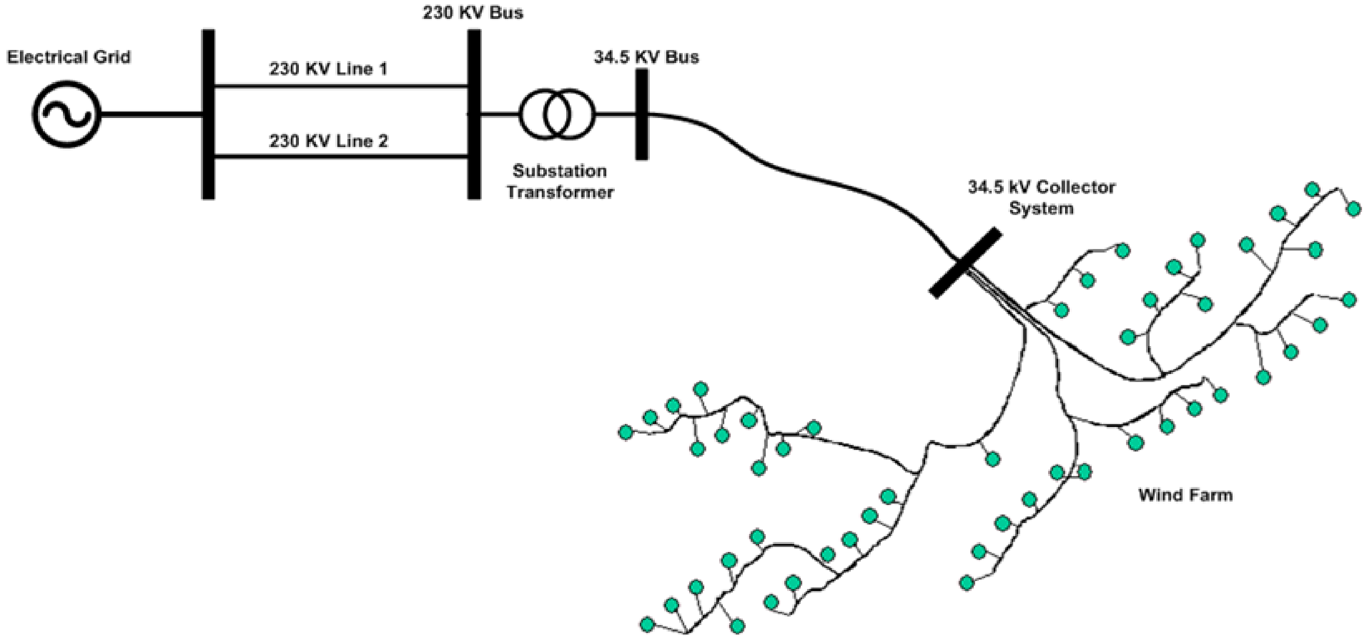
- Some variations in BOS capital cost not related to site's geographical characteristics are still present
- In many cases, such variations can be tracked down to suboptimal design and/or specifications
- Improvements and further standardization, bidding optimization can help
- Need in larger mobile cranes, improved road infrastructure, etc.

Many BOS components for **offshore** still need significant improvements. Valid optimization tools designed specifically for offshore are needed

- Optimize construction and building practices
- Optimize project layout
- Optimize electrical infrastructure / Maximize reliability

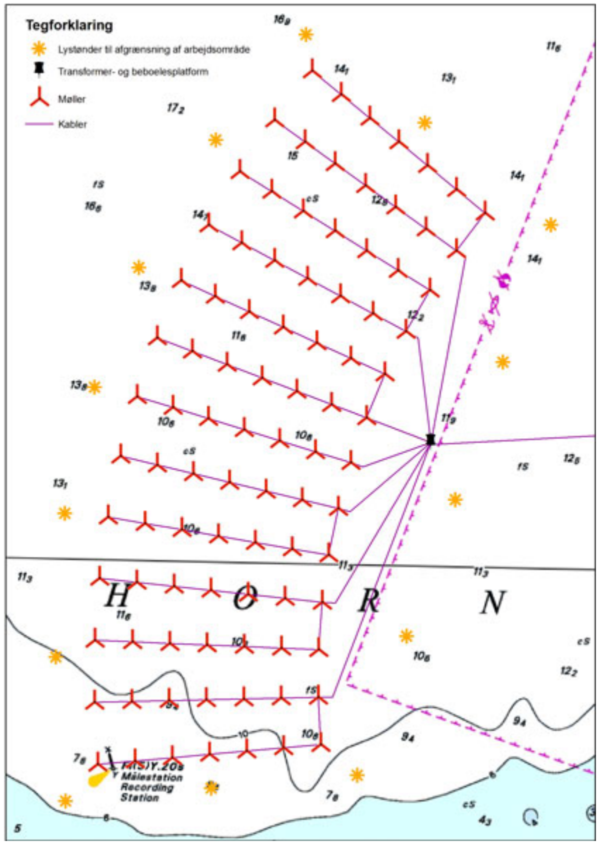
Onshore Plant Cabling – Current State of the Art

- Typical on-shore wind turbine in US generates up to 2.5 MW at 690V
- Stepped up to 34.5kV by pad-mount or nacelle transformer
- MV collector system connected to substation via underground or overhead line
- The voltage is stepped up to transmission level (69 kV or above) by a substation transformer facility
- In North America Wind Power Plants (WPP) are predominantly connected to HV transmission
- Interconnection to distribution systems level is common for only small wind farms



Offshore Plant Cabling – Current State of the Art

Layout of Horns Rev 2 Wind Farm



- Radial designs have been used in European offshore wind farms
- 22-33 kV MV infield cables
- Usually single substation platform (in some cases 2 platforms)
- 132-155 kV export cables
- Spacing between turbines in a row: 5-10 rotor diameters
- Spacing between rows: 7-12 rotor diameters

Source: Dong Energy. http:// www.dongenergy.dk.

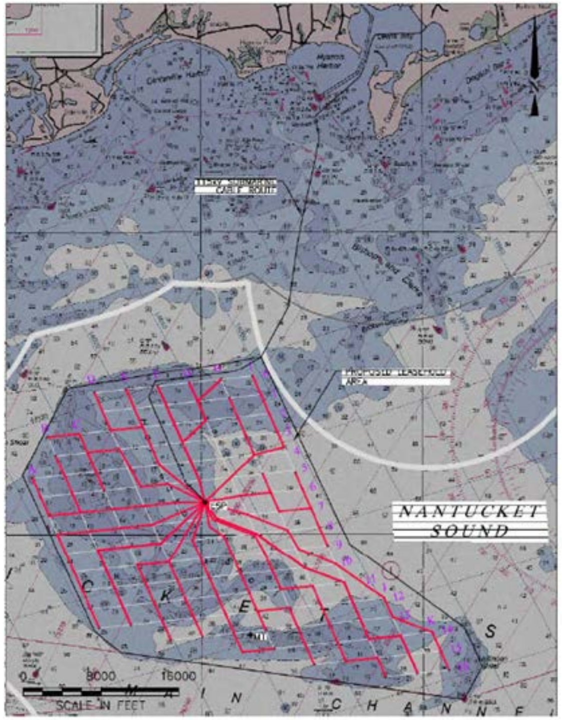
Existing Offshore Wind Farm Characteristics

Wind farm	Total Capacity / Single Turbine (MW)	Diameter / Hub Height (m)	Distance / diameter ratio	Water Depths , (m)	Cable to shore	Cable infield	# of offshore substations
Thanet, UK	300/3	90 / 70	5.55	14 – 23	2x132 kV / 26 km	33 kV / 75 km	1
Greater Gabbard, UK	504 / 3.6	107 / 78	6.1 – 6.77	4 – 37	3x132 kV / 45km	33 kV / 173 km	2
Bard 1, Germany	400 / 5	122 / 90	-	39 – 41	2x155 k V / 125 km	33 kV / 107 km	1
Horns Rev1, Denmark	160 / 2	80 / 70	7.0	6 – 11	150 kV / 21 km	30 kV / 63 km	1
Horns Rev2, Denmark	209 / 2.3	93 / 68	-	9 - 17	150 kV / 42 km	33 kV / 70 km	1
Rodsand 2, Denmark	207 / 2.3	93 / 68	5.4 – 6.4	6 – 12	132 kV / 80 km	33 kV / 75 km	1
Princes Am, Netherlands	120 / 2	80 / 59	6.88	19 – 24	3x150 kV / 29 km	22 kV / 45 km	1
Nysted, Denmark	166 / 2.3	82 / 90	10.5 (5.8)	6 – 9	132 kV / 11 km	33 kV / 48 km	1
Robin Rigg, UK	180 / 3	90 / 80	-	4 - 12	2x132 kV / 12.5 km	33 kV / 42 km	2

Optimized Offshore Plant Cabling

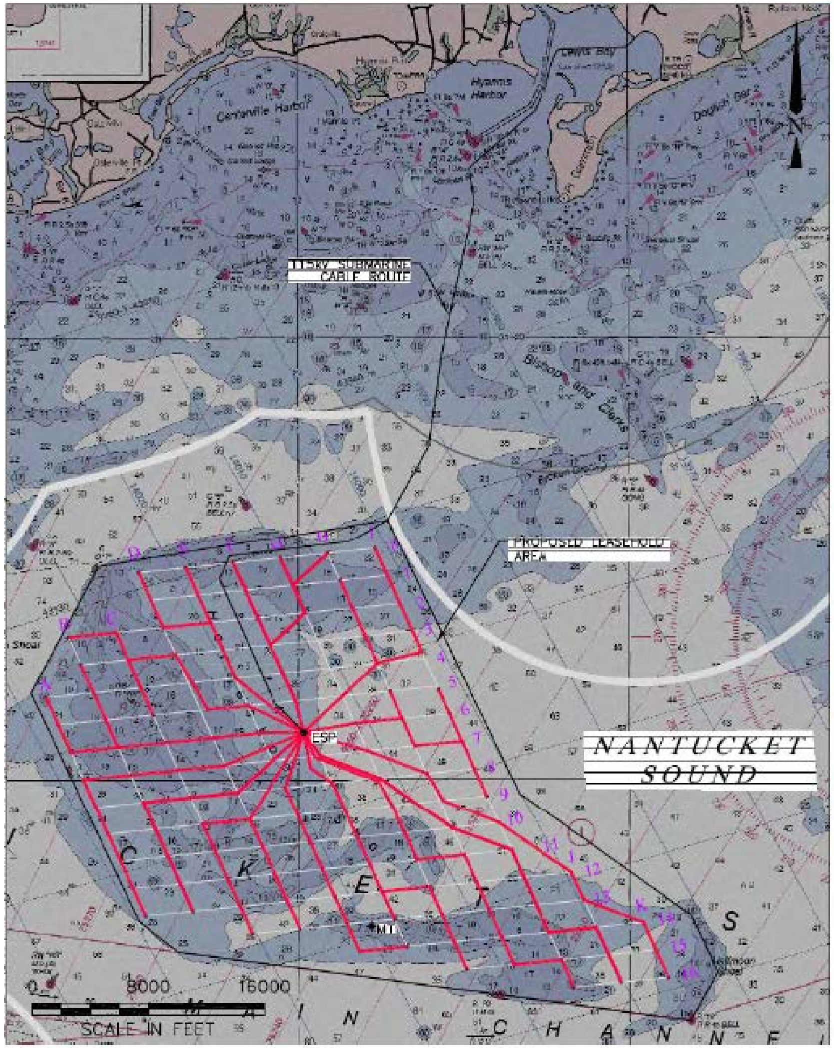
Still needs significant improvements as optimization must consider:

