Baltic InteGrid

Integrated Baltic Offshore Wind Electricity Grid Development

Technology options and development trends for OWE and grids

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DTU Wind Energy

WindEurope CONFERENCE & EXHIBITION 2017 28-30 NOVEMBER AMSTERDAM
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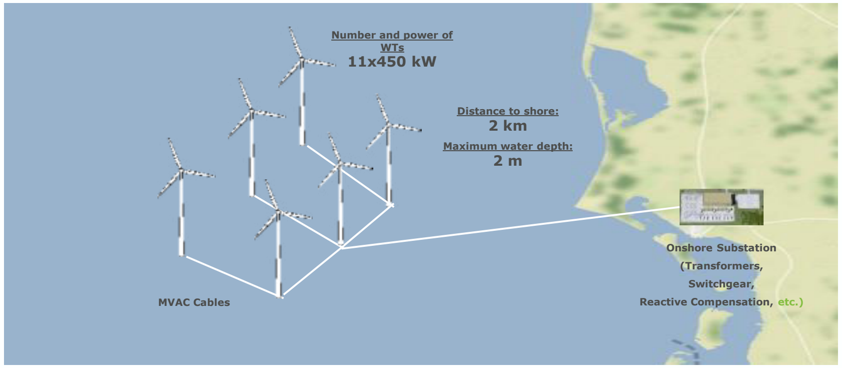
DTU

EU STRATEGY FOR THE BALTIC SEA REGION FLAGSHIP

Interreg Baltic Sea Region

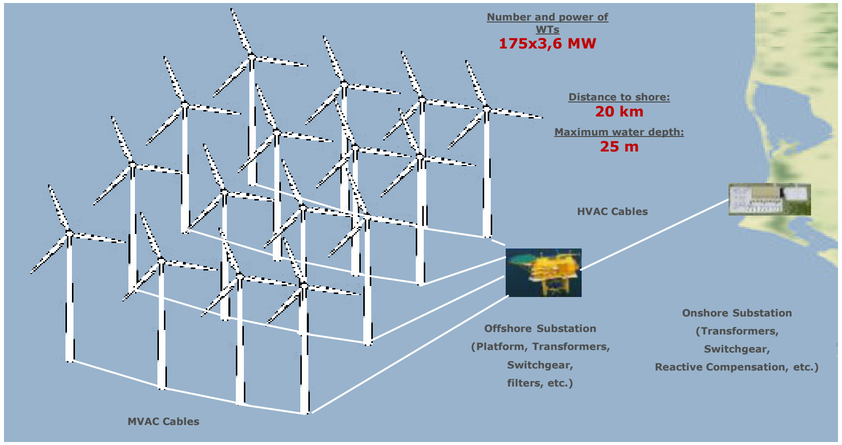
EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION



Wind Farm: Vindeby in Denmark. First installed Wind Farm in the world back in the year 1991.

Source: https://wattsupwiththat.com/2017/03/22/by-the-numbers-lifetime-performance-of-worlds-first-offshore-wind-farm/

LCOE: 16 cents of €/kWh (2017 Euro)

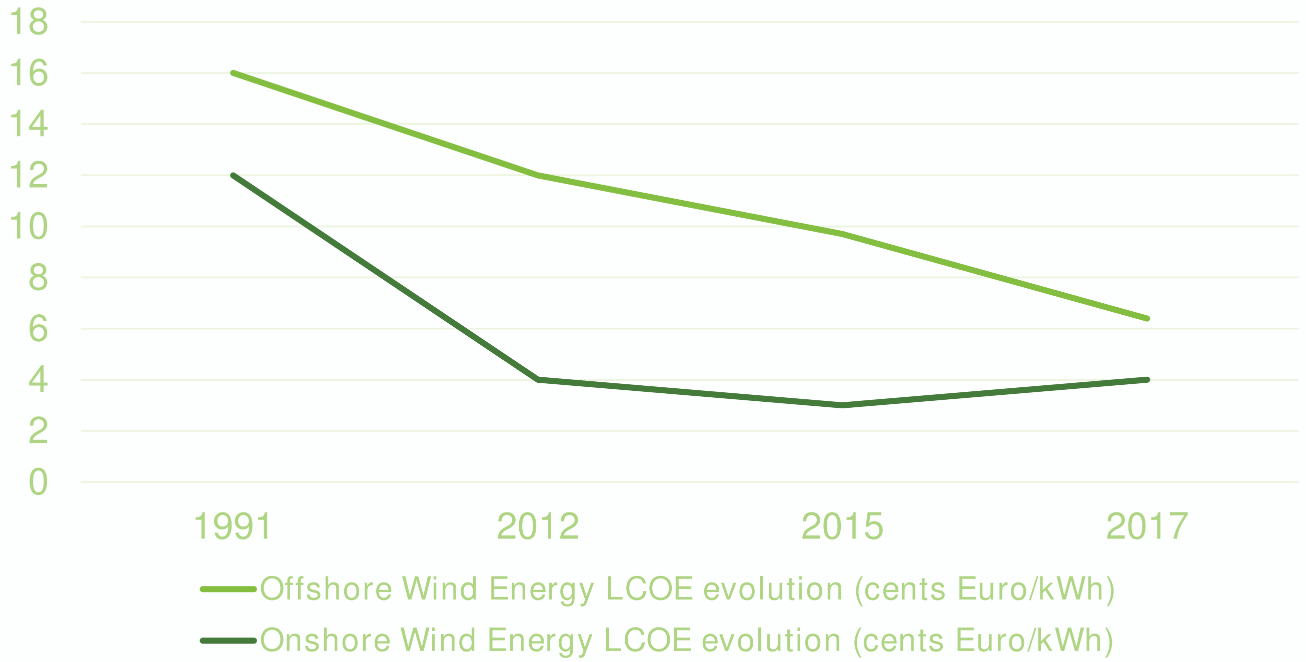


Wind Farm: London array in UK. Largest installed Wind Farm under operation in the world currently.

