The Benefit and Cost of Preserving the Option to Create a Meshed Offshore Grid for New York

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Appendix: Hatch Offshore Wind Meshed Grid Design and Cost Analysis

I. Executive Summary

NYSERDA has asked The Brattle Group, in collaboration with Hatch and Siemens, to analyze the design, costs, and benefits of a meshed offshore grid, as compared to a design of offshore wind (OSW) plants with only radial interconnections. In particular, we were asked to explore the costs and benefits of a "mesh-ready" design for offshore substations that would support the cost-effective future implementation of meshed interconnections between the OSW plants.

As recommended in the Initial Power Grid Study Report (PGS Report),[1] the state has the unique opportunity to create the option for a meshed offshore network that would link the offshore substations of several individual OSW plants near each other. Such a meshed offshore grid offers the following benefits:

- Mitigation of facilities outages of the OSW gen tie and at the point of interconnection (POI) by providing alternative paths to deliver OSW generation;
- Reduced OSW curtailments due to onshore grid constraints through the ability to redirect injections to other POIs that do not face curtailments;
- Congestion-relief benefits (beyond reduced curtailments) by allowing for power transfers from lower-priced onshore POIs (e.g., located on Long Island) to higher-priced POIs (e.g., located in New York City);
- Improved onshore grid reliability and resiliency by adding redundancy to the onshore transmission system, including during grid outages due to severe weather or a physical disturbance;
- Ancillary services provided by HVDC technology, including voltage support and blackstart service, at each of the meshed POIs;
- Capacity value provided by increased transfer capability between capacity zones in the NYISO market; and
- Interregional energy and capacity values if OSW plants serving New York are linked with OSW plants with gen ties to neighboring power market regions (PJM and ISO-NE).

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[1] Pfeifenberger, J., *et al.*, "Initial Report on the New York Power Grid Study," Prepared for New York State Public Service Commission, January 19, 2021. Accessed: https://www.nyserda.ny.gov/About/Publications/New-York-Power-Grid-Study

The engineering analysis by Hatch (provided in the Appendix) concludes that the most attractive meshed grid design would link each OSW plant with two nearby OSW plants using three 66kV HVAC cables with a combined capability of 300 MW per link. The cost of creating a "mesh ready" offshore substation that can accommodate two such 300 MW links is estimated to add approximately $15 million (less than 0.4%) to the total cost of a 1,000 MW OSW plant. The additional cost of implementing a link between mesh-ready offshore substations (at some point in the future) would be approximately $120-240 million per link.

Siemens has undertaken an illustrative simulation of the 2040 energy market benefits of a meshed grid linking OSW plants with radial connection to Long Island and New York City. The analysis shows that (1) the optimal flows on links between OSW plants are generally less than 300 MW and (2) the savings associated with implementing such links may be in the order of $60 million annually. This suggests that, if state procured mesh-ready OSW plants, the payback periods associated with implementing meshed links in the future may possibly be as short as several years.

Allowing NYSERDA to require OSW developers to make small incremental investments today to preserve the option to create the mesh offshore grid gives the state time and flexibility on when and where to exercise that option to implement meshed links in the future.

II. Background

This report provides a discussion of a meshed offshore grid and mesh-ready substation designs, articulates the various types of benefits provided by a meshed grid, presents the results of an indicative analysis that quantifies some of those benefits, and provides an overview of the incremental cost of designing mesh-ready offshore substations that preserve the option to create a meshed grid if and when doing so is desirable in the future.

A meshed configuration can achieve a more reliable, economic and resilient delivery of OSW generation. However, a decision to implement a meshed system can be delayed (and perhaps should be delayed pending federal approval of new wind energy areas), as long as the State ensures that any projects with radial connections are constructed in ways that include the option to integrate the radial lines into a meshed system later. To create this option, the Commission has the unique opportunity to allow NYSERDA to require that the winners of future offshore wind procurements design their projects so they can be cost-effectively integrated into a meshed offshore transmission grid in the future, as recommended and discussed PGS Report.