- Site specifics, such as distance to shore, water depths, seabed geology, number & type of wind turbines, construction & maintenance operations
- Turbine spacing, trade-off between increased wake effect if placed too close together and increased infrastructure costs if placed too far apart
- Reliability, dependent on many factors
- Electrical loss minimization
- Where to place substation platform(s)?
- Layout for collector system – trade-off reliability and costs, can run redundant ring configurations, which allow greater reliability but higher costs

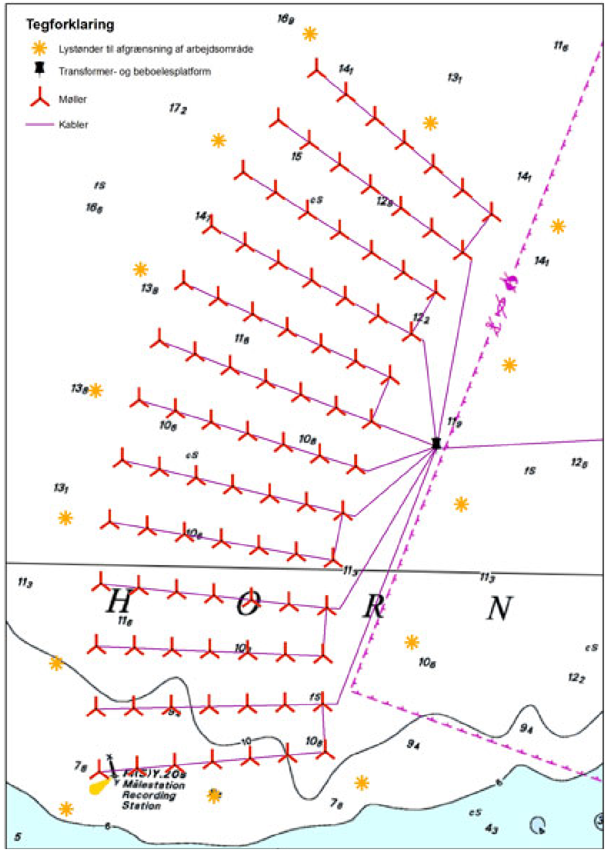


Offshore Layout Examples

Proposed Cape Wind Layout



Layout of Horns Rev 2 Wind Farm

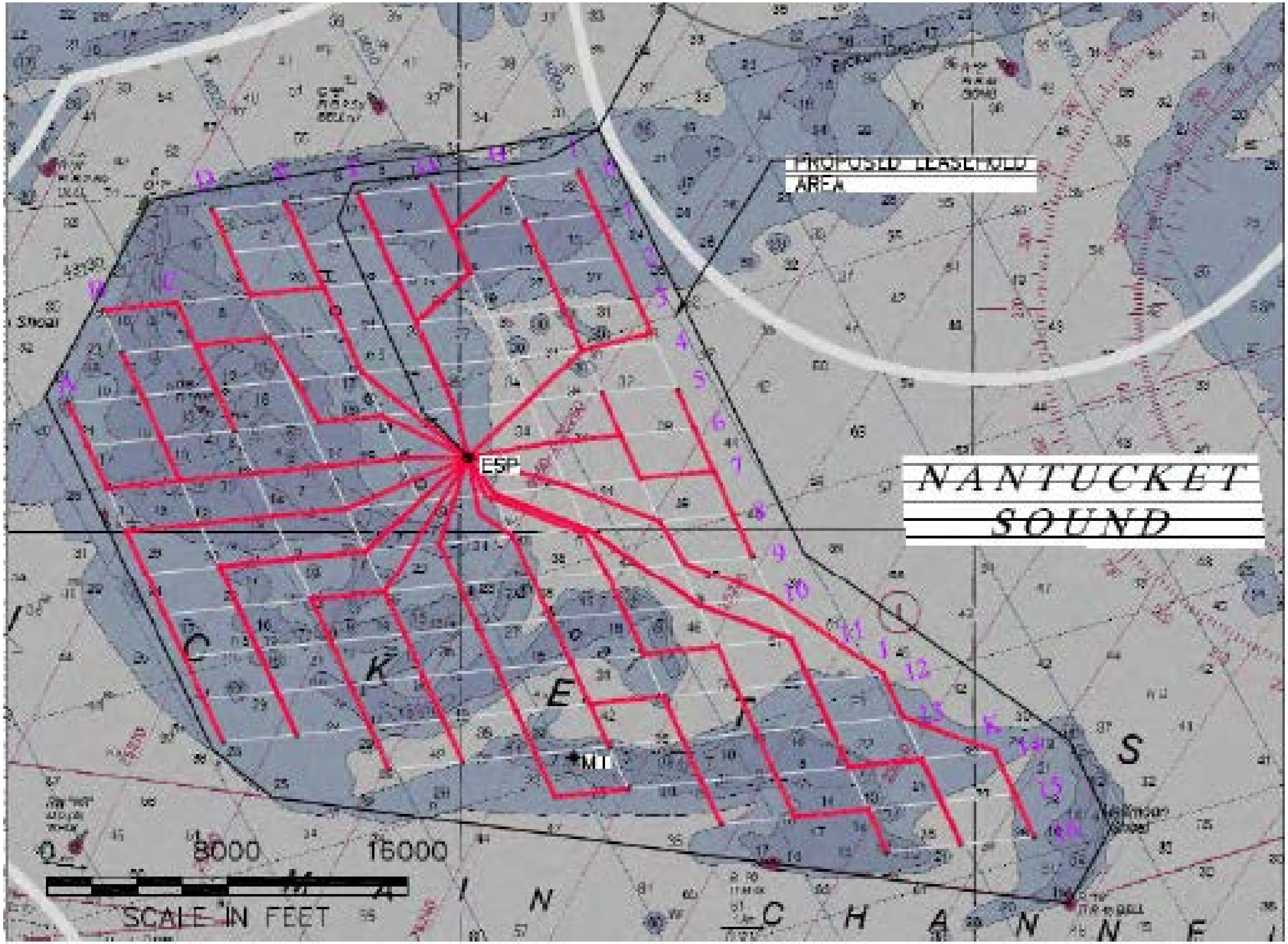


Source: Dong Energy. http:// www.dongenergy.dk.