Source: https://renewablesnow.com/news/study-says-gbp-100mwh-lcoe-for-uk-offshore-wind-achievable-by-2020-465585/

LCOE: 12 cents of €/kWh (2017 Euro)

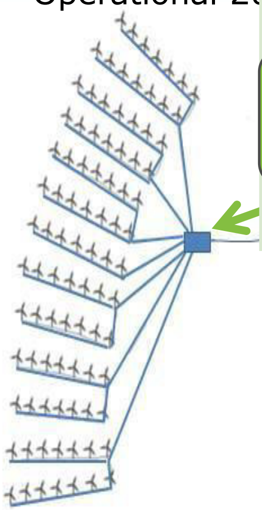
LCOE Evolution of Wind Energy Projects

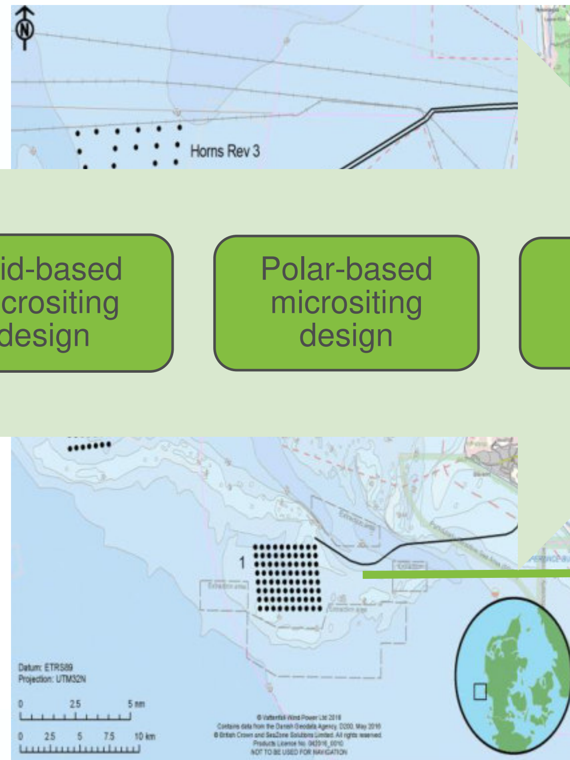


Horns Rev 2

91 WT x 2.3 MW=209 MW

Operational 20





Grid-based micrositing design

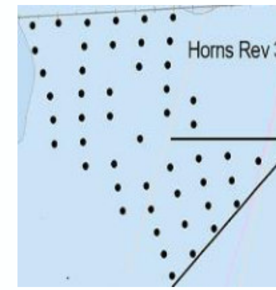
Polar-based micrositing design

Coordinate-based micrositing design

Horns Rev 3

49 WT x 8.3 MW=406.7 MW

Operational 2020

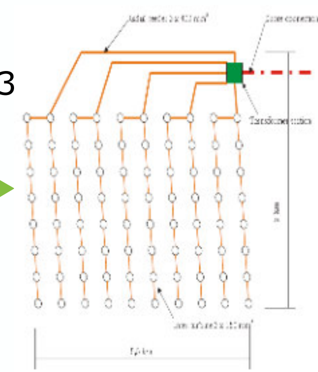


v 1

x 2.0

=160 MW

Operational 2003



