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Comparative Benefit Analysis of Meshed Offshore Wind Grid

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SUMMARY

As the demand for renewable energy sources continues to escalate, offshore wind farms have emerged as a prominent solution for sustainable electricity generation. The effective design and layout of these wind farms play a pivotal role in optimizing energy output, reducing costs, and ensuring overall operational efficiency. This paper delves into a comparative analysis of two typical offshore wind farm topologies, namely the Radial and Meshed configurations using production cost model. Three years, i.e., 2035, 2040 and 2050, are simulated with 8760-hour data for a fictitious system with three different Pathways to reach the targeted offshore capacity in 2050, which is 15 GW. The benefit of meshed topology is quantified using annual energy curtailment and system-wide production cost savings.

KEYWORDS

Wind energy, offshore grid topology, radial and meshed topology, production cost model, power transmission.

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1. Introduction

The offshore wind (OSW) development has experienced a rapid surge in recent years, driven by increasing concerns over climate change, the quest for cleaner energy sources, and government initiatives to boost renewable energy production. For example, to encourage offshore wind development, in 2019, New Jersey governor signed executive order to raise New Jersey's offshore wind goal from 3,500 MW by 2030 to 7,500 MW by 2035 [1]. In 2022, the goal is further increase by nearly 50 percent to 11,000 MW by 2040 [2]. New York also passed several landmark pieces of legislation such as the Climate Leadership and Community Protection Act (CLCPA) in 2019 which set ambitious targets including achieving 9,000 MW of offshore wind capacity by 2035 [3]. Those aggressive targets provide a clear signal to investors and developers, fostering confidence in the long-term viability of offshore wind projects.

There are normally two types of topologies regarding offshore wind farms. The traditional offshore wind farms, often near-shore or at a relative short distance from shore, are connected individually to the main electricity grid through dedicated radial cables, either using HVAC or HVDC. On the other hand, the meshed configuration represents a more intricate design wherein each wind farm is connected to multiple neighboring wind farms in a mesh-like network. This interconnection of wind farms allows for the creation of a redundant and flexible infrastructure for energy transmission and collection. For future large-scale wind farms, different connection possibilities should be analyzed to determine the best connection topology.

There are papers analyzing the optimal configuration for offshore wind farms [4]-[6]. However, they usually focus on the wind farms and do not include the model of large-scale onshore power grid. The real benefit of different interconnection topology can only be fully realized if the entire power grid model is included. Also, the benefit incurred from renewable energy curtailment reduction and production cost savings can only be fully calculated if all constraints in the system are modeled.

The objective of this paper is to perform an availability evaluation of various offshore wind connection scenarios under radial and meshed configurations. Three years, i.e., 2035, 2040 and 2050, are simulated under Security Constrained Economic Dispatch (SCED) with 8760-hour data to reach the targeted offshore capacity in 2050, which is 15 GW. The benefit of interlinks towards minimizing curtailment of offshore wind resources and reduce overall production cost are quantified.

2. The Modeling of Meshed Network

The guidelines for meshing are dictated by the NYSERDA Mesh Ready Requirements [7]. Each individual wind farm will have a dedicated radial HVDC link that will transmit power to shore. The radial HVDC link can transfer the rated capacity of the wind power generated by the corresponding Offshore Wind Generation Facility regardless of its connection to the Meshed Network. The meshed network is using 230 kV AC connections between offshore facilities with 400 MW rating of facility 20-40 miles limitation between connections. A conceptual design of meshed topology is shown in Figure I.