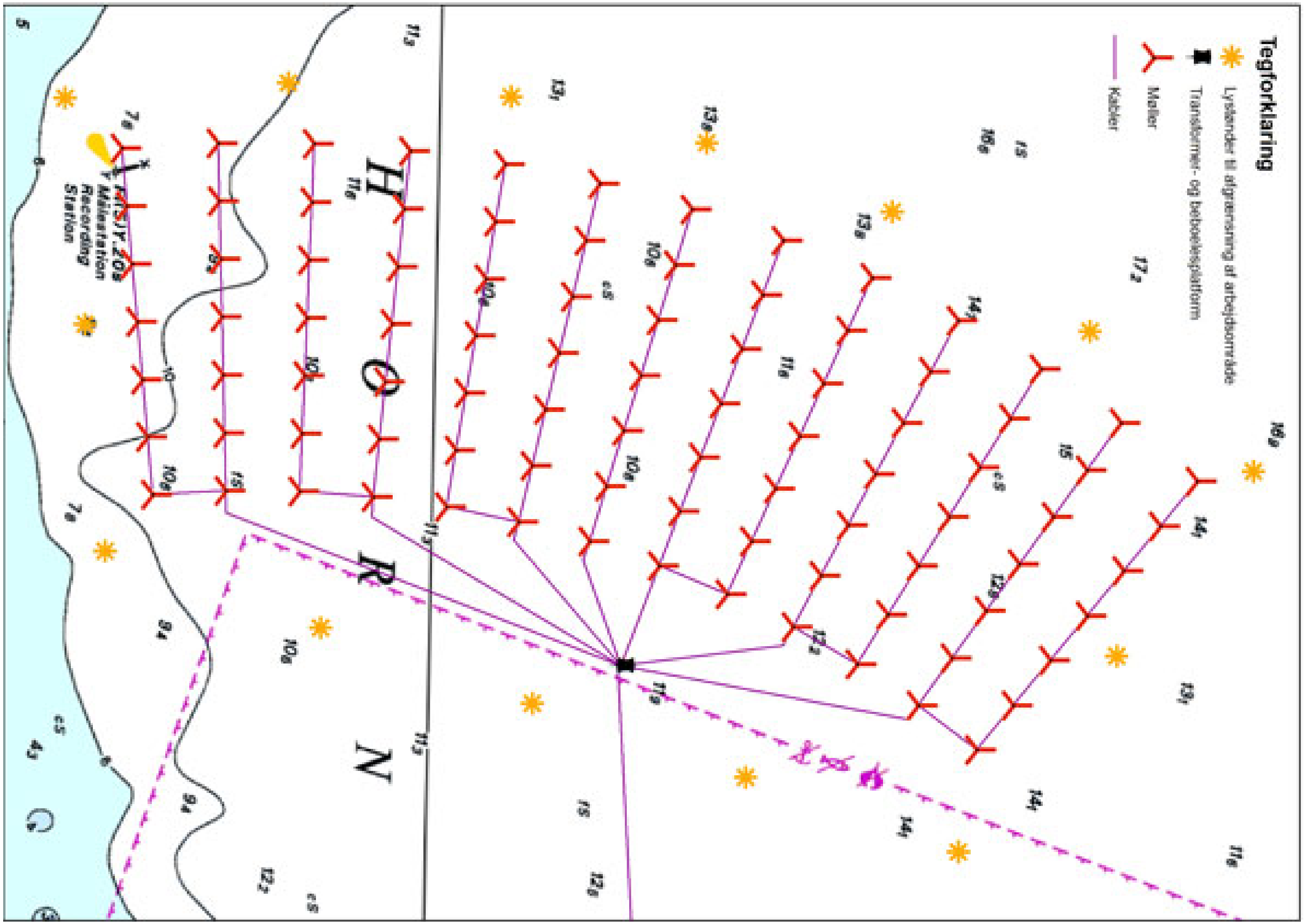
Differences

- Optimization
- Substation location

Proposed Cape Wind Layout



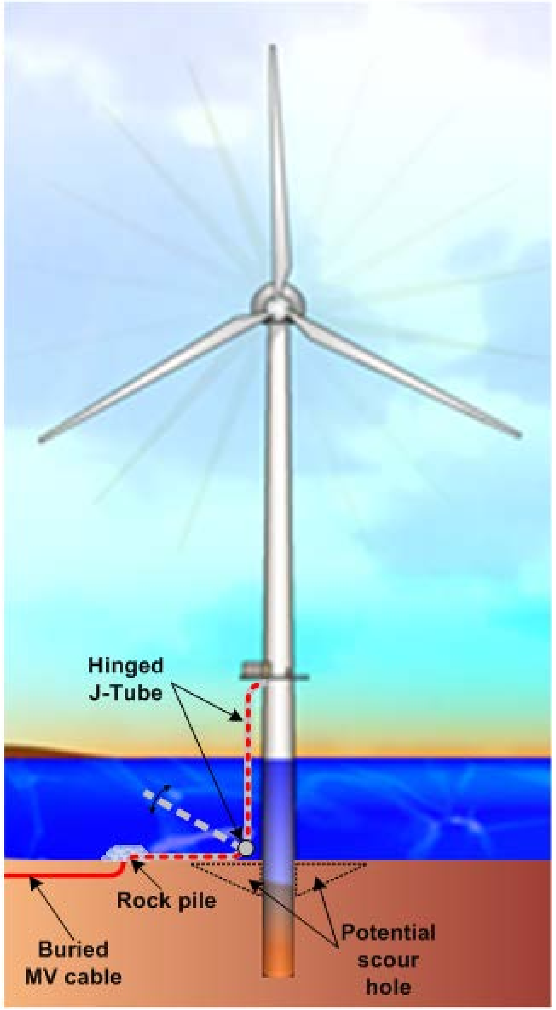
Layout of Horns Rev 2 Wind Farm



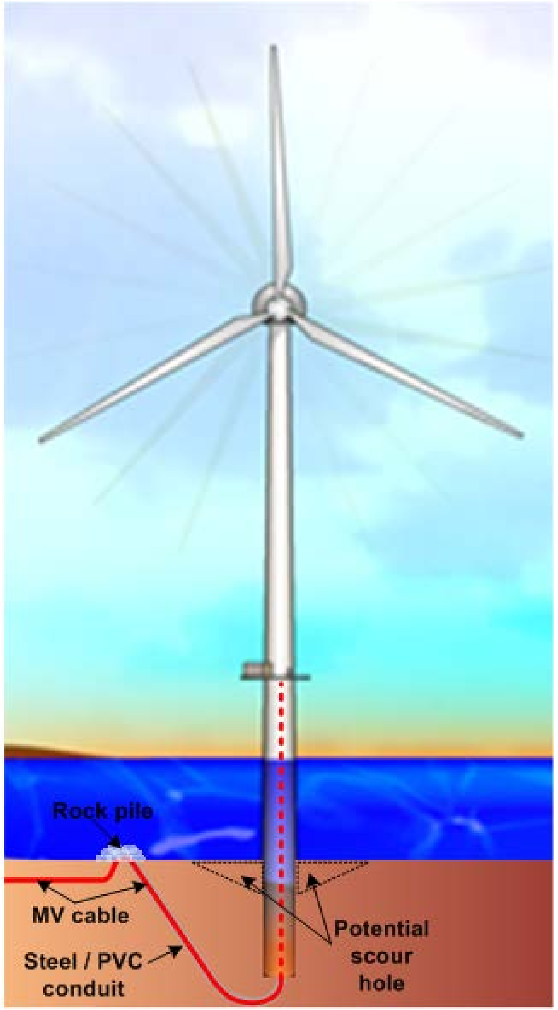
Source: Dong Energy. http:// www.dongenergy.dk.