$$LCOE = \frac{CAPEX + OPEX}{AEP}$$

LCOE: Levelized Cost of Energy

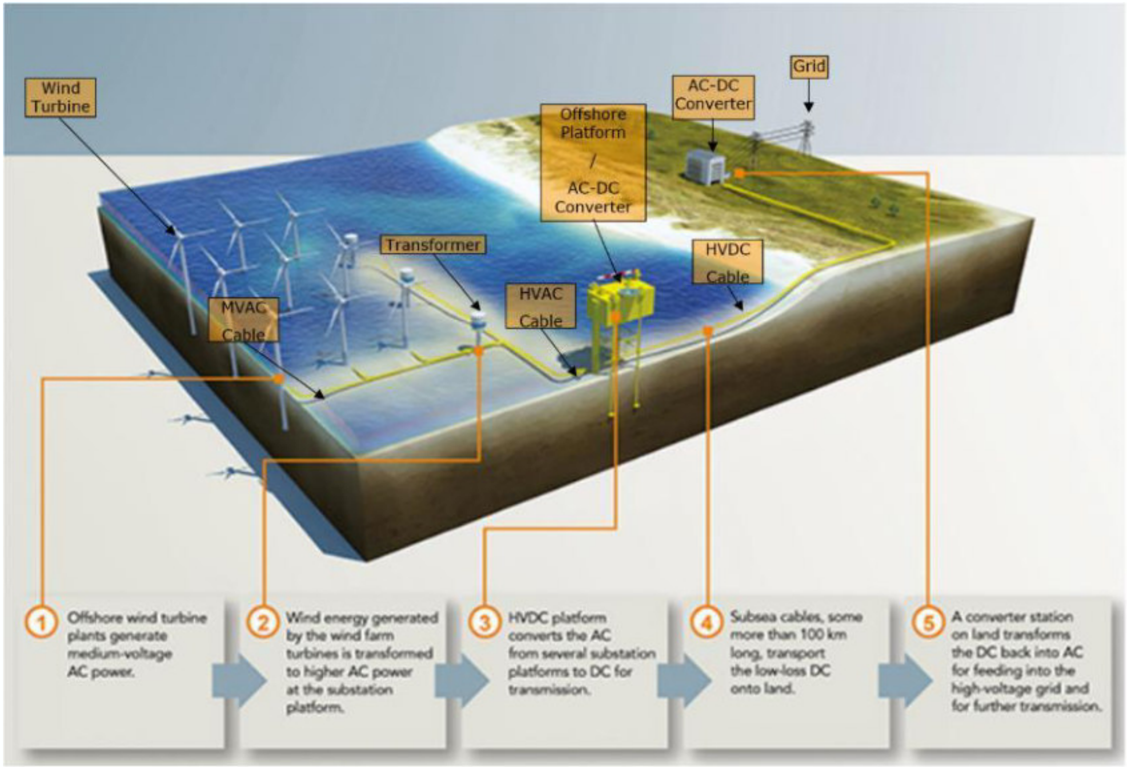
CAPEX: Capital investment expenditures

OPEX: Operation and maintenance cost

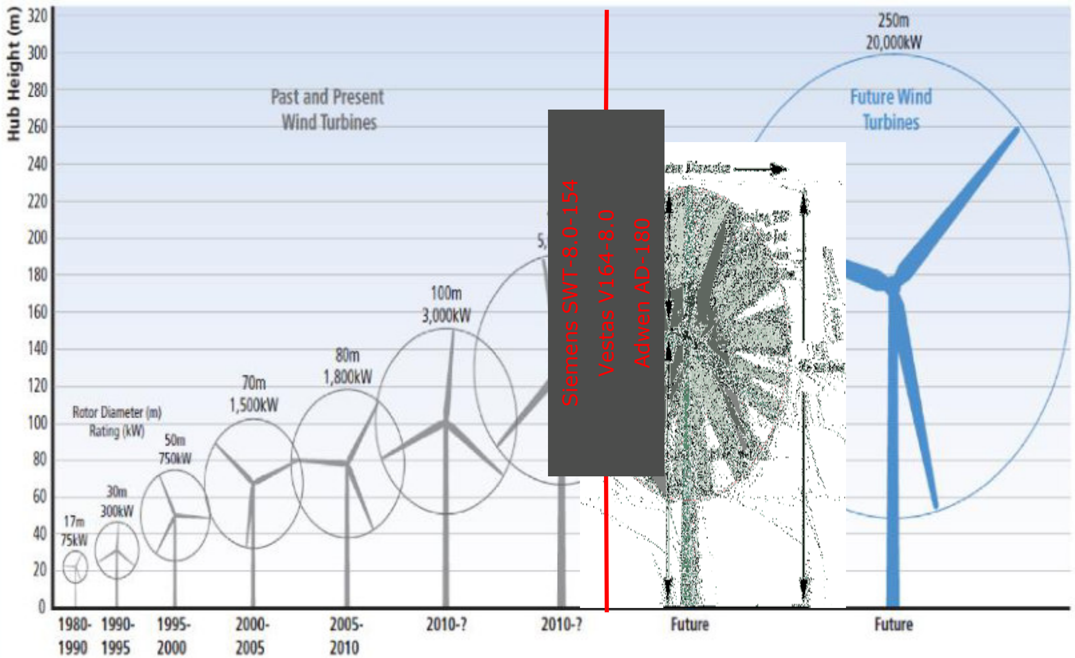
AEP: Annual Energy Production

Minimizing LCOE

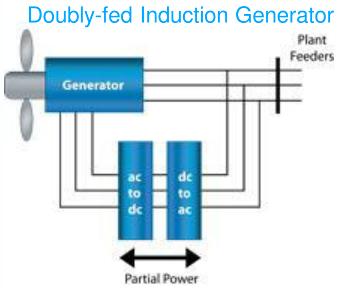
- **Minimizing CAPEX**
- **Minimizing OPEX**
- **Maximizing AEP**

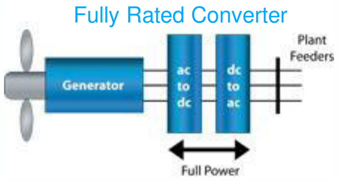


Source: tdworld.com

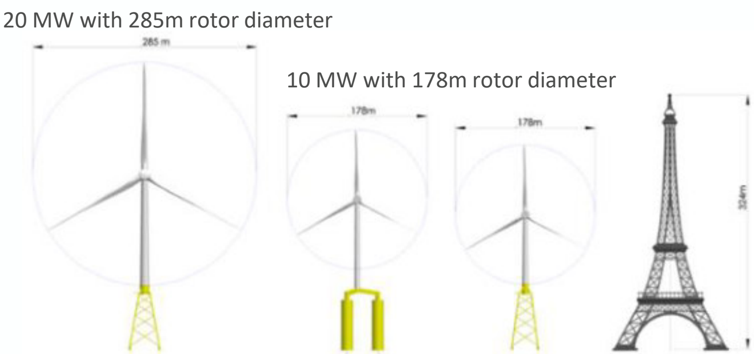


Source: Wiser et al. (2011). Wind Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge: Cambridge University Press.