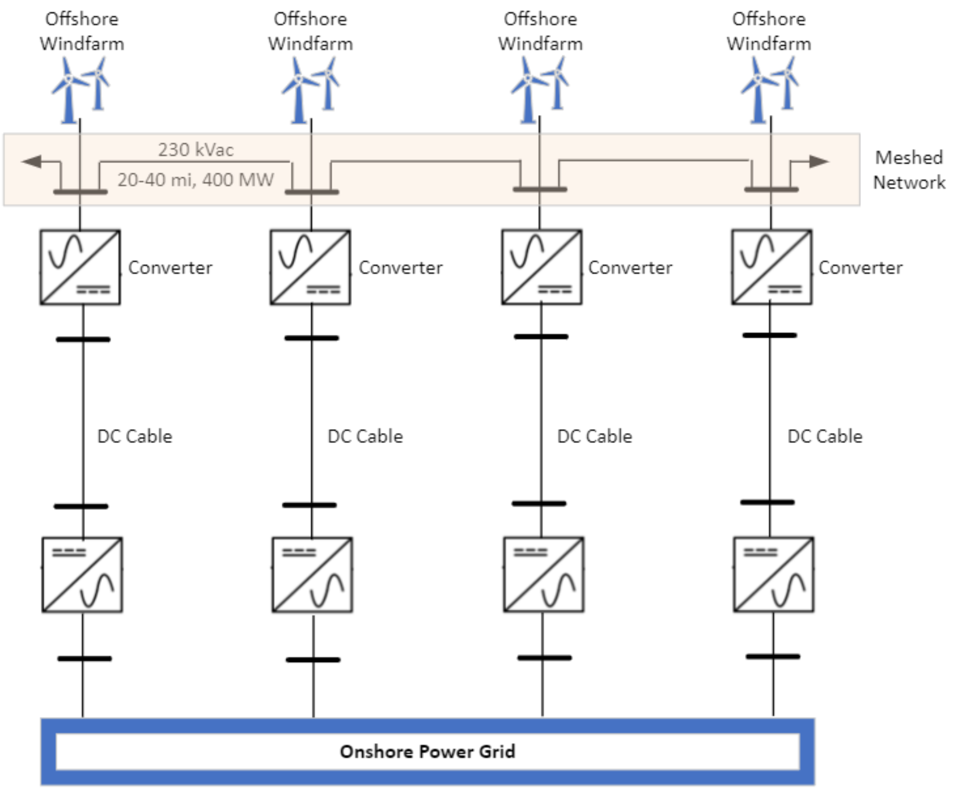

FIGURE I – MESHED TOPOLOGY FOR WIND FARMS

3. Road map from 2035 to 2050

A fictitious system, namely "the Main System", are simulated with two neighboring Balancing Authorities, namely "BA1" and "BA2". Three offshore wind buildout plans, namely Pathway 1, 2 and 3, are shown in Table I. The goal is to reach 15 GW total offshore wind by 2050. The net load for the Main System and total OSW generation (without considering curtailment) in 2035, 2040 and 2050 is shown in Table II.

TABLE I – OFFSHORE WIND BUILDOUT PLAN

Pathway	Scenario Definition	Year	Total OSW	Main System (GW)	BA1 (GW)	BA2 (GW)
1	1A	2050	15 GW	15	0	0
1	1B	2040	7.5 GW	7.5	0	0
1	1C	2035	4.5 GW	4.5	0	0
2	2A	2050	15 GW	12.4	2.6	0
2	2B	2040	7.5 GW	7	0.5	0
2	2C	2035	4.5 GW	4.5	0	0
3	3A	2050	15 GW	12	1.5	1.5
3	3B	2040	7.5 GW	7	0	0.5
3	3C	2035	4.5 GW	4.5	0	0

TABLE II – THE MAIN SYSTEM NET LOAD AND TOTAL OSW GENERATION

Year	Main System Load (GWh)	Total OSW Capacity (GW)	Total OSW Generation (GWh)	Percentage (%)
2050	146,400	15	60,400	41.3%
2040	125,300	7.5	30,200	24.1%
2035	107,500	4.5	18,100	16.8%

Meshed network is established for all pathways. Figure II shows the final stage of meshed network in 2050 for all three pathways.