Fixed Foundation Electrical Connections

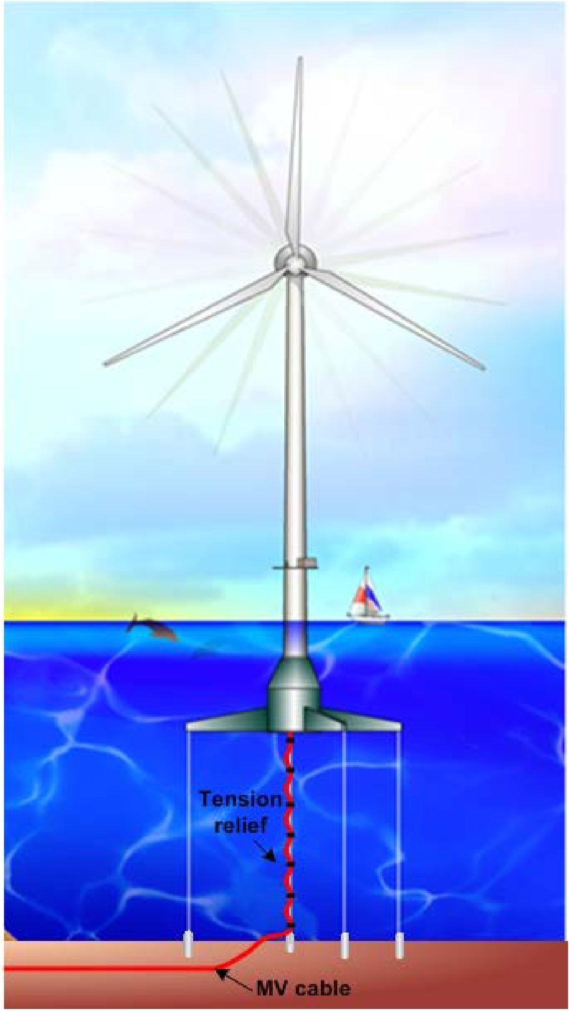
a) J-tube method



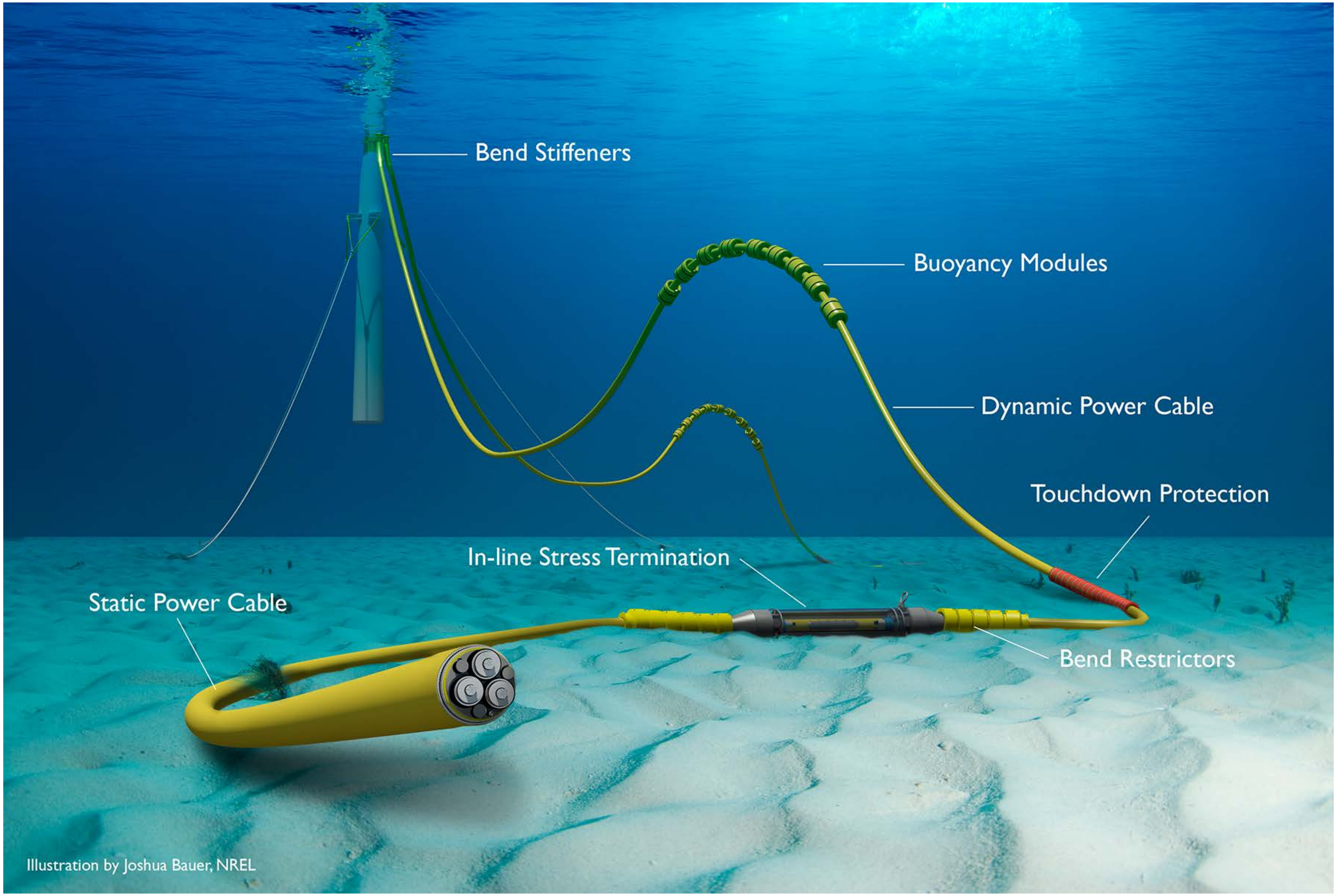
b) Directional drilling method



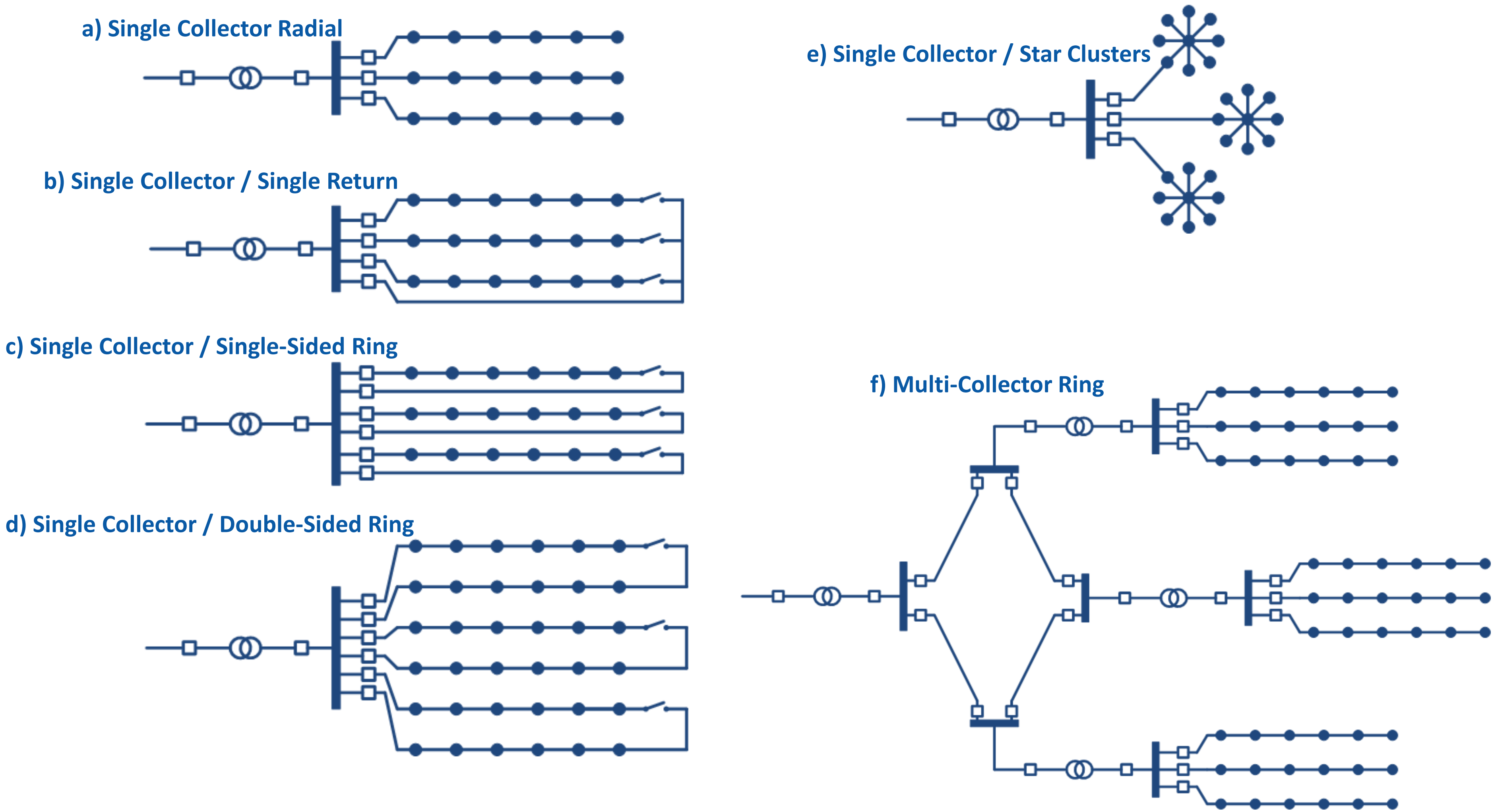
c) Floating platform connection



Floating Electrical Connections

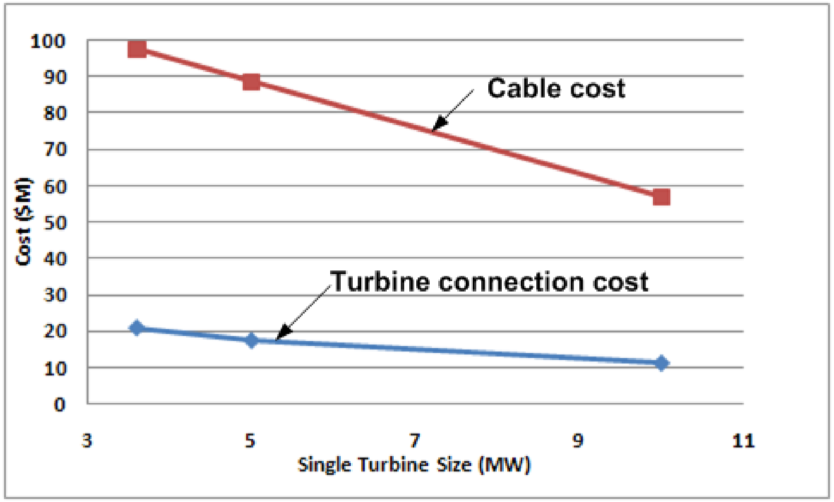


Offshore AC Collector System Options



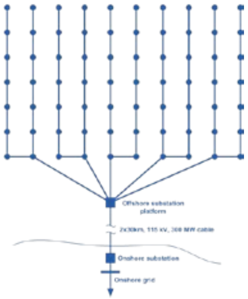
OSW Plant Cabling –Economies of Scale

- Significant cost savings can be achieved in both cabling and turbine connection costs depending on individual turbine size
- Such savings can be up to 5-6% of overall project cost depending on WPP layout and distances between turbines and rows (which is largely impacted by turbine size)
- Note – Array losses and other factors also impact plant layout and many factors impact turbine choice

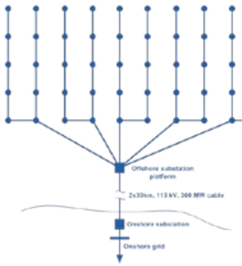


Same 250 MW WPP, distance between individual turbines is kept at 8x rotor diameter