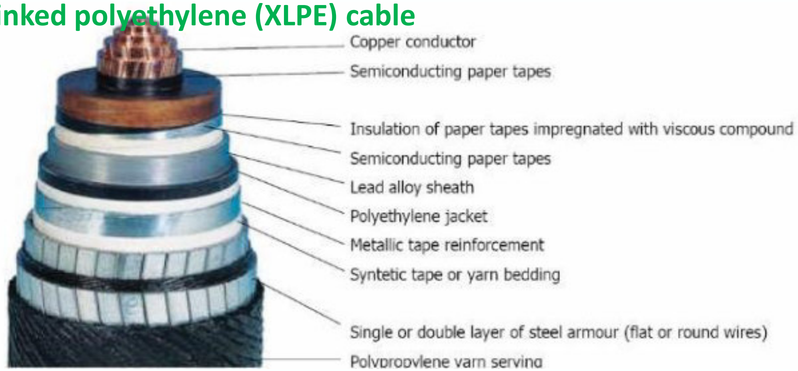


Source: etap



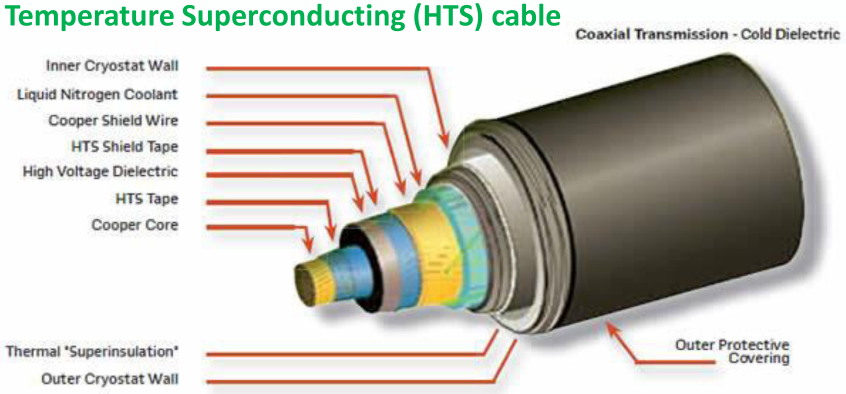
Source: INNWIND.EU

Cross-linked polyethylene (XLPE) cable



Source: Electrical India

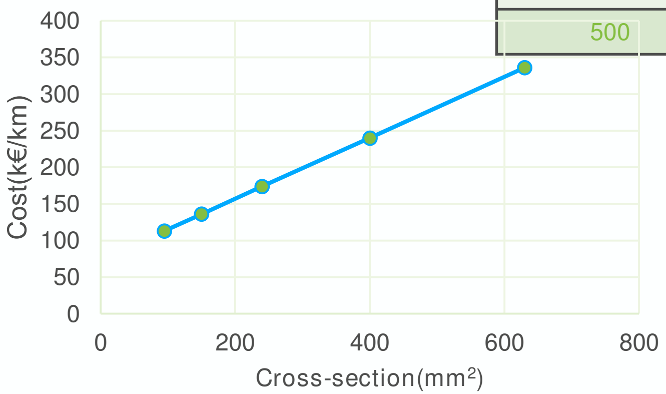
High Temperature Superconducting (HTS) cable



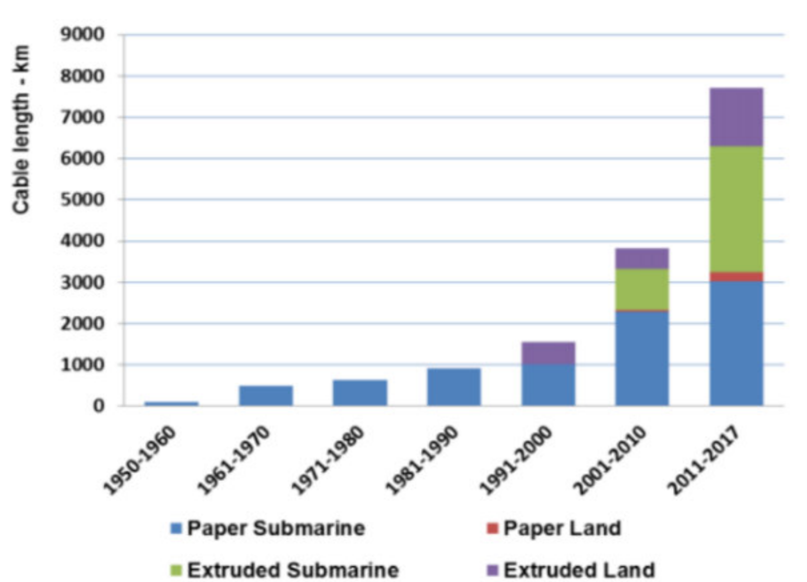
Source: PAC World

- Length: 20-100 km depending on voltage rating and shunt compensation
- Maximum Voltage: 500 kV
- Current Rating: 1.9-2.6 kA

Rated Voltage (kV)	Cross-section (mm^2)
66	240-2000
110	400-2500
132	400-2500
150	400-2500
220	630-2500
275	630-2500
345	800-2500
400	800-2500
500	1600-2500



- Self-Contained Fluid Filled Cables
- Mass Impregnated Cables
- Cross-Linked Poly-Ethylene Cables



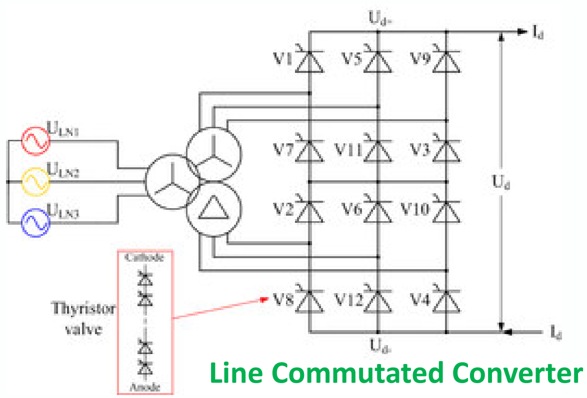
Source: E. Zaccone, High voltage underground and subsea cable technology options for future transmission in Europe, presentation at E-Highway2050 WP3 workshop, 2014