As shown below, the economic benefits of being able to create a meshed offshore grid in the future are large (with payback periods possibly as short as several years), while the cost of creating this option through the procurement of “mesh-ready” offshore wind (OSW) projects is small (estimated to add less than 0.4% to the cost of an OSW plant).

The remainder of this report is organized as follows. Section II explores options for integrating OSW plants; Section III discusses the benefits of a meshed grid; and Section IV explores the cost and option value of procuring mesh-ready OSW projects and future meshed links. The Appendix includes the separate analysis by Hatch, specifying the technical design requirements for, and the estimated costs of, developing mesh-ready OSW projects and of implementing a meshed offshore grid in the future.

III. Options for Integrating Offshore Wind Resources

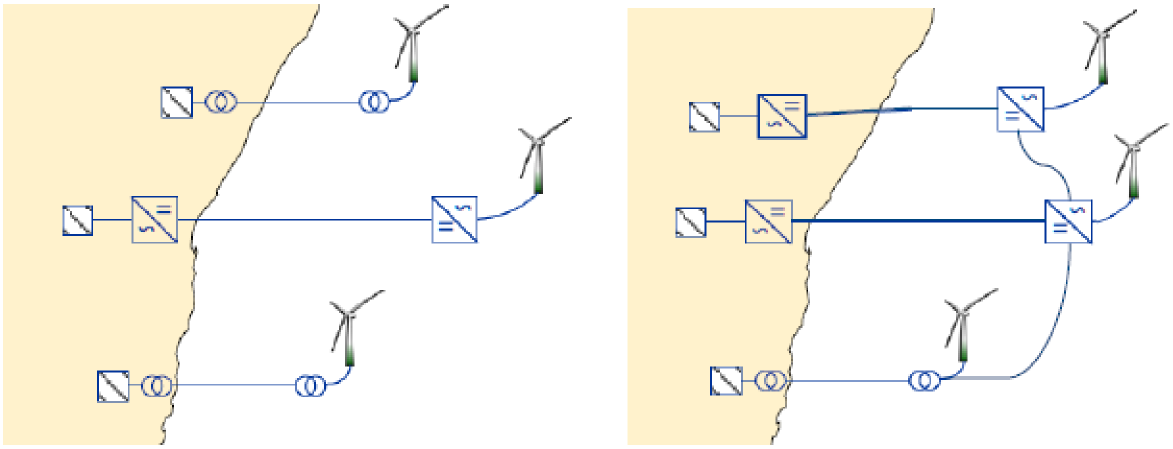
New York State has a unique opportunity to choose between two options for interconnecting and integrating the OSW resources to the state’s power system to comply with the Climate Leadership and Community Protection Act (Climate Act):

- **Individual Generation Interties (Gen Ties):** Under this first approach, projects are interconnected individually with transmission facilities built to support just a single offshore wind project. This approach is referred to as “direct radial” or “radial” interconnection. Current Orders from the New York Public Service Commission (the Commission) allow for the direct radial interconnection, and the OSW projects under development in the state apply this approach.[2]

- **Meshed-ready Gen Ties:** The State also has the opportunity to interconnect OSW resources through mesh-ready gen ties that could (in the future) be linked offshore to create a meshed offshore grid. In such a meshed offshore grid, the offshore substations of individual OSW projects are connected to each other, which provides a way to transfer energy between the individual OSW generation projects without first transferring power onshore, thus being able to mitigate gen tie outages. Even without outages, the meshed grid provides economic benefits becaues: (a) it allows to direct OSW generation to the points of interconnections (POIs) that offer the highest price for the injected OSW generation (to the extent transfer capability remains available on the other linked gen ties) and (b) provides a way to transfer energy between the onshore POIs by flowing power over the linked gen ties, creating a parallel path to the onshore grid to reduce network congestion.