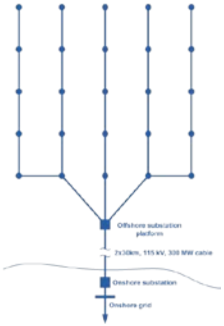
3.6 MW WTGs
Area = 40 km^2



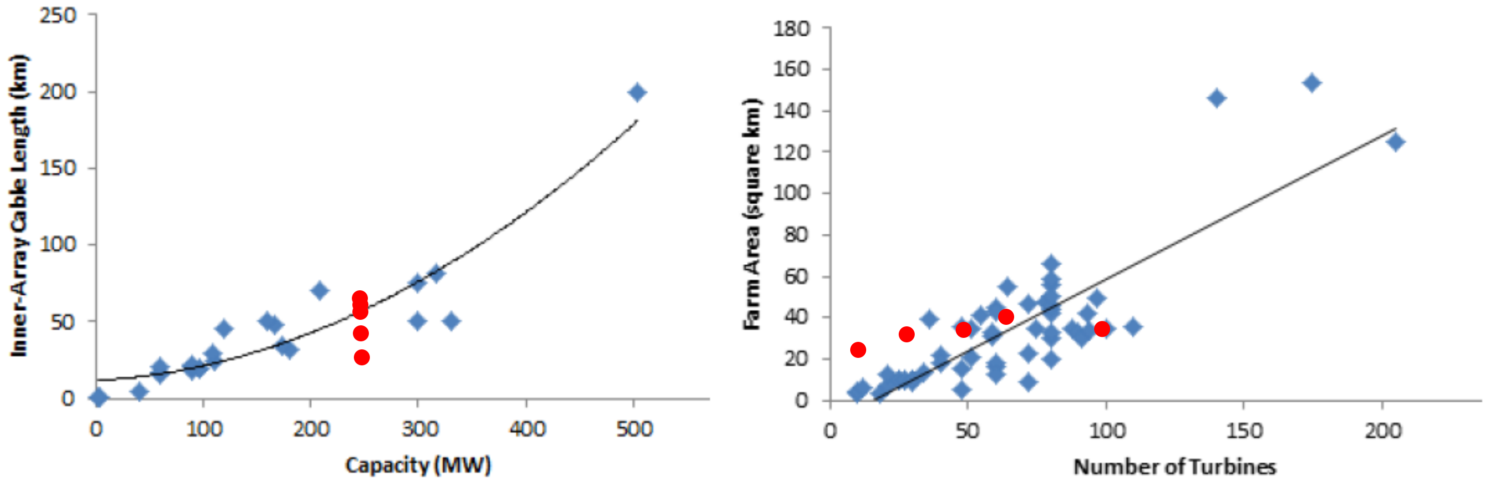
5 MW WTGs
Area = 36 km^2



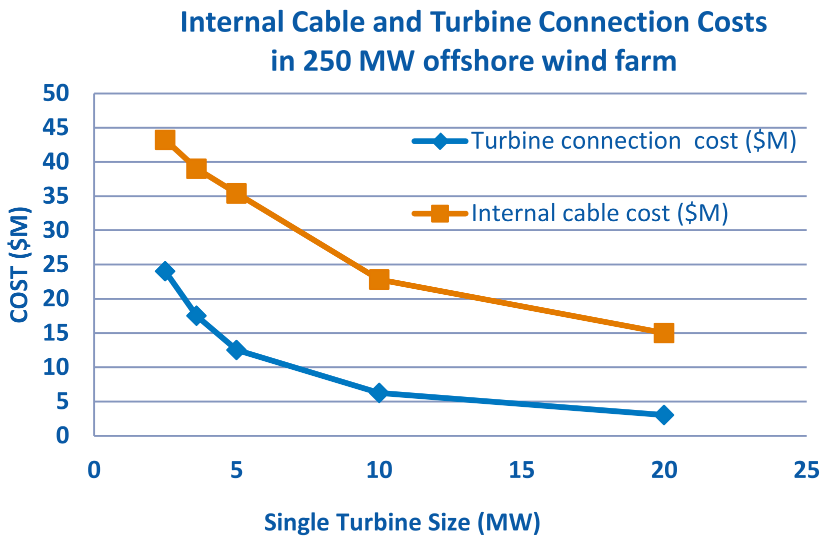
10 MW WTGs
Area = 33 km^2



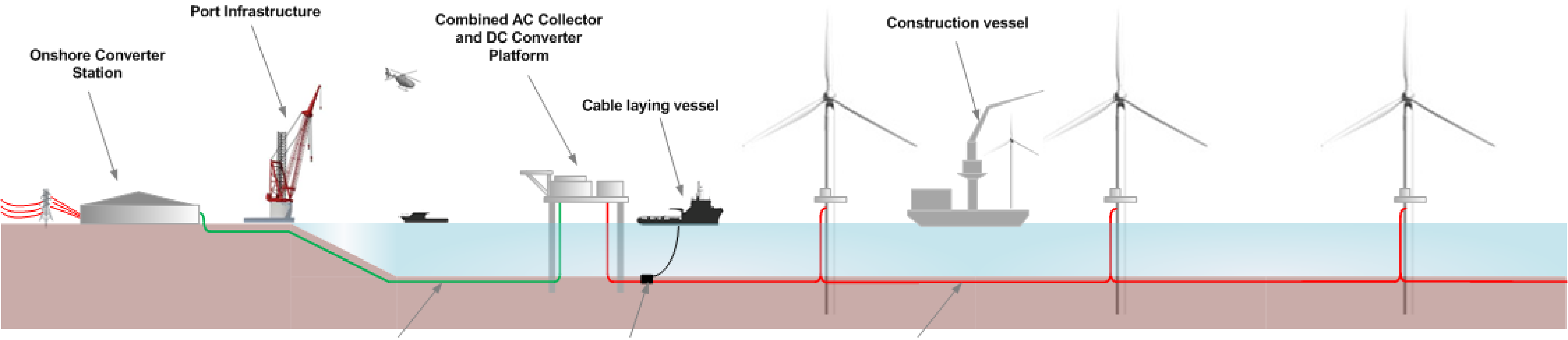
Example Offshore Layouts



Source: Offshore Wind Energy Installation and Decommissioning Cost Estimation in the US Outer Continental Shelf. ERG report, Nov 2010



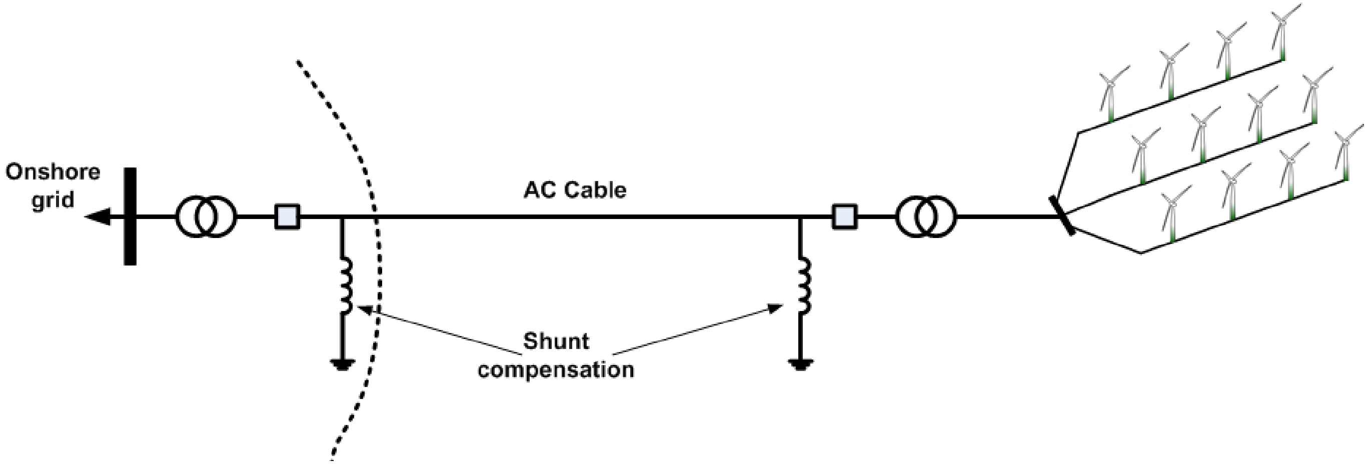
Transmission to Shore

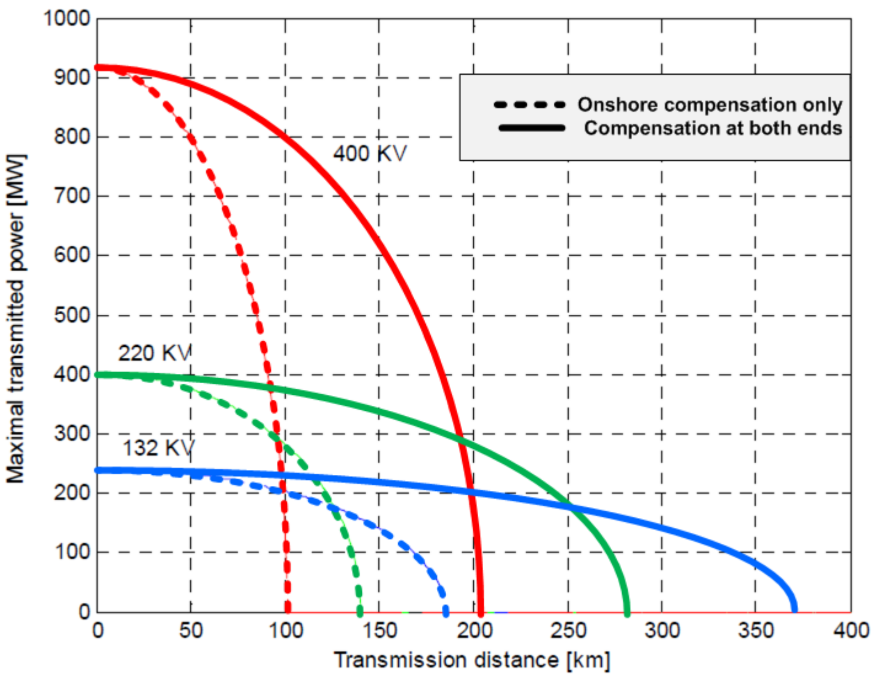


Interconnection from the wind power plant to grid is the next element of the electrical interconnection, including

- Wind plant substation and power converters (HVDC)
- Transmission (Configuration and cable)
    - HVAC, HVDC-classic, HVDC-VSC
- Cable Landing
- Grid substation and power converters (HVDC)

AC Transmission (HVAC)





Source: T. Ackerman – Evaluation of electrical transmission concepts for large offshore wind farms

Transmission Voltage (kV)	Critical Distance (km)
132	370
220	281
400	202

Critical distance is achieved when half of the reactive current produced by the cable is equal to nominal current

HVDC Transmission Technologies

High Voltage Direct Current (HVDC) has been used worldwide to cover long transmission distances or links between grids of different electrical characteristics (HVDC links)

- HVDC terminals have higher capital cost compared to AC substations due to the need for power conversion equipment
- Much lower line losses, decreased cable cost but higher EMF impact
- Two basic topologies of HVDC interconnection – Classic or line commutated and Voltage Source (VSC) or “light”

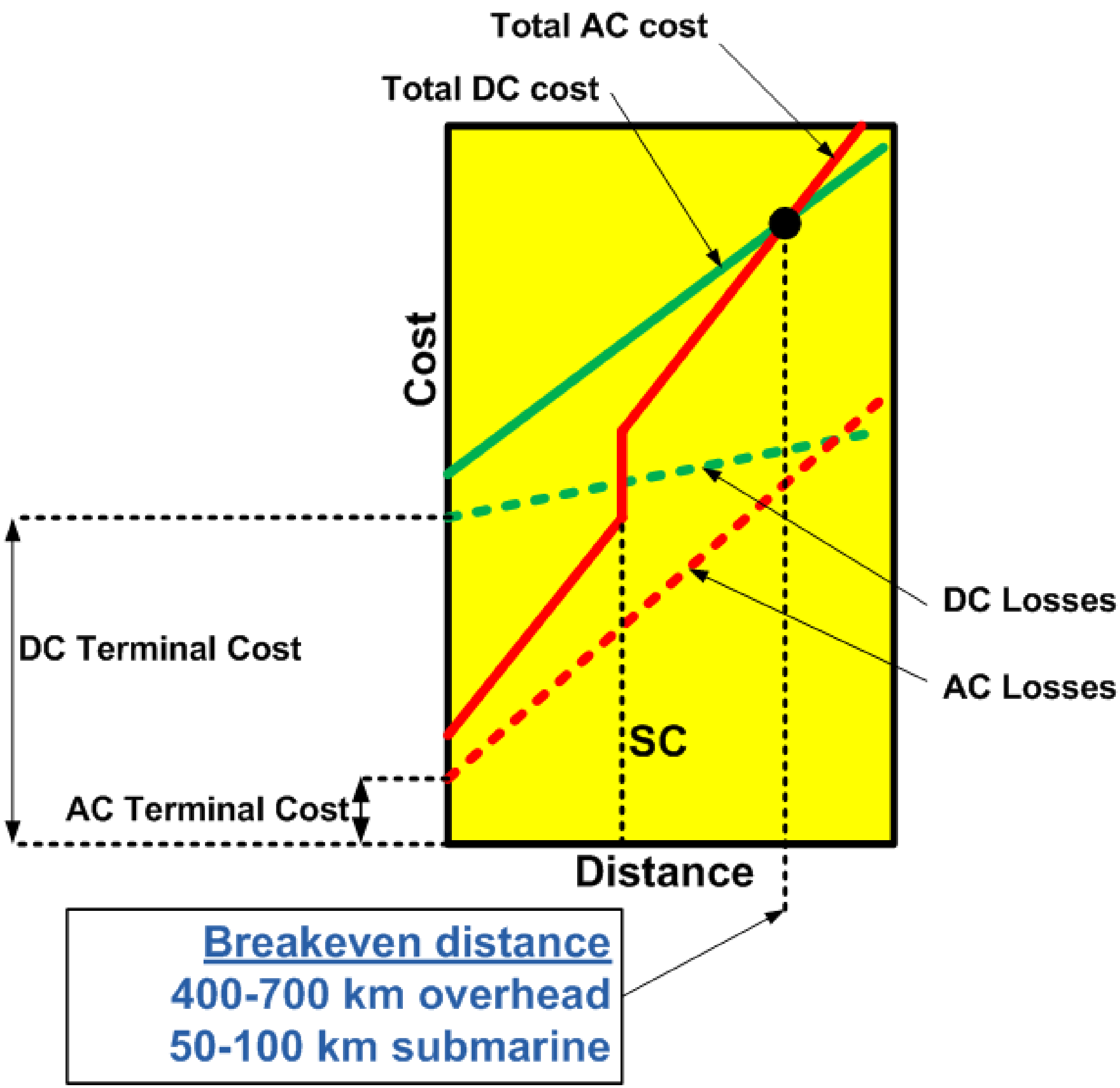
HVDC – Classic

- Many years of operational experience
- Point to point only
- Requires a very firm grid – sensitive to voltage fluctuations
- Dumb system, cannot provide grid support services