Typical Data

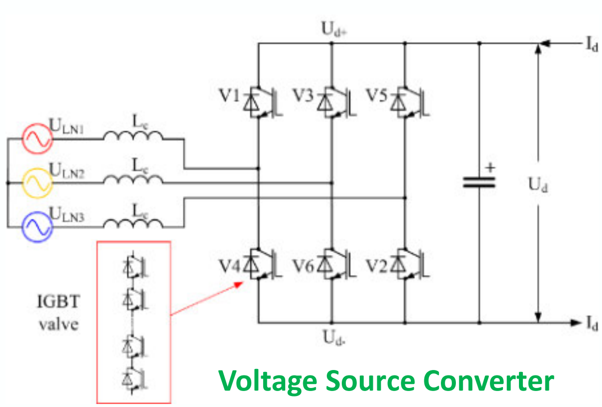
- Transmission Distance: >1000 km
- Typical losses per circuit (bipole): 27 W/m (21 W/m in future)
- Maximum Voltage: 400-525-640 kV
- Current rating: 1900 kA
- Max Power per VSC substation (bipole): 1524-1710MW(1710-1895MW in future)
- Max Power per LCC substation (bipole): 600 MW
- Cross-section Area: 3000 mm^2 for 2000 MW at 250 kV in Kii Channel
- Deep sea installations: 500 m (1000 m in future)

Cost Example: XLPE HVDC cables

- Capex: 1470-1625 k€/ km (Installation costs: 29%)
- Opex: 2.9-3.2 k€/km
- Lifespan: >40 years

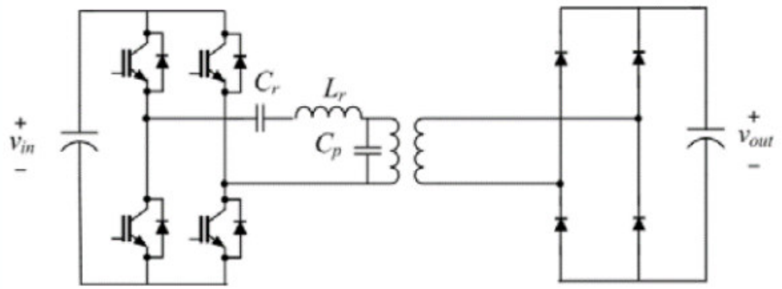


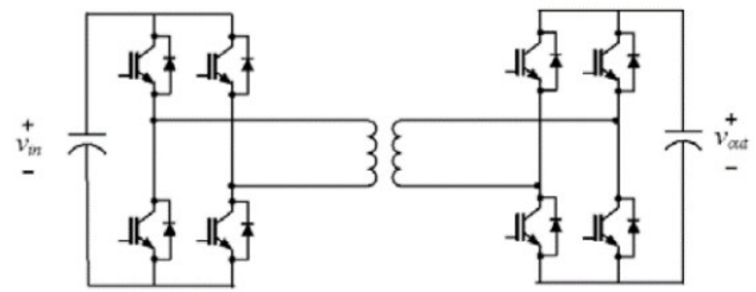
Line Commutated Converter



Voltage Source Converter

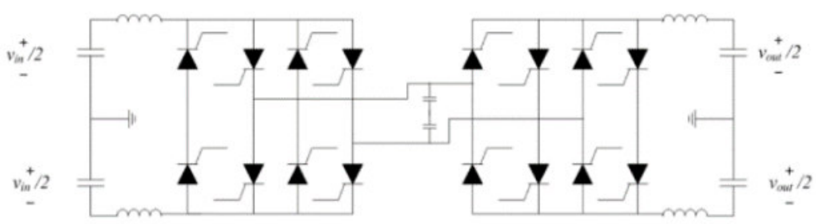
Line Commutated Converters	Voltage Source Converters
• Since early 1950 • Typically uses thyristors • More powerful, lower losses • Requires more space • Induces more severe requirements for cables	• Since 1999 • Uses IGBTs, GTOs, etc. • Currently limited in power & voltage • More controllable, flexible, smaller and lighter • Allows independent control of active and reactive power
Typical Data • Voltage (line to ground) for converter: 800-1100 kV • Voltage (line to ground) for cables: 550 kV • Current: 4-5 kA (6 kA in future) • Max Power per substation (bipole) : 8-11 GW (upto 13.2 GW in future) • Maximum length of the line: 2000 km • Maximum length of the cable: 580-600 km • Transmission Losses: 0.7-1.1% of rated power per converter station	Typical Data • Voltage (line to ground) for converter: 500-800 kV • Voltage (line to ground) for cables: 500 kV • Current: 1.5-3 kA (3-4 kA in future) • Max Power per substation (bipole) : 2000-4800 MW (6400 MW in future) • Maximum length of the line: 700-2000 km (3000 km in future) • Maximum length of the cable: 400 km (600-1000 km in future • Transmission Losses: 0.9-1.3% of rated power (0.7-1.1% in future) per converter station.

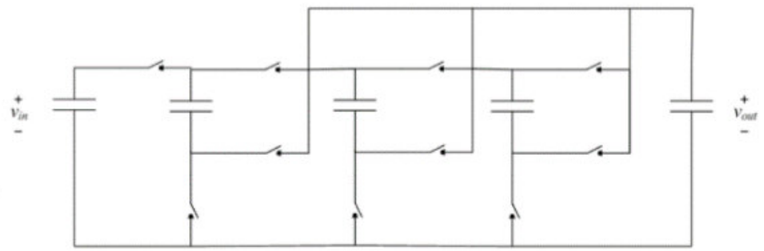




Isolated DC-DC converters

left: Resonant bridge converter; right: Dual active bridge converter





Non-isolated DC-DC converters

left: Bidirectional high-power DC transformer; right: Modular multi-level capacitor clamped DC-DC converter

2 ways to mitigate harmonics in WPPs –

- Avoiding harmonic resonance and emission by appropriate design
- Use of harmonic filters

Passive Filter

- **A bank of tuned LC filters and/or low-pass/high-pass filter**
- **Low initial cost and high efficiency**
- **Disadvantages-**
  - **Strongly depended on source impedance**
  - **Excessive harmonic currents can flow due to resonance**