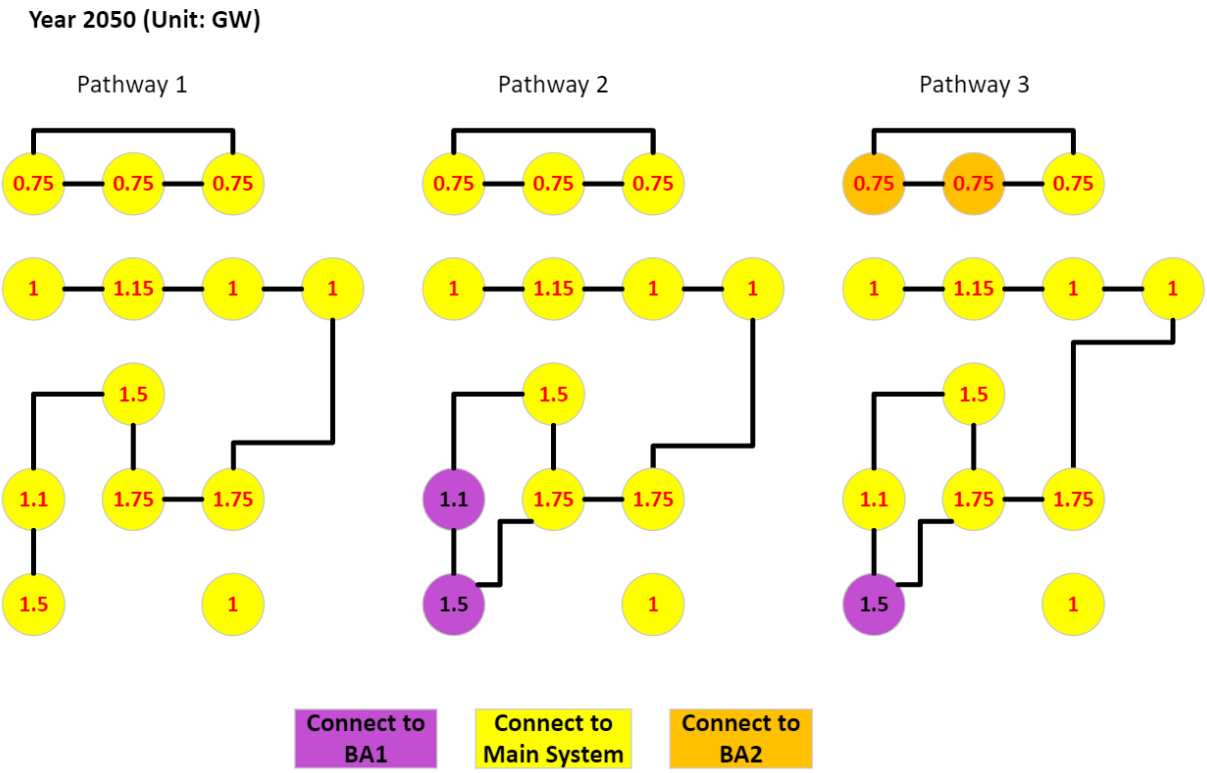

FIGURE I – MESHED NETWORK FOR THREE PATHWAYS IN 2050

The production cost simulation model is built for year 2035, 2040 and 2050. The system-wide total production cost is defined as the total generation cost, plus the net cost of energy import/export from neighboring BAs.

4. Simulation Results

A total of 18 cases, including the 9 scenarios with radial or meshed topology, were simulated using production cost model. The total production cost of the Main System of each case was calculated from the 8760-hour simulation results and shown in Table III.

TABLE III – CURTAILMENT REDUCTION AND PRODUCTION COST SAVINGS UNDER MESHED TOPOLOGY

Pathway	Scenario Definition	Study Year	Main System Production Cost under Radial Topology ($M)	Main System Production Cost under Meshed Topology ($M)	Main System Production Cost Saving under Meshed Topology ($M)
1	1A	2050	4393	4211	182
1	1B	2040	1927	1858	69
1	1C	2035	773	773	0
2	2A	2050	5129	4691	438
2	2B	2040	1994	1865	129
2	2C	2035	774	774	0
3	3A	2050	5116	4746	370
3	3B	2040	1933	1815	118
3	3C	2035	776	776	0

The result shows that from year 2035 to 2050, the benefit of meshed configuration increases. In 2050, meshed network for Pathway 1, 2 and 3 can reduce Main System total production cost by $182M, $438M, and $370M, respectively. Pathway 2 has the highest production cost savings. Note that Pathway 2 and 3 in 2050 have about $700 million higher production cost than Pathway 1. It is because under Pathway 1, all offshore winds are located within main system, reducing the cost of energy import from BA1 or BA2.

In order to under where does the production cost savings of meshed topology come from, a breakdown of different metrics in 2050 case for all Pathways are shown in Table IV.

TABLE IV – BREAKDOWN OF CURTAILMENT AND PRODUCTION COST REDUCTION IN 2050

	Pathway 1	Pathway 2	Pathway 3
OSW curtailment under radial topology (GWh)	4958	3996	2453
OSW curtailment reduction under meshed topology (GWh)	1022	2018	225
Main System Thermal Generation Reduction under meshed topology (GWh)	772	2003	2153
Main System Import Increase from BA1/BA2 under meshed topology (GWh)	-100	194	2143
Main System Production Cost Saving under meshed topology ($Million)	182	438	370

From Table III, it is seen that in year 2050, under meshed configuration:

- For Pathway 1, OSW curtailment is reduced by 1022 GWh. It causes 772 GWh less thermal generation in the Main System. The Main System total production cost saving is $182M, mostly due to savings from its thermal generation, replaced by OSW generation. No major changes of flow between Main System and BA1/BA2.

- For Pathway 2, OSW curtailment is reduced by 2018 GWh. It causes 2003 GWh less thermal generation in the Main System and 194 GWh more imports from BA1 and BA2. The Main System total production cost saving is $438M. The Main System pays more to BA1 and BA2 for the imports, but also saves a lot from internal thermal generation, replaced by imports and OSW generation.

- For Pathway 3, there is no significant OSW curtailment reduction, partially because the total curtailment is smaller to start with. The Main System thermal generation is reduced by 2153 GWh, primarily because of 2143 GWh more net import from BA1 and BA2. Main System total production cost saving is $370M. The Main System pays more to BA1/BA2 for the imports, but also saves a lot from internal thermal generation, replaced by the imports.

5. Conclusions

Based on production cost model simulation, the meshed topology provides significant total production cost savings and curtailment reduction, especially for future system which is highly congested and dependent on renewable resources. The 3 Pathways in this paper show different mechanism of total production cost reduction under meshed configuration. For Pathway 1, OSW curtailment is reduced within Main System, leading to reduced generation from high-cost thermal generation without major import changes. For Pathway 2, OSW curtailment is reduced, also leading to reduced generation from high-cost thermal generation in the Main System. Although net import/export changes are relatively modest from the Main System to neighbors, time and location of flows changes enough that system dispatch is more efficient. For Pathway 3, overall curtailment impacts are small, partially because the total curtailment is smaller to start with. Meshed topology allows for more net imports of lower-cost generation from neighbor BAs to displace higher-cost thermal generation in the Main System. Time and location of flows improve overall system dispatch. As a summary, the meshed topology shows significant potentials for OSW buildout optimization.

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