HVDV – VSC

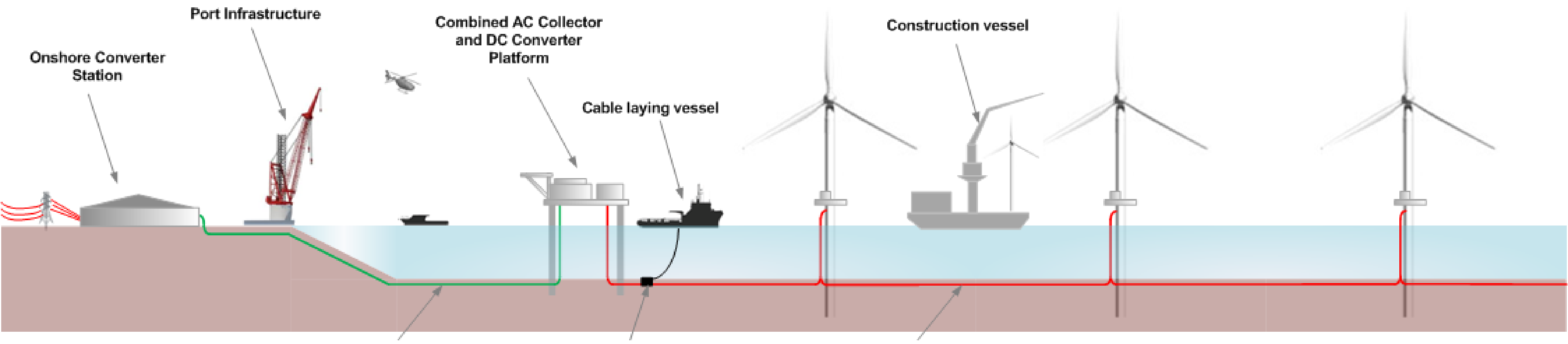
- Very new – lots of products, not a lot of experience
- Multi-point configurations possible
- Allows great flexibility and can even provide expanded grid support beyond wind farm
- Slightly higher cost (but evolving rapidly)

AC vs. DC Transmission



Distance to shore is the most important factor as it impacts cable and installation cost and potential electrical line losses

Cable Landing/Interconnection



Technology:

- Typically use directional drilling to go under beaches and coastal areas
- Place structure on the seafloor where cable goes underground for protection
- Onshore switchyard and grid interconnection space requirements

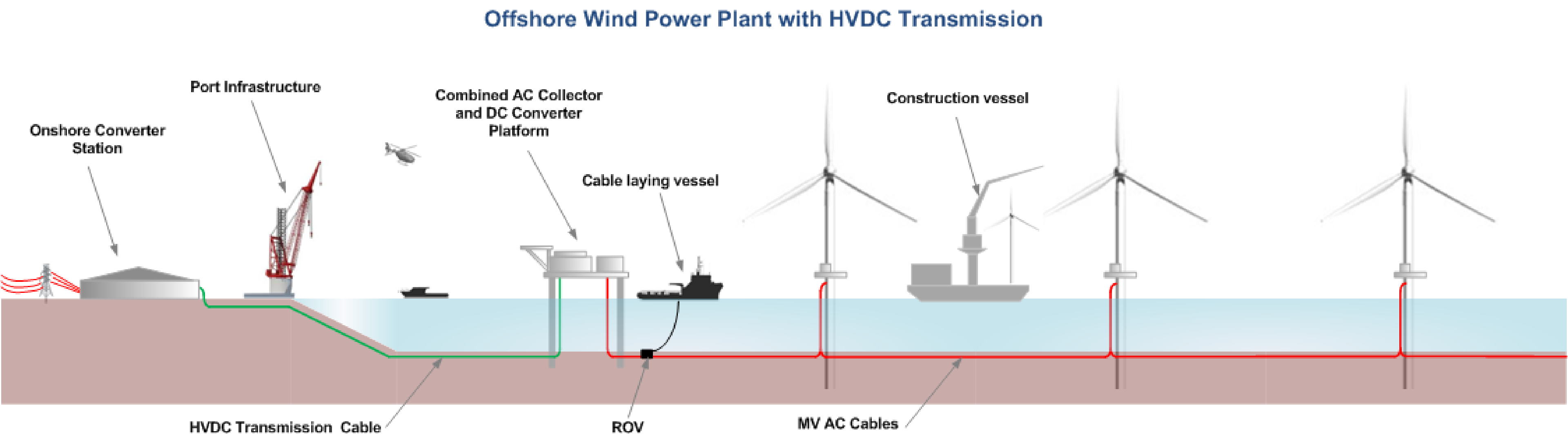
Permitting:

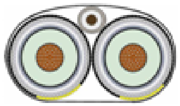
- Pass through state waters – all state permitting required
- Local zoning requirements for installation and interconnection
- FERC interconnection regulations (Same as any power plant)

Cable Landing - What not to do…

Google earth panoramio photo

Electrical Cable





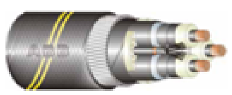
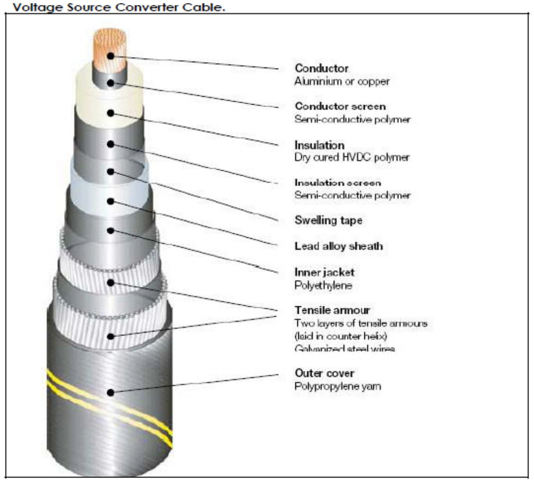
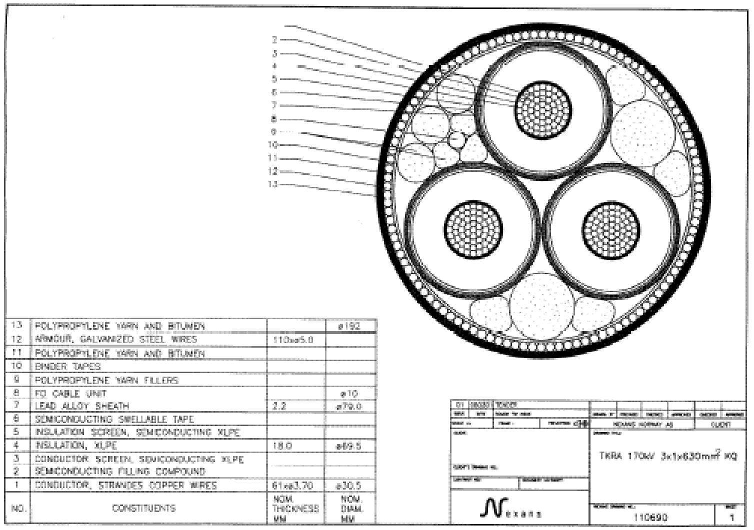


Fig. 5 Typical HVDC subsea cable with double layer armouring for deepwater. Voltage Source Converter Cable.