Technical feasibilities

Voltage : 550 kV

Power : >3 Mvar

Active Filter

- **They consist of voltage- or current-source PWM inverters and have the ability to overcome the inherent disadvantages in passive filters**
- **Hybrid filter consists of mainly two parts-**
  - **Passive part comprises of a double tuned passive filter**
  - **Active part consists of - Current transducer, Control system, Amplifier, Transformer, Protection Circuit and arrester, Bypass switch and disconnectors**

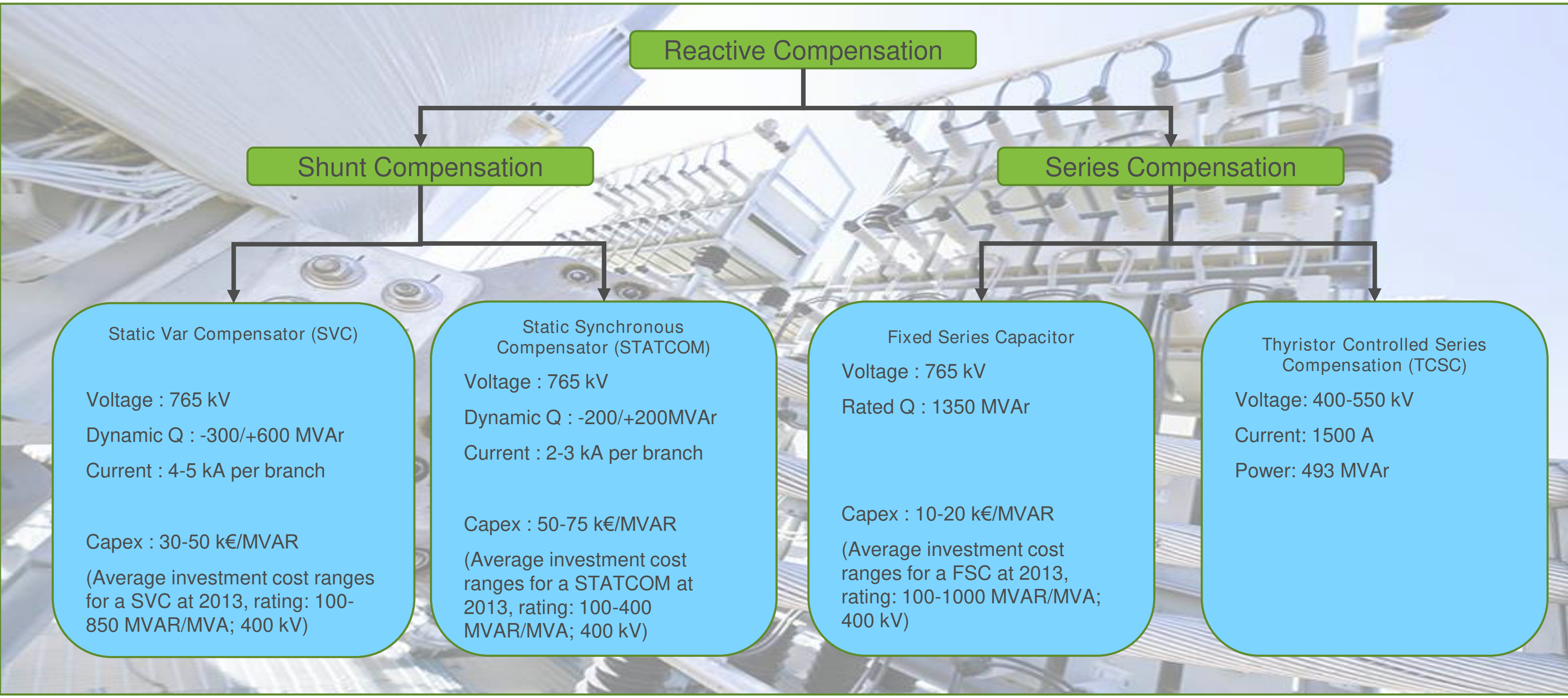
Technical feasibilities

Voltage : 500 kV

Filtering frequency range :

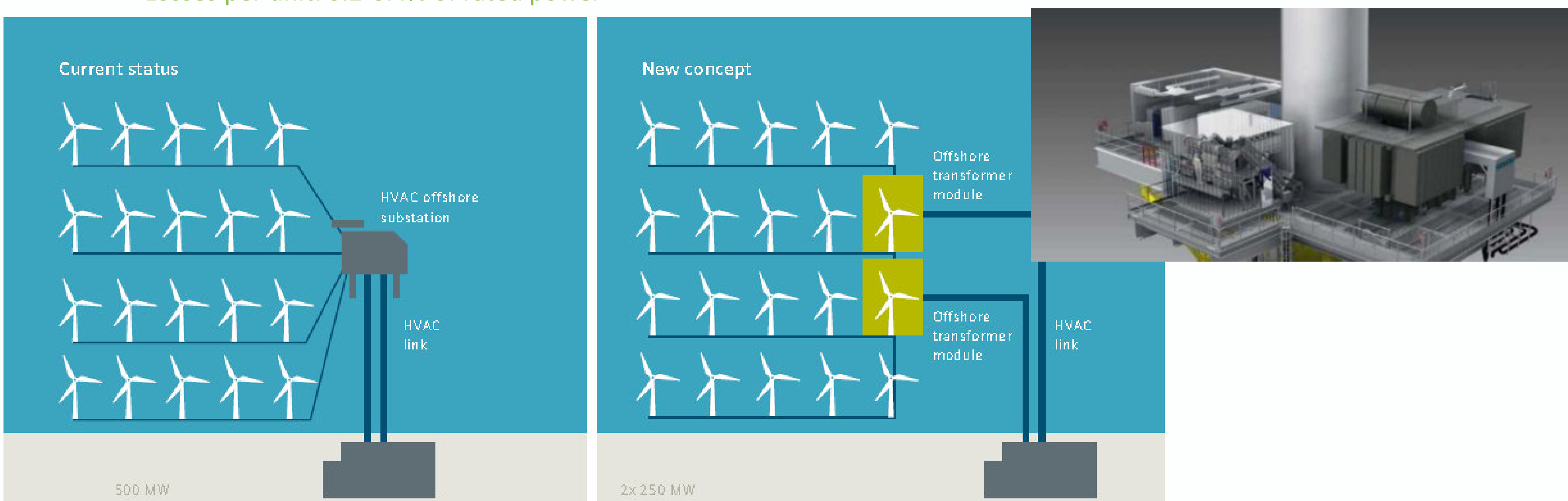
350-2500 Hz (Chandrapur-Padghe HVDC)