Figure 1 illustrates the topology difference between the two approaches. In the diagram on the left side of the figure, the three OSW projects are radially connected to the onshore transmission system. In this configuration, there is no connection between the three offshore projects, and power from each project is injected onshore only through the individual gen ties.

FIGURE 1: RADIAL VS. MESHED OFFSHORE WIND INTEGRATION



On the right side of Figure 1, two offshore transmission links connect the three OSW projects. The illustrated meshed configuration allows power from each project to flow onshore through

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[2] July 2018 Order, pp. 56–58, and October 2020 Order, pp. 47–48.

any one of the three interconnections. However, to be able to control and optimize the power flows on the three radial gen ties, at least two of the three gen ties (or N-1 of N gen ties) need to deploy technology that can control power flows, such as HVDC gen ties.

As noted in the attached Hatch analysis, a configuration with only HVDC gen ties is advantageous, as it simplifies the operational control of the meshed grid. Importantly, as discussed in other NYSERDA analyses, the use of HVDC technology for the radial gen ties also offers: (a) much higher transfer capability per cable (*e.g.*, 1200 megawatts (MW) per HVDC cable compared to 400 MW per HVAC cable), which would allow for a more effective use of the limited cable routing space to reach POIs in New York City; and (b) certain benefits at the onshore POIs, such as reactive power control and blackstart capability.

The Commission Orders currently focus on radial designs. However, the Commission has the ability to preserve the option for developing a meshed grid in the future, by allowing for the procurement of mesh-ready radial gen ties, which could later be linked to create a meshed grid (if and when it would be beneficial to do so). As noted in the PGS Report:

> Creating the option for a meshed offshore network by linking the offshore substations of several individual OSW plants near each other is valuable because a meshed configuration can achieve a more reliable and resilient delivery of OSW generation. However, a decision to implement a meshed system can be delayed (and perhaps should be delayed pending federal approval of new wind energy areas), as long as the State ensures that any projects with radial connections are constructed in ways that include the option to integrate the radial lines into a meshed system later.[3]

The next section of this report presents a discussion and an illustrative quantification of the potential benefits that a meshed offshore grid could provide to the State's grid, to inform the question whether the State should create that option through the procurement of mesh-ready OSW gen ties.

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[3] Pfeifenberger, J., *et al.*, "Initial Report on the New York Power Grid Study," Prepared for New York State Public Service Commission, January 19, 2021, pp. 2–3. Accessed: https://www.nyserda.ny.gov/About/Publications/New-York-Power-Grid-Study

IV. The Benefits of a Meshed Offshore Transmission Grid

The integration of OSW projects through a meshed offshore transmission network would create several benefits for New York power customers. A meshed offshore grid exploits the fact that OSW resources will interconnect at multiple onshore locations that are geographically diverse and electrically different. A meshed grid allows power to be diverted from one OSW resource to the gen ties of the linked OSW resources, which can help manage a gen tie outage, capture higher prices in the market, reduce congestion and increase reliability by reinforcing the NYISO onshore grid, provide additional ancillary services at the POIs, and (possibly) provide additional transfer capacity to a neighboring region if the OSW mesh includes OSW generators with gen ties to neighboring power markets (such as ISO New England or the New Jersey portion of PJM).

A. Types of Meshed Offshore Network Benefits

A meshed offshore grid can create the following benefits for wholesale power customers and ratepayers in New York.

- **Gen Tie and POI Outage Mitigation:** Meshed configurations provide alternative paths to deliver OSW generation from plants with outages on their generation tie lines or POI-related facilities (such as the HVDC converter station, onshore substation, or onshore grid facility outages that reduce how much power can be injected at the POI). While such alternative deliveries will be possible only to the extent that the other meshed gen ties are not fully utilized, significant outage mitigation will be provided by the fact that OSW plants rarely generate at their full output levels for which the gen ties are sized.
- **Reduced Curtailments due to Onshore Constraints:** an interconnected offshore system will result in lower curtailments for OSW resources (even beyond the outage mitigation benefit discussed above). In a radial system, if congestion exists on the onshore grid near the POIs, it may limit the amount of power that can be injected from the OSW resource, potentially resulting in a curtailment. In a meshed system, that power could be redirected to other gen ties and injected into POIs that don't face curtailments. The reduction in OSW curtailments will reduce production costs by avoiding the use of conventional resources to serve load, which will lower the price of power for New York consumers. The reduction in curtailments will also have environmental benefits, as fewer curtailments imply lower production from thermal resources that emit greenhouse gases and other pollutants.

