Offshore Horizons: HVDC Wind Farms - Exploring Techno-Economic Dimensions Poster

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Motivation

- Offshore wind has grown tremendously and has incredible growth potential
- One of the biggest costs of offshore wind is transmission systems
- Recent work suggests HVDC systems may improve economics of offshore wind
- Joint technical and economic analysis needed to understand feasibility of OWF transmission systems

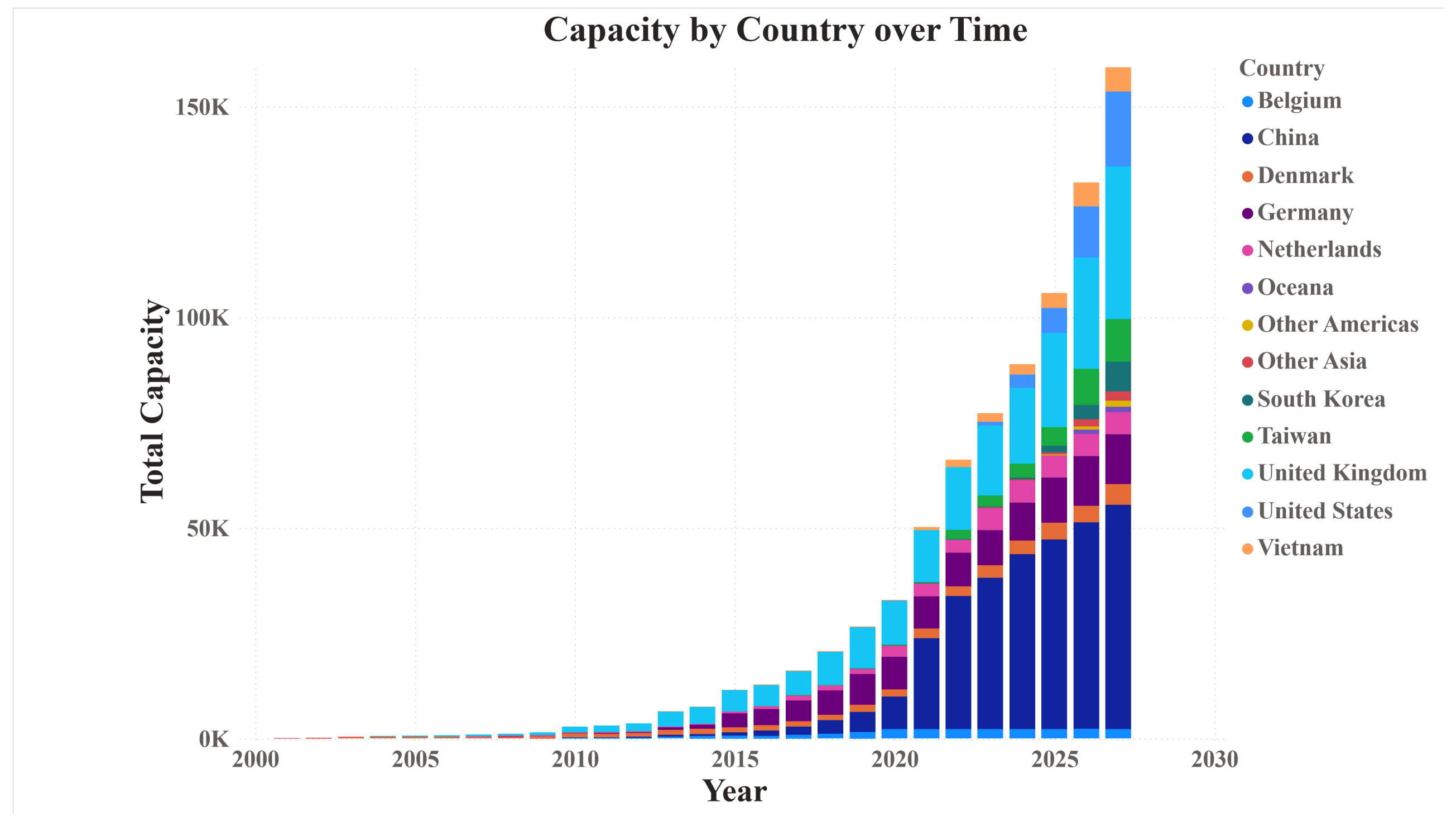


Figure 1. Total capacity (MW) of OWF by country by year according to DOE.