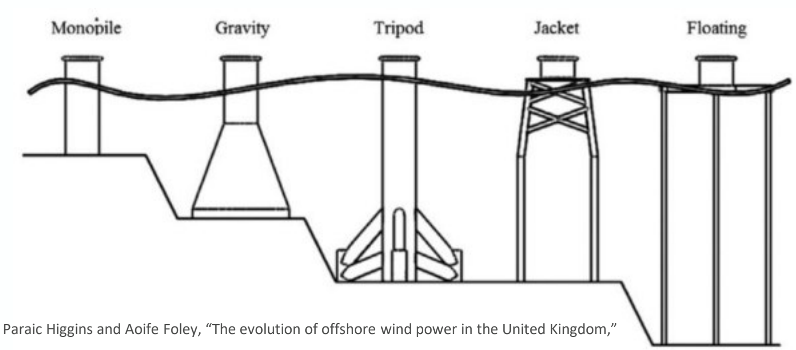
300-3000 Hz (Baltic Cable HVDC Link)


Reactive Compensation
Shunt Compensation
Series Compensation
Static Var Compensator (SVC)
Voltage : 765 kV
Dynamic Q : -300/+600 MVAr
Current : 4-5 kA per branch
Capex : 30-50 k€/MVAR
(Average investment cost ranges for a SVC at 2013, rating: 100-850 MVAR/MVA; 400 kV)
Static Synchronous Compensator (STATCOM)
Voltage : 765 kV
Dynamic Q : -200/+200MVAr
Current : 2-3 kA per branch
Capex : 50-75 k€/MVAR
(Average investment cost ranges for a STATCOM at 2013, rating: 100-400 MVAR/MVA; 400 kV)
Fixed Series Capacitor
Voltage : 765 kV
Rated Q : 1350 MVAr
Capex : 10-20 k€/MVAR
(Average investment cost ranges for a FSC at 2013, rating: 100-1000 MVAR/MVA; 400 kV)
Thyristor Controlled Series Compensation (TCSC)
Voltage: 400-550 kV
Current: 1500 A
Power: 493 MVAr

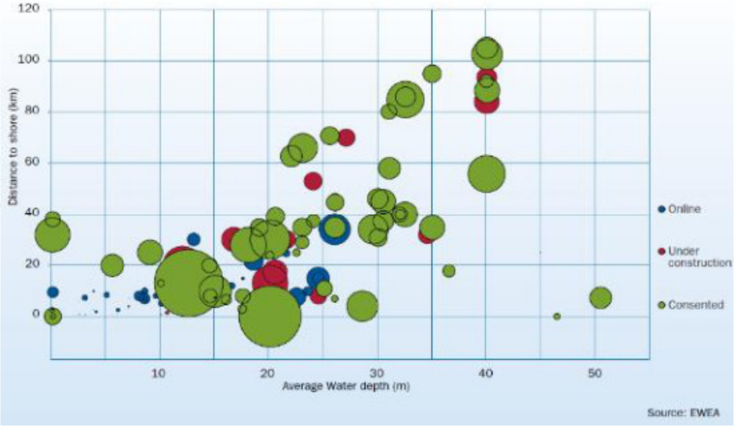
Typical Data

- Voltage (line to ground): 765 kV
- Current: 10 kA (Not a limiting factor)
- Max Power per unit: dictated by cables (Typical 765 kV transformers have power rating close to 800 MVA)
- Losses per unit: 0.2-0.4% of rated power

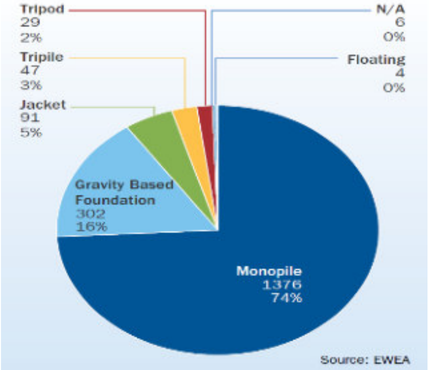




Source: Paraic Higgins and Aoife Foley, “The evolution of offshore wind power in the United Kingdom,” Renewable and sustainable energy reviews, 37 (2014): 599–612.

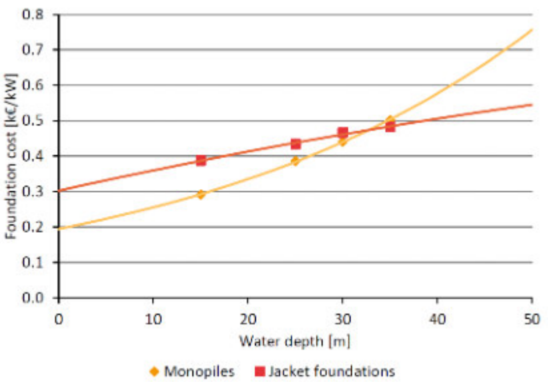


Source: European Wind Energy Association(EWEA), Deep water. the next step for offshore wind energy, http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf, 2013.