- **Congestion Relief:** even without curtailments, a meshed system provides economic benefits by facilitating increased injections into higher-priced ("constrained-on") POIs and allowing for power transfers from lower-priced onshore POIs to higher-priced POIs. Congestion relief results in lower overall system production costs, ultimately reducing costs for customers. The meshed offshore system will provide congestion relief whenever price separation occurs between the onshore POIs and there is available capacity on the offshore transmission system to shift power from on onshore POI to another. Congestion relief benefits will be larger in meshed grids that connect to a more diverse set of POIs, such as when some POIs are located on opposite sides of congested paths or across regions with large price differentials. For example, a meshed offshore grid that connects onshore interconnection points in New York City (NYISO Zone J) with an onshore interconnection point on Long Island (NYISO Zone K) can provide large congestion benefits. We analyzed the historical real-time energy prices in Zones J and K over the last five years and found that the average hourly price difference between the two zones is $9.34/MWh, which is likely to increase as more renewable energy is injected in both zones. Therefore, the ability to transfer 100 MW of power between the zones could result in over $8 million/year in congestion relief benefits based on recent history.[4]
- **Improved Onshore Grid Reliability and Resiliency:** a meshed offshore grid adds redundancy to the transmission system, which improves reliability and resiliency. The offshore grid improves transfer capability on the onshore system, which can help system operators manage contingency conditions without shedding load. The offshore grid may also avoid onshore transmission upgrades that otherwise would be necessary to maintain reliability. A meshed offshore transmission system will improve the resiliency of the system, by being able to transfer power between the POIs, thereby offering an alternative to onshore facilities that may face an outage or be limited due to severe weather (*e.g.*, a flood or concentrated storm damage) or a physical disturbance. Resilience is further improved by the ability to provide blackstart capability at each POI of the meshed grid, which can help reduce restoration times.
- **Ancillary services:** if OSW resources are connected using HVDC technology, the meshed gird will be able to directly provide certain types of ancillary services. Specifically, as noted above, an HVDC meshed offshore grid can provide blackstart service to the onshore grid at each of the POIs. The use of HVDC technology also allows the system to provide or absorb reactive power and voltage support at the respective POIs to address local grid needs.

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[4] Data accessed from "Hitachi ABB Power Grids, Velocity Suite, ISO Real Time and Day Ahead LMP Pricing Database," accessed October 6, 2021, NYISO Real Time LMPs for January 1, 2016 – December 31, 2020.

- **Capacity Value:** a meshed offshore network can increase the transfer capability between regions in the NYISO market, which would allow for higher imports and exports of capacity resources across those regions. For example, an offshore grid that links OSW resources that interconnect in Zone J and Zone K would increase the import capability into Zone J during peak hours and potentially lower capacity prices in Zone J. We studied capacity prices in Zones J and K over the last five years, and found that prices in Zone J have been $5.35/kW-Month higher than in Zone K ($8.55/kW-month in Zone J vs. $3.20/kW-Month in Zone K).[5] The annual value of this capacity cost difference is $6.4 million for 100 MW of transfer capability.
- **Interregional Energy and Capacity Values:** The ability to link OSW plants serving New York with OSW plants with gen ties to neighboring power market regions (PJM and ISO-NE) provides additional benefits by enabling interregional energy and capacity transfers. For example, based on NYISO's resource adequacy framework, interregional capacity benefits can be captured either through capacity imports or the resource adequacy value of uncommitted intertie capacity to neighboring markets.