Introduction

- Reviews existing research, innovations, and methodologies in HVDC offshore wind farms (OWFs) focusing on economic analysis, connection topology, converter design, and technical modeling.
- Economic Analysis:
  - Summarizes literature on costs, reliability, and discounting.
  - Highlights integration of economic and technical perspectives.
  - Identifies gaps to refine techno-economic analysis.
- Connection Architectures:
  - Evaluates AC, DC, and emerging configurations.
  - Explores implications for reliability, control, scalability, and cost.
- Converter Designs:
  - Analyzes various converter types (VSCs, LCCs, DC-DC converters).
  - Assesses efficiency, reliability, and adaptability for offshore use.
- Technical Modeling:
  - Reviews simulation and modeling techniques.
  - Focuses on optimizing performance and computational efficiency.
  - Supports decision-making by predicting operational behaviors and system reliability.

Component Cost

System	Transmission System	
Component	HVDC	HVAC
Substation	24-45	10-45
Cable	.6/KM	1.5/KM
Offshore Platform	73.5	24
Onshore Platform	24	24
Cable Installation	215	215
Line Losses % per 1000 KM	.035	.067

Breakeven between HVDC and HVAC

Figure 2. Breakeven in fixed cost overstates breakeven point.

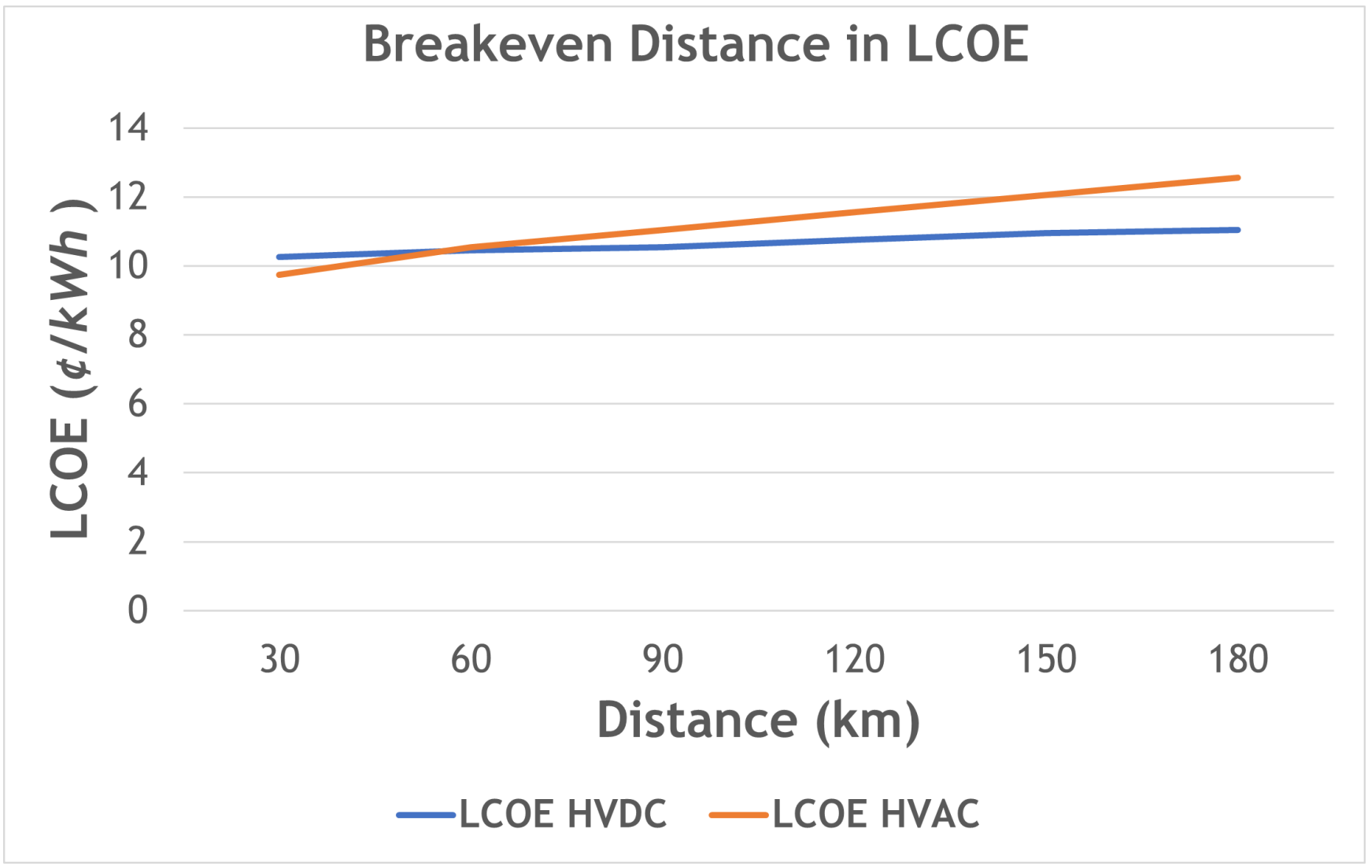
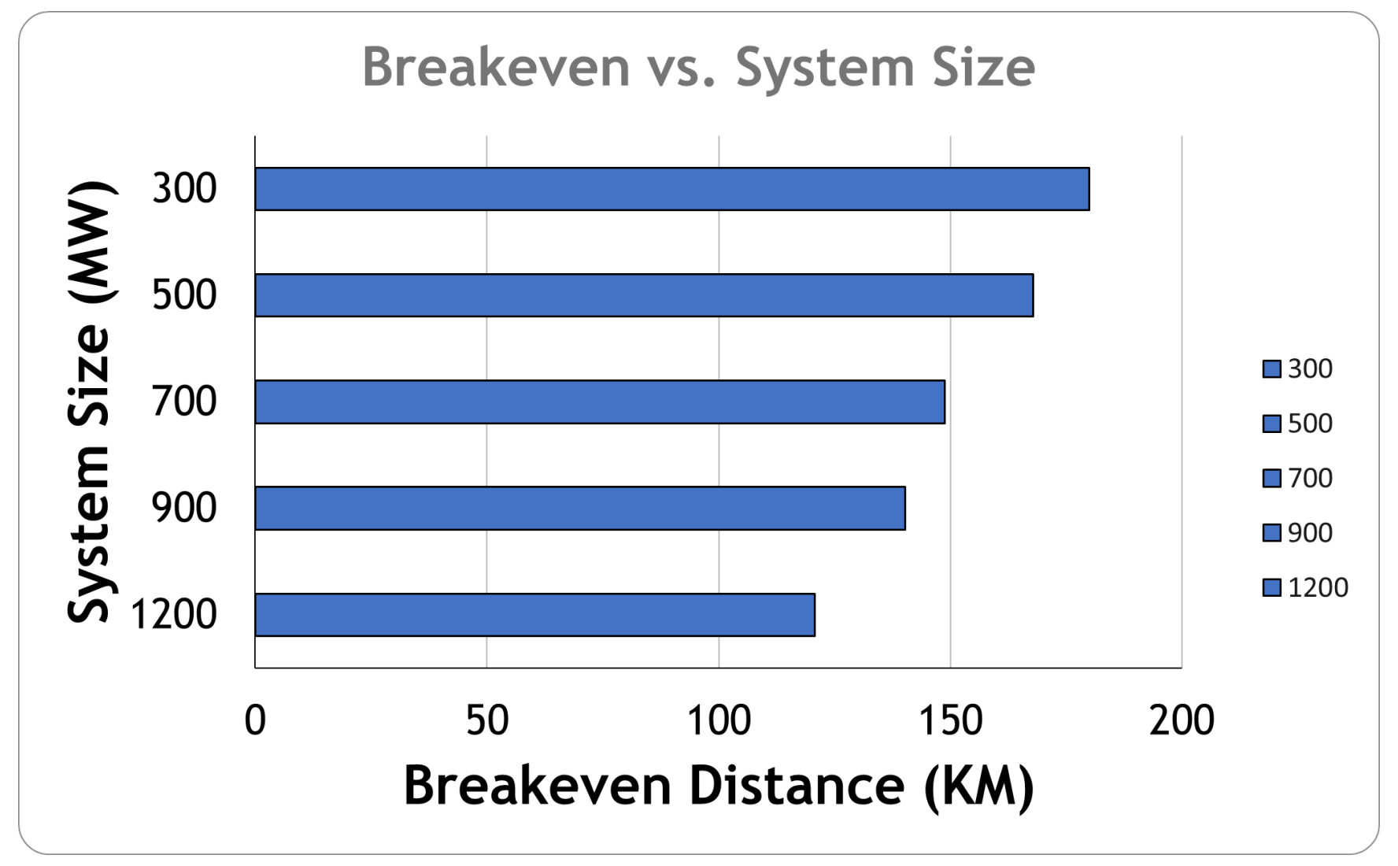


Figure 3. HVDC has better economics with size.