NO.	CONSTITUENTS	NOM. THICKNESS MM	NOM. DIAM. MM
13	POLYPROPYLENE YARN AND BITUMEN		ø192
12	ARMOUR, GALVANIZED STEEL WIRES	110xø5.0	
11	POLYPROPYLENE YARN AND BITUMEN		
10	BINDER TAPES		
9	POLYPROPYLENE YARN FILLERS		
8	FO CABLE UNIT		ø10
7	LEAD ALLOY SHEATH	2.2	ø79.0
6	SEMICONDUCTING SWELLABLE TAPE		
5	INSULATION SCREEN, SEMICONDUCTING XLPE		
4	INSULATION, XLPE	18.0	ø69.5
3	CONDUCTOR SCREEN, SEMICONDUCTING XLPE		
2	SEMICONDUCTING FILLING COMPOUND		
1	CONDUCTOR, STRANDES COPPER WIRES	61xø3.70	ø30.5

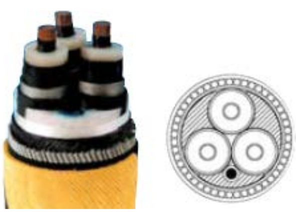
Submarine Cable Technologies

Major submarine cable suppliers: ABB, Prysmian, Nexans, Sumitomo, Fujikura

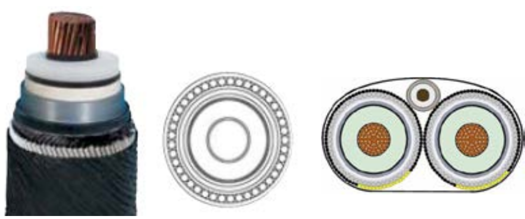
- **Type 1: Self-contained Fluid-Filled (SCFF) – 1000 kVAC, 600 kVDC**
    - **Vancouver Island – 525 kVAC, 1200MW.circuit, 30/8 km**

- **Type 2: Mass-Impregnated (MI) – 69 kVAC, 500 kVDC**
    - **Neptune project (NJ / Long Island)– 500 kVDC, 85/20 km**

- **Type 3: Cross-Linked Polyethylene (XLPE) – 500 kVAC**
    - **Sardinia-Corsica, 150 kVAC, 150 MVA**



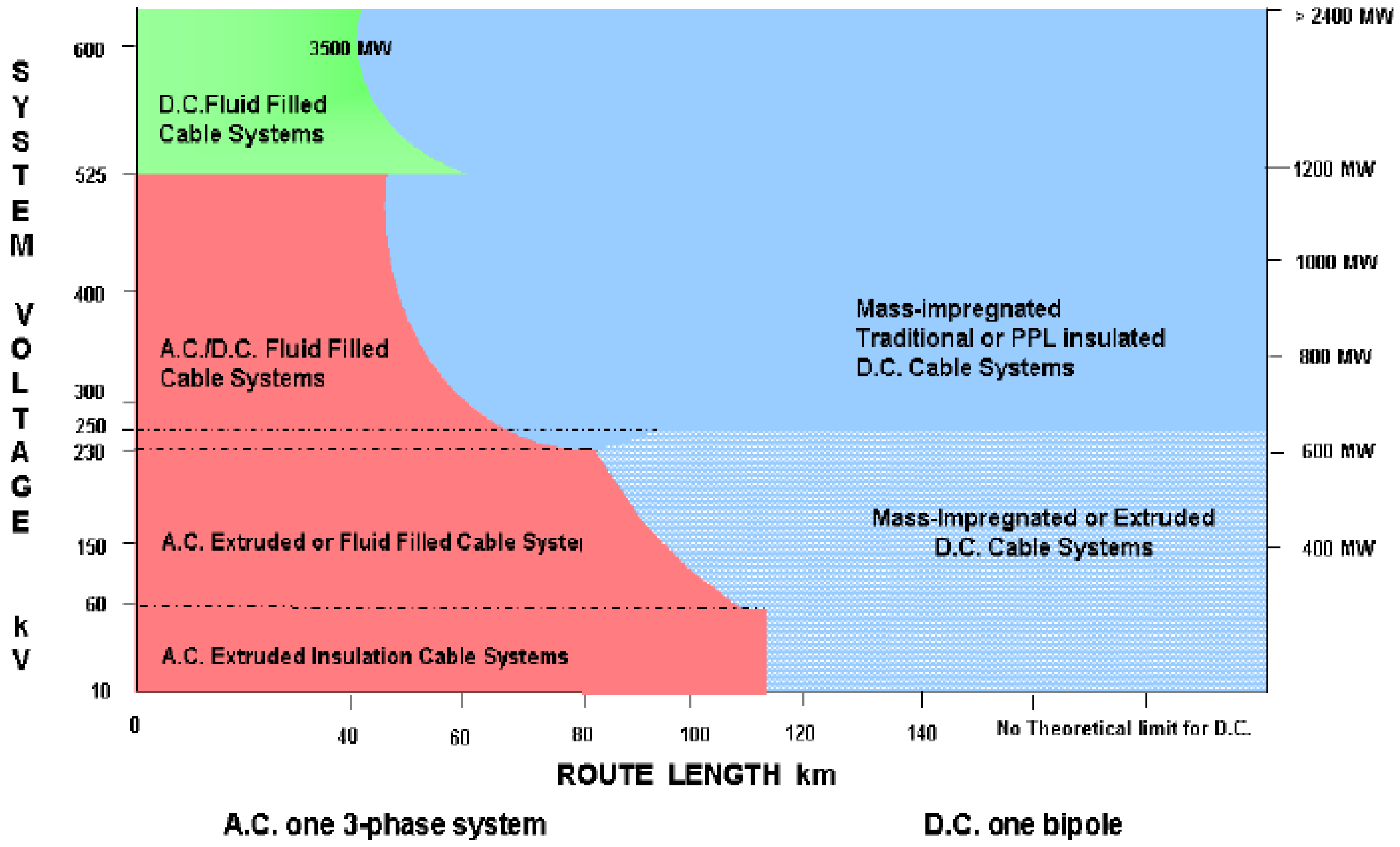
- **Type 4: Cross-Linked DC Polymer (XLDC) – +/-320 kVDC**
    - **Transbay, +/- 200 kVDC, 400 MW, 88 km**



Source: Prysmian Cables and Systems

- **Type 5: Cross-Linked Ethylene-Propylene (EPR) – 150 kVAC**

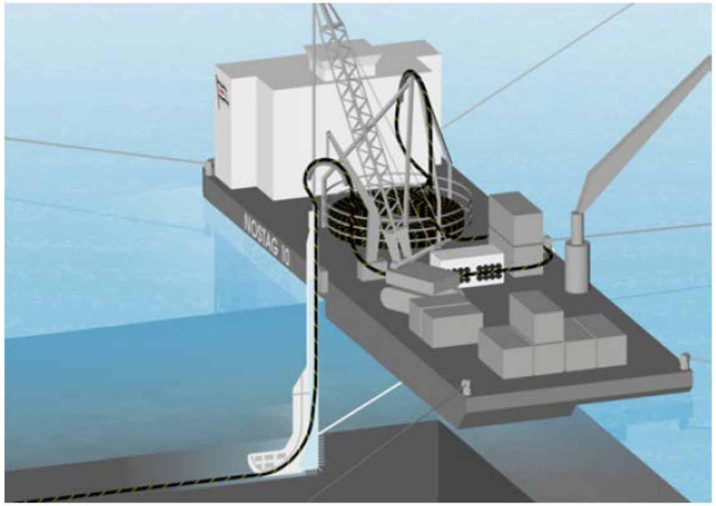
Submarine Cable Selection Criteria



Courtesy of Prysmian Cables and Systems

Source: T. Ackerman – Evaluation of electrical transmission concepts for large offshore wind farms

Cable Installation and Hazards



Cable Damage Hazards

- Seabed variations/mobility leading to exposure and suspensions
- Seismic activity
- Iceberg scour
- Submarine landslides
- Dredging hazard
- Fishing/trawling
- Anchor hazard
- Dropped objects/constructions

Subsea Survey Requirements

- Determination of landing locations
- Identification of historical sites
- Identification of dump or development zones
- Competing use identification (pipelines, fishing
- Seabed formations and levels
- Strong currents
- Sediment makeup
- Sand ripples, waves and migration

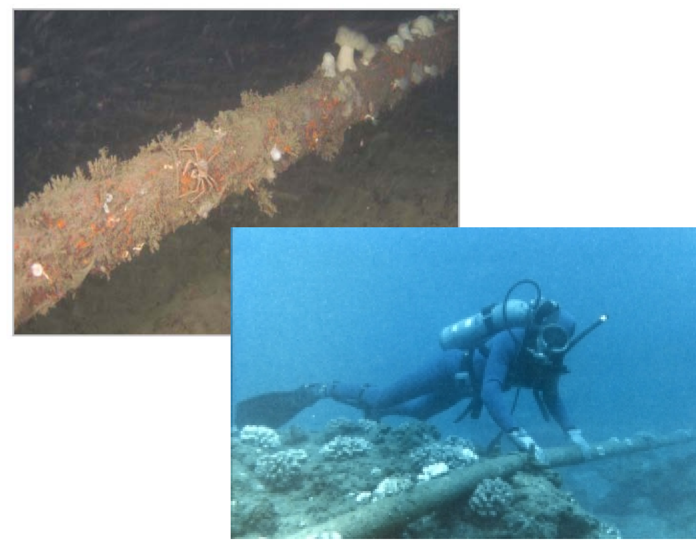
Installation equipment

- Cable lay vessels
- Burial tools
- Support vessel with crane
- Dive crews
- Anchor handing tug with survey equipment
- Shore equipment, directional digging

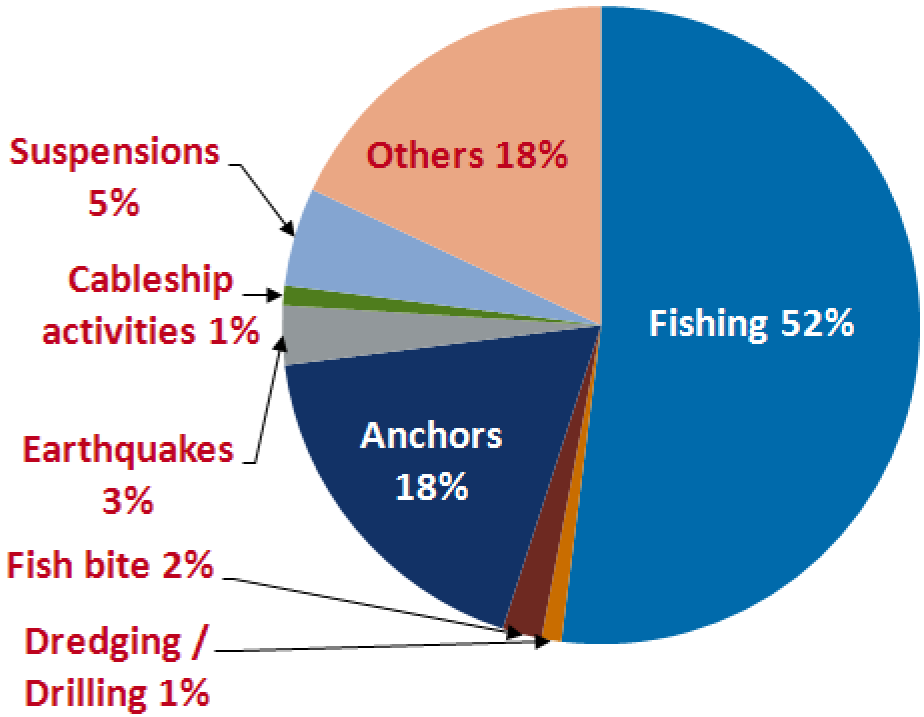
Potential Environmental Impacts

Installation, Maintenance and Repair
- Seabed disturbance
- Damage / disturbance of organisms
- Re-suspension of contaminants
- Visual disturbance
- Noise (vessels, laying machinery)
- Emissions and waste from vessels
- Region specific impacts (i.e. coral reefs, turtle egg-laying beaches, etc.)