Substructures for online offshore wind farms till 2012

Source: European Wind Energy Association(EWEA), Deep water. the next step for offshore wind energy, http://www.ewea.org/fileadmin/files/library/publications/reports/Deep_Water.pdf, 2013



Monopile and jacket foundation costs for an 8 MW Wind Turbine

AC Circuit Breaker – Highly reliable, cheap, matured technology

SIEMENS
Ingenuity for life

Energy Management

DC commutation breaker successfully tested in 5000-A HVDC system in China

Erlangen, 2015-Jan-29

The Siemens MRTB DC commutation breaker (Metallic Return Transfer Breaker) with a rated current of 5000 ampere (A) has been successfully tested in its Xiluodu-Zhejiang high-voltage direct-current (HVDC) transmission system. Special breaker properties are required for transferring such high currents from one current path to another, a process also known as commutation. The circuit-breaker was integrated in the direct-current switchgear of the Shuanlong converter station and allows the uninterrupted switchover from grounding electrode mode to metallic return transfer mode and vice versa with no need for the operator to reduce the transmission power of the system. Until now, this only functioned with rate[...] 5000 A. Siemens has now successfully exceeded this limit w[...] thereby improving the operation, stability and reliability of this [...] HVDC system in China.

DC Circuit Breaker – Future technology

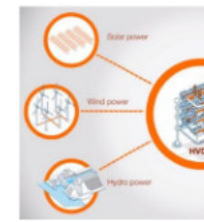
ABB POWER GRIDS • CIGRE 2014 • HVDC BREAKER

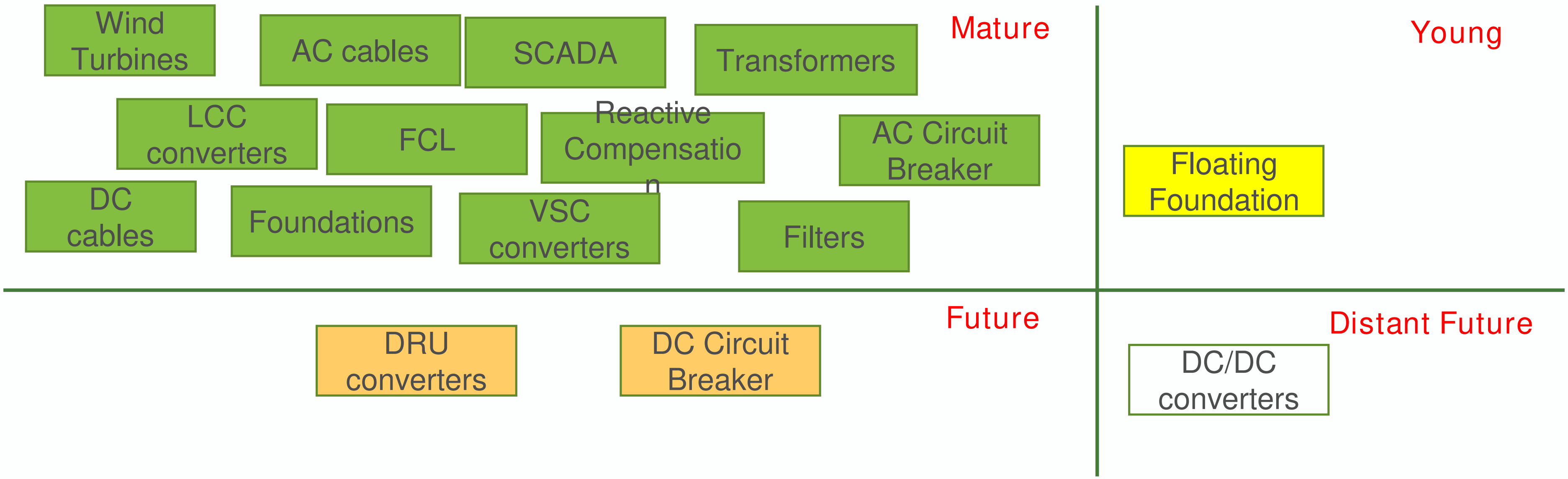
ABB's Hybrid HVDC Circuit Breaker

Solving a 100 year old dilemma

Deployment of HVDC has led to an increasing number of point to point connections in different parts of the world. The logical next step is to connect the lines and optimize the reliability of the network. This will also enable balancing of loads, integration of intermittent renewables, lowering of transmission losses and facilitate energy trading across borders. Then why don't we just interconnect these lines into a grid ? A major stumbling block or missing link has been the absence of an HVDC breaker that acts fast enough to interrupt current and isolate faults and at the same time keeps losses to a minimum.

ABB's hybrid DC breaker was developed after years of research, functional testing and simulation in the R&D laboratories. It is a breakthrough that solves a technical challenge that has been unresolved for over a hundred years and was perhaps one the main influencers in the 'war of currents' outcome. The 'hybrid' [...] and power electronics switching that enables it to interrupt power flows [...]uclear power station within 5 milliseconds – that's as fast as a honey bee takes [...] than 30 times faster than the reaction time of an Olympic 100-meter medalist to react to the starter's gun! But it's not just about speed. The challenge was to do it 'ultra-fast' with minimal operational losses and this has been achieved by combining advanced ultrafast mechanical actuators with our inhouse semiconductor IGBT valve technologies or power electronics (watch video: Hybrid HVDC Breaker – How does it work).





- Mature: commercially available today; with (some) operational experience (TRL-9 today)
- Young: full scale prototypes available; very close to commercialization (TRL 6-8 today)
- Future: some prototypes available, but development still needed (TRL 4-5 today)
- Distant future: proof of concept and small scale prototypes, significant development still needed (TRL 1-3 today)

Questions & Discussions

Thank You