Offshore Wind Farm Connection Topology

Figure 4. Offshore Wind Farm Topology.

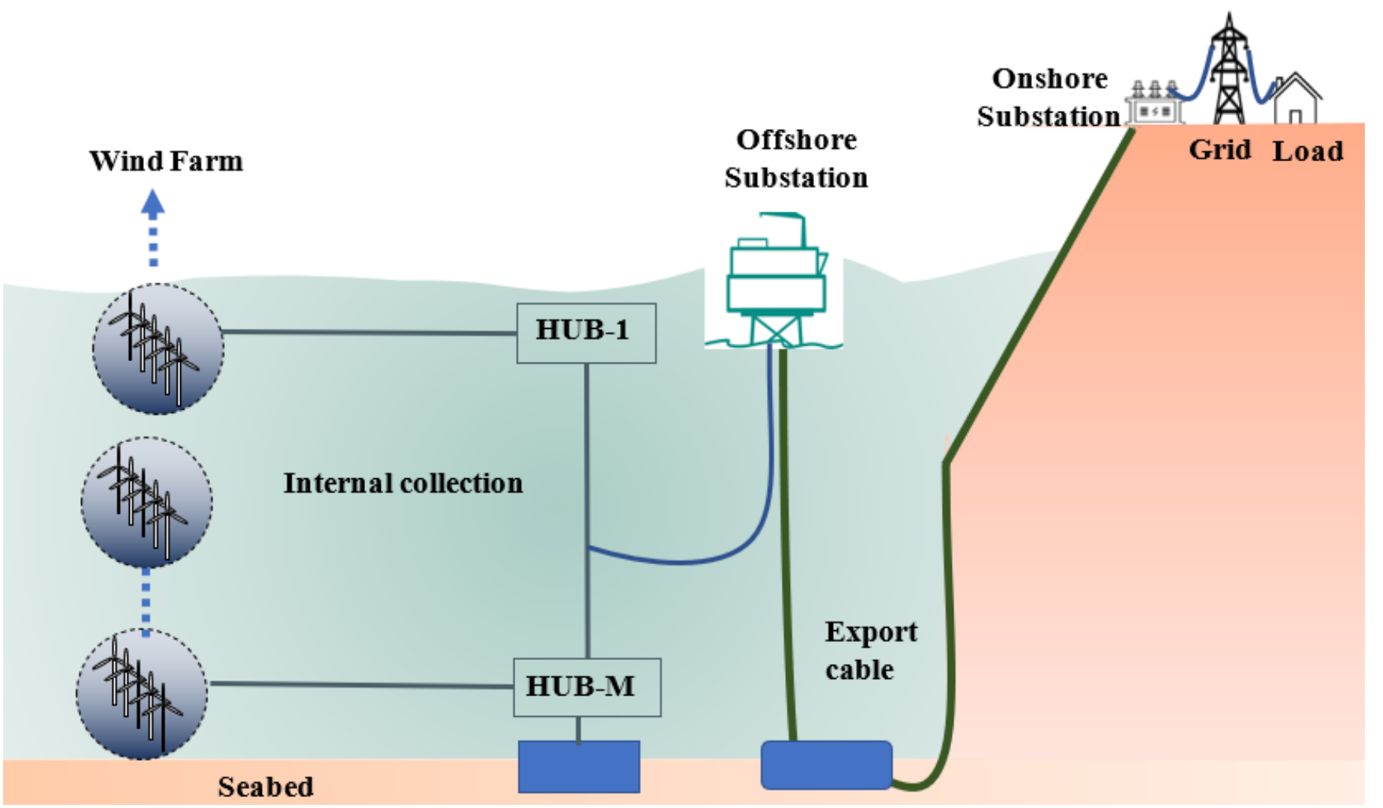
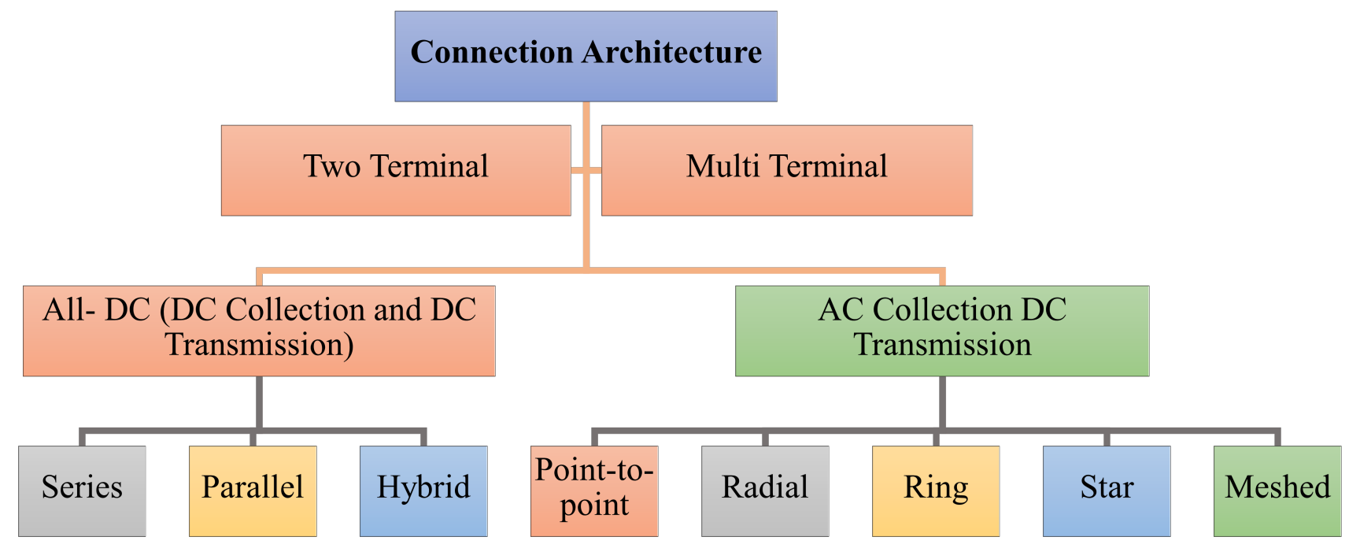