B. Illustrative Quantification of Cost Savings Offered by a Meshed Offshore Grid

On behalf of NYSERDA and in coordination with the Brattle team, Siemens conducted an illustrative simulation of the NYISO power system and neighboring markets for 2040 to estimate the cost savings from a meshed offshore grid between Zones J and K. The Siemens analysis studied the grid in 2040 (based on study assumptions used in simulation work Siemens recently performed for NYSERDA for other purposes), assuming that about 12,500 MW of OSW are installed and interconnected in Zones J and K at that point in time. This analysis simulated two cases:

1. A **Base Case** all 12,500 MW of OSW are radially interconnected into Zones J and K; and
2. A **Mesh Case** in which four OSW resources are linked into a fully controllable (HVDC-based) offshore meshed grid. The simulated illustrative links can transfer up to 1200 MW between the four offshore wind plants and their POIs, which are located in Zone K and Zone J. The four resources that form the illustrative meshed grid configuration include two OSW resources interconnected in Zone J, totaling 1,400 MW, and two resources interconnected in Zone K, totaling 800 MW.

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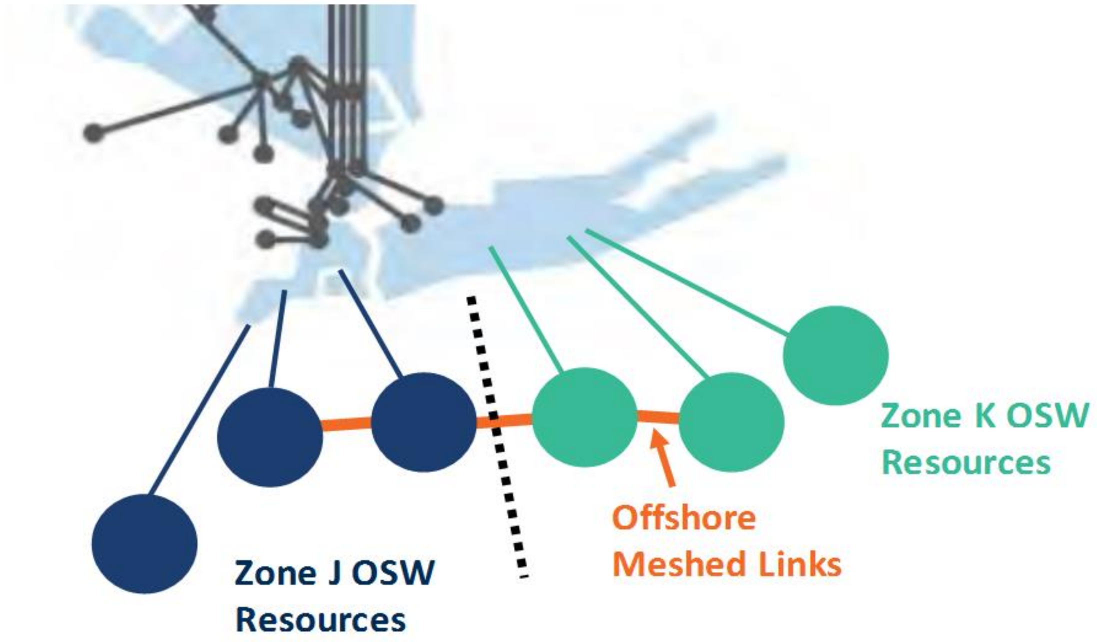
[5] Potomac Economic, 2020 State of the Market Report for the New York ISO Markets, May 2021, pp. 47–48

Figure 2 below illustrates the simulated OSW generation plants, the gen ties from these plants to their respective onshore POIs, and the meshed links between four of these plants. OSW plants and their gen ties that are interconnected to POIs in Zone J are shown in blue, while plants and gen ties connected to POIs in Zone K are shown in green. The relative short meshed links between the four nearby OSW plants (modeled only in the mesh case) are shown in orange.