Operational phase
- Introduction of artificial hard substrate (installed for cable protection)
- Electromagnetic fields (OCS Report: 2011-09 and NSL#: PC-11-03) impact on migration and behavior
- Navigational equipment impacts (HVDC using sea as a return)
- Thermal radiation - known general impact though no studies exsist



Submarine Cable Reliability



Source: Submarine Power Cables by Thomas Worzyk, Springer, 2009 (page 212)

CIGRE Investigation - 2009

- 7000 circuit km of submarine power cables
- 49 faults reported during 1990-2005
- Only 4 faults identified as "internal"

Assessment of Energy Unavailability can be conducted on specific electrical system configurations and can vary between 1 and 3 percent of total energy generation

Design Tools

Power system simulation software tools (PSCAD, DigSilent, etc.) can be used for electrical/cabling system design for both offshore and onshore applications. However:

Onshore: There are several wind farm design optimization tools that address BOS cost components

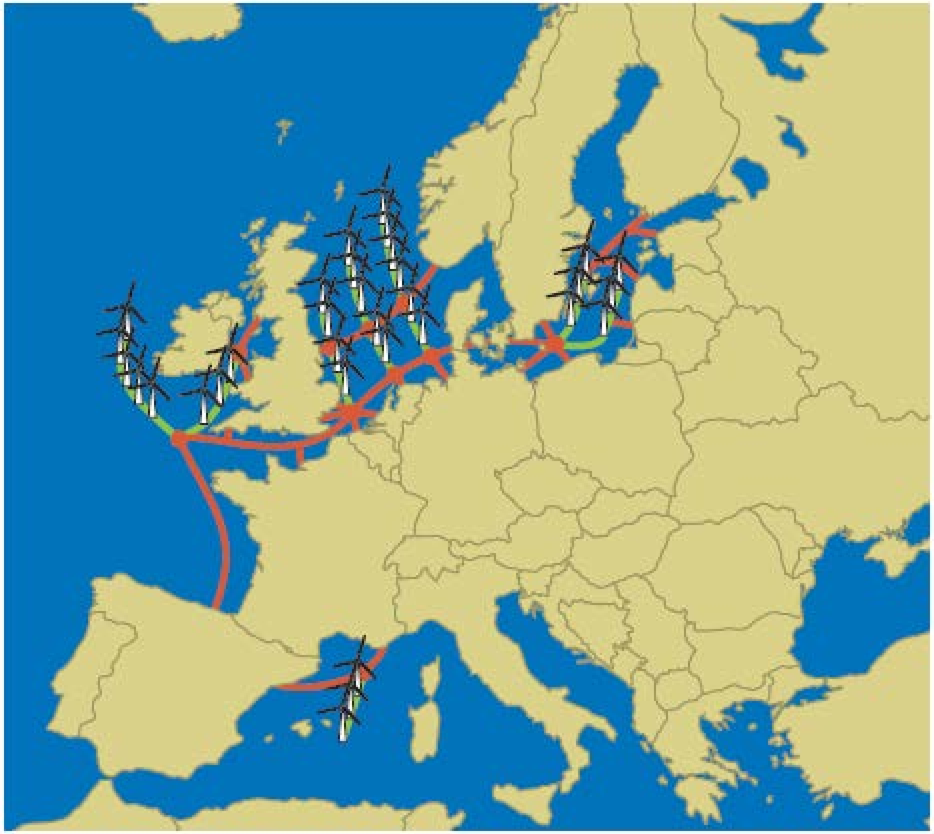
- GE WindLayout, GH/GL WindMaster, etc.
- Layout optimization, electrical loss minimization

Offshore: Only some parts of the existing tools can be applied to offshore BOS costs and in many cases key decision variables are not integrated, reducing the ability to optimize

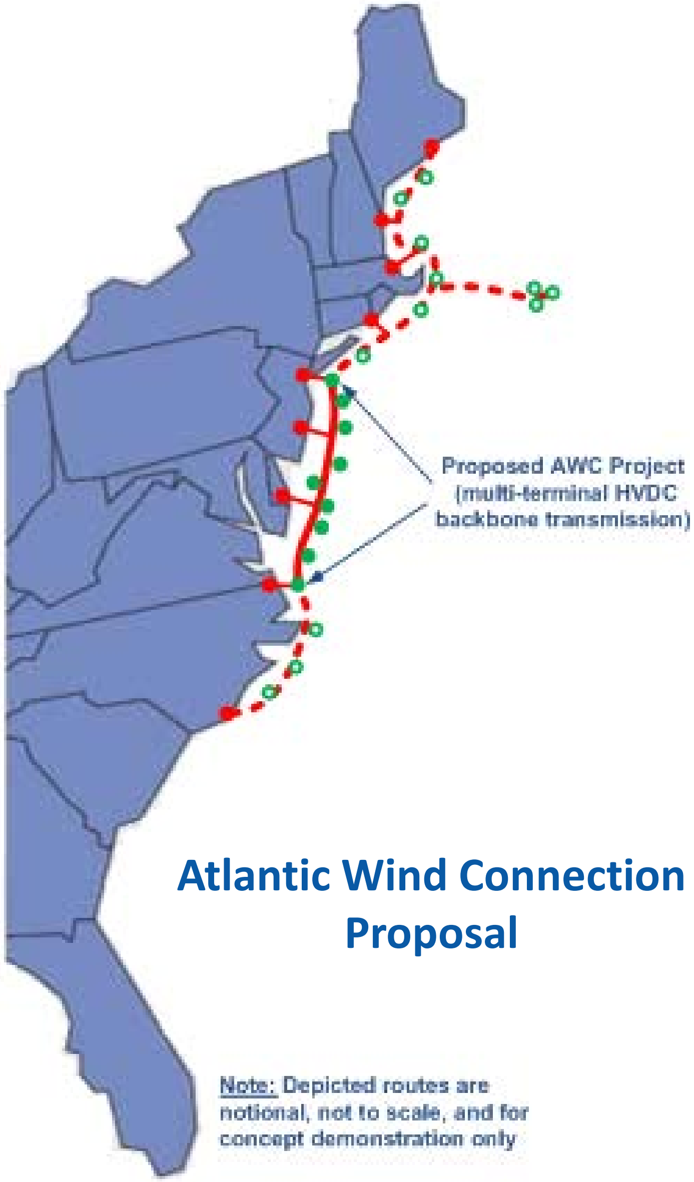
- Offshore Wind Farm Layout Optimization project

Concepts of Offshore Super Grids

European Offshore Super Grid Proposal



Source: www.airtricity.com



Atlantic Wind Connection Proposal

Concepts of Advanced Offshore Collector Systems

- MVDC collector systems using MVDC wind turbines
- Removes need for turbine mounted transformers
- Reduced costs of turbine hardware, including turbine power converters which are currently required
- Lighter and less expensive cabling

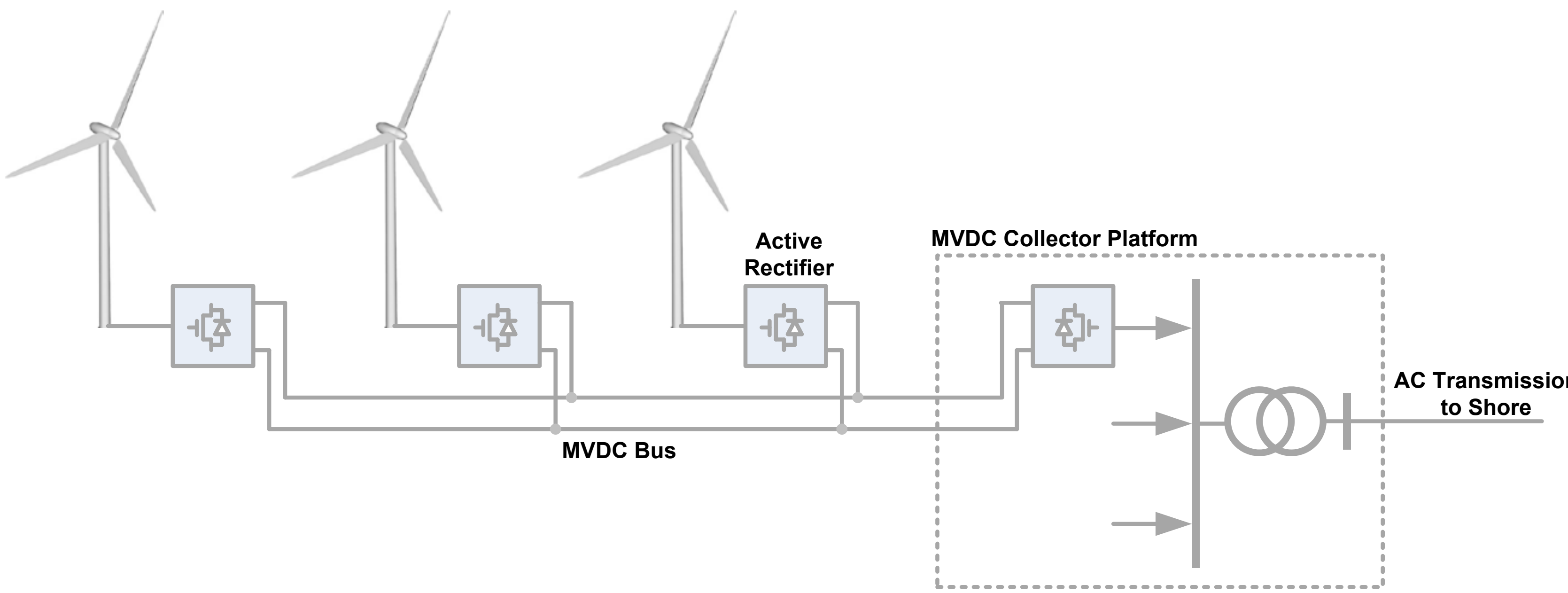


Photo from Nebraska Public Power District, NREL 16442

Carpe Ventum

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