Figure 5. Connection topology diagram.



Technical Challenges for Offshore Wind

Main Challenge		Mitigation Strategy	References
Power Quality	Harmonic Distortion	–Use of active/passive filters; –Advanced Control Algorithms.	[1, 2, 3]
	Voltage Unbalance	–Dynamic voltage balancing techniques	[4]
	Voltage Sag, Swell, Flickers	–Use of FACTS devices – Dynamic VAR compensators – Power conditioning systems.	[5, 6]
Stability	Voltage Stability	–Reactive power compensation –Advanced Control Techniques –Wind turbine converters with reactive power control capabilities.	[7]
	Frequency Stability	–De-loading by Variable Speed Wind Turbine –Capacitor energy storage in VSC-HVDC –Coordinated frequency regulation between OWF and VSC-HVDC	[8]
	Fault Ride-Through Capability (LVRT/HVRT)	–Implement LVRT and HVRT schemes in wind turbines and HVDC converters	[9]
Fault Diagnosis and Protection	Offshore Converter Protection	–Use of advanced protection systems and fault detection technologies	[10, 11, 12, 13]
	Short-Circuit Current Limitation	–Use of superconducting fault current limiters (SFCLs) –Adaptive relays for precise fault detection and response	[14, 15, 16]
Inertia	System Inertia Reduction	–Use of synthetic inertia from wind turbine control –ESS-based inertia emulation –Virtual synchronous machines to mimic conventional inertia	[17, 18, 19]
Ancillary Services Provision	Provision of Frequency Regulation	–Battery Energy Storage Systems (BESS) –Synthetic inertia for fast frequency response –Advanced control algorithms	[20, 21, 22]
	Provision of Voltage Control and Reactive Power Support	–Use of FACTS devices (STATCOM, SVC) –Wind turbine converters with reactive power support	[23, 24, 25, 26]
	Provision of Reserve Power	–Novel large-scale ESS –Coordinated operation with other RES	[27, 28, 29, 30, 31]
	Black Start Capability	–Implement black start capability in ESS –Specific wind turbines designed for black start operations –Coordinated black-start strategy	[32, 33, 34, 35]
Sizing of Converters and Efficiency	Converter Weight and Volume	–Use of modular multilevel converters (MMC) –Advanced materials to reduce size and weight –Novel collection systems	[36, 37, 38, 39, 40]
	Converter Losses	–Use of high-efficiency semiconductor technologies (e.g., SiC or GaN) –Advanced converter topologies for lower losses	[41, 42]
Grid Code Compliance	Compliance with Grid Codes	–Adaptive control schemes to meet diverse grid code requirements –Ensuring LVRT/HVRT capabilities	[43, 44]

Economic Challenges to Offshore Wind Industry

Main Challenge		Mitigation Strategy	References
Long-term Financing	Capital Intensive	– Subsidies for wind energy development – Renewable Portfolio Standards – Feed-in tariffs	[45, 46]
	Cost and Revenue Uncertainty	– Contracts for Differences – Long-term electricity price modeling – Power purchase agreements – Inflation Adjustments	[47, 48, 49]
Missing Money Problem	Low Revenues for Baseload Generators	– Capacity market redesign – Convex hull pricing	[50, 51, 52]
	Increased Ramping by Dispatchable Resources	– Improved cold start efficiency – Diversified portfolios (fossil and renewable)	[53, 54, 55]
	Price Variability	– Demand response – Energy storage systems (ESS) – Long-distance transmission	[56, 57, 58]
Sustainable Supply Chain	Waste of Wind Turbines	– Turbine recycling – Reduced metal intensity	[59, 60]
	Securing Metals for Turbine Production	– Development of mineral sources – Supply chain transparency	[61, 62]
Intermittency	Non-dispatchability	– Coordination with ESS – Black-start natural gas cooperation – Capacity market redesign	[30, 56, 63]
Concept to Industry	Initial Investments	– Public-private partnerships – Loans via DOE programs – Government contracts (e.g., Executive Order 14057)	[64, 65, 66]
	Workforce Development	– Education funding – Project pipelines to retain knowledge	[67, 68, 69]
Political Support	Uncertain Technology Funding	– Long-term funding guarantees – Resilience to leadership changes	[70, 69]

Converter Designs

Figure 6. Power electronic converters.

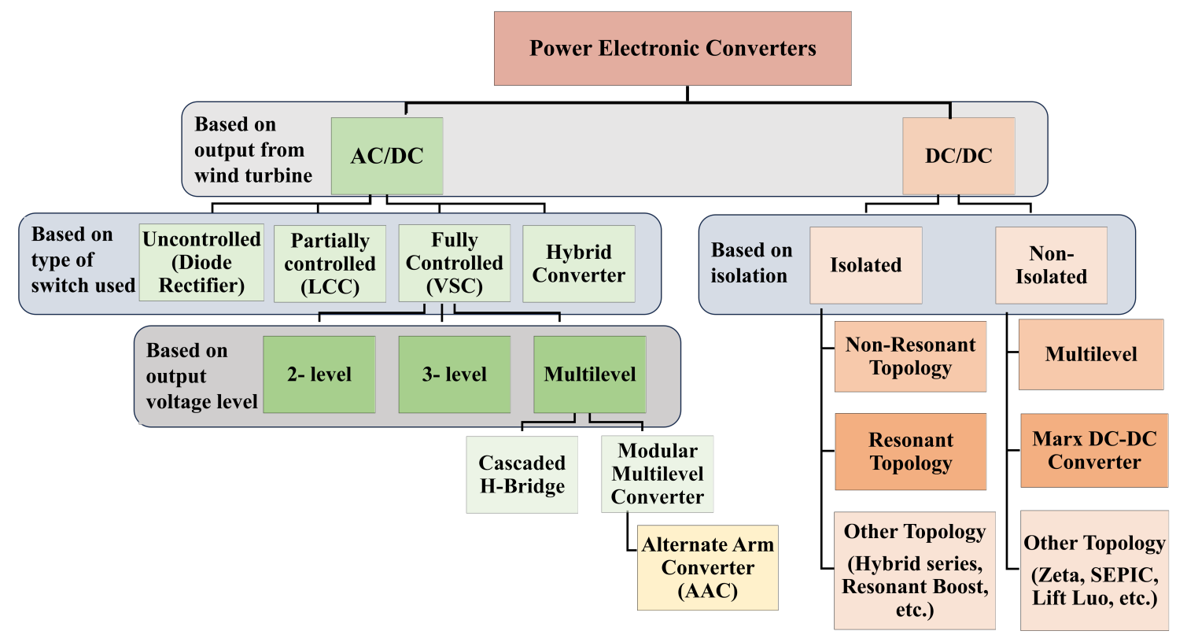
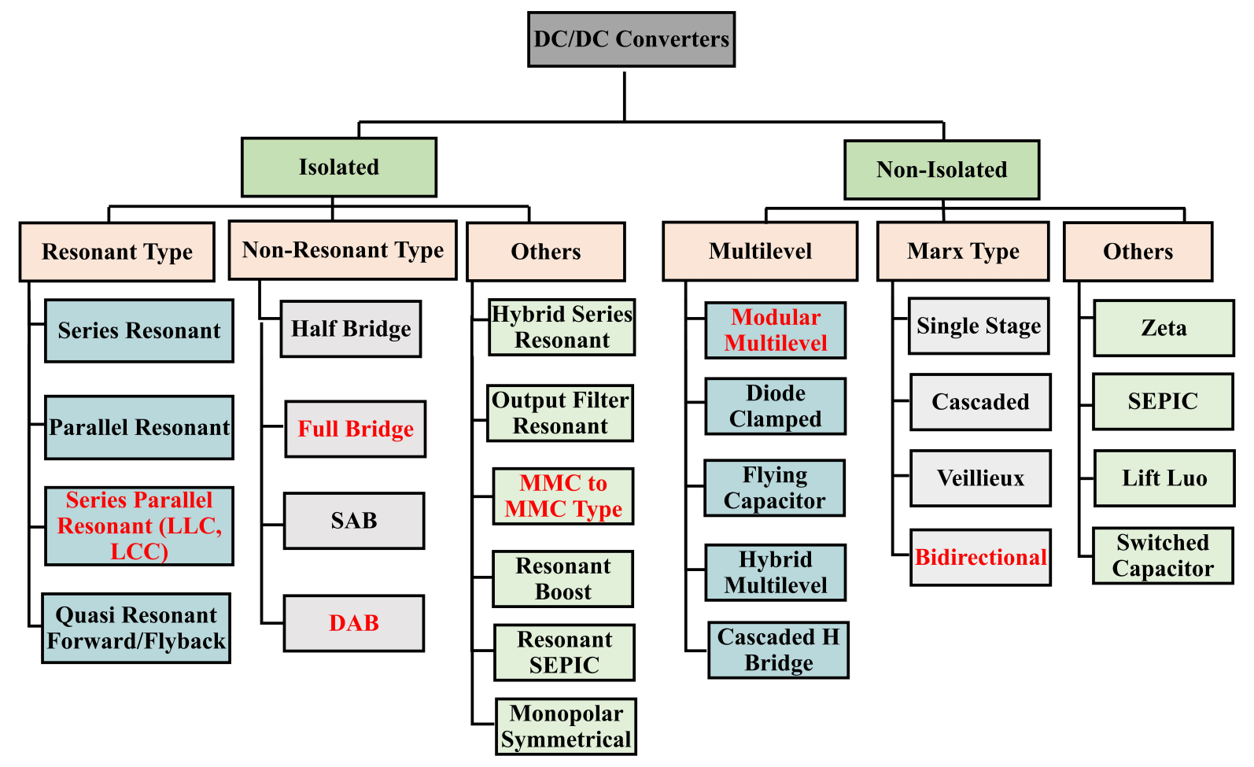


Figure 7. DC/DC Converters.



Conclusions and Next Steps

- Grid Architecture:
  - Conclusions: New architectures like MTDC and Mesh have strong potentially for fault-tolerance
  - Next Steps: Focus on scalability and reliability and onshore integration through improved load management.
- Converter Technologies:
  - Conclusions: Substations major cost of HVDC, DC-to-DC converters could potentially eliminate the offshore substation
  - Next Steps: Emerging technologies like medium-frequency systems, HVDC with transformer integration, and series DC grids. Investigate solid-state transformers and DC-DC converters for better cost, reliability, and performance.
- Modeling and Computational Advances:
  - Conclusions: Need for improved impedance modeling, joint techno-economic operations modeling
  - Next Steps: Improve modeling techniques by enhancing dynamics, accuracy, and co-simulation capabilities. Develop computational innovations for efficient simulation and system operation.
- Economic and Market Integration:
  - Conclusions: Economics get better with system size and line length, need economic analysis of reliability
  - Next Steps: Techno-economic sensitivity analysis and equilibrium models of OWF. Stochastic optimal control for economic and technical variables.

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