FIGURE 2: SIMULATED OSW GENERATION, TIE LINES, AND MESHED LINKS



The simulations assume that (1) the Champlain Hudson Power Express (CHPE) is in service and interconnected at the Rainey substation in Zone J; and (2) each of the gen ties between the OSW resources and their onshore POIs would experience a planned (not simultaneous) 1 week outage each year (representing a 2% annual outage rate).

A comparison of how the production costs change between the two cases provides a lower-bound estimate of the production cost benefits that a meshed grid would provide by 2040. Figure 3 below summarizes the results of this illustrative analysis. The analysis finds that the meshed grid provides roughly $40 million/year of adjusted production cost (APC) savings in 2040 (but expressed in current, 2021 dollars).[6] The largest driver of the simulated cost

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[6] Adjusted production costs are a proxy for the cost of serving load that includes (a) the cost of operating generation resources (*i.e.*, fuel costs, variable O&M, startup costs), plus (b) the cost of system purchases, less (c) the revenues earned from off system sales.

reduction comes from net reduced purchases from neighboring markets ($33.2 million)[7]. The remaining cost reduction comes from a savings of $5.2 million from reduced operation of local thermal resources, an increase in sales revenue from exports to neighboring markets of $2.0 million/year (even though less power is exported in the Meshed Case), and the avoided cost of unserved load of $2.6 million/year (when valued at only $1,000/MWh).[8] The "Reduction in Quantity (MWh)" column shows the avoided MWh of thermal production, emergency power, and net purchases due to the meshed offshore grid.

The Siemens analysis further demonstrates how a meshed offshore grid can help reduce congestion between the linked POIs. In the analysis, due to the injection of OSW and additional renewable energy through CHPE into Zone J, the prices in Zone K tend to be higher than in Zone J in the Base Case. The analysis finds that the resources most likely to be curtailed in the Base Case are the OSW resources interconnected to Zone J and CHPE. The meshed grid alleviates those curtailments and allows power to flow from Zone J to Zone K to capture higher prices, which results in the decrease in thermal production shown in Figure 3 and the corresponding cost savings.

FIGURE 3: ESTIMATED 2040 ADJUSTED PRODUCTION COST SAVINGS DUE TO ILLUSTRATIVE MESHED OFFSHORE GRID BETWEEN ZONES J AND K (BASE CASE VS. MESH CASE)

	Avoided Cost (2021$)	Reduction in Quantity (MWh)
Thermal Production	$5,152,957	26,834
Avoided Unserved Customer Load	$2,612,185	3,805
Net Purchases from Neighboring Markets	$33,225,378	449,684
Total Adjusted Production Cost	**$40,990,520**	

The 2040 simulation is based on a meshed grid with a 1,200 MW transfer capability between the linked OSW resources and, correspondingly, between Zones J and K. The study results,

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[7] Net purchases are cost of purchases less sale revenues. It is a better metric for comparison as it accounts for hours when there is a change from purchasing to selling and vice versa between the Mesh and the Base Case results.

[8] Since typical estimates of the average value of lost load (VOLL) tend to range from $3,000/MWh to $20,000/MWh, more realistic estimates of this value likely exceed $10 million/year.

however, show that simulated transfers never exceed 1,000 MW and almost never exceed 800 MW. Importantly, transfers over the individual links are less than 300 MW during 80–90% of the year, as shown in Figure 4 below.

Figure 4 shows the flows on each of the three 1200 MW links simulated in the illustrative meshed grid configuration analyzed by Siemens.[9] As shown in the dark blue line, power on the link between the two 400 MW OSW resources with POIs in Zone K flows in both directions during roughly the same amount of time with flows rarely exceeding 200–300 MW. The green line shows that the link between the 400 MW and 1000 MW OSW resources in Zone J flows away from the 1000 MW OSW resource (with flows that rarely exceed 400 MW even though the linked nearby OSW plants offer 1200 MW of gen tie capacity), reflecting both Zone J surplus generation conditions (during periods of high CHPE and OSW injections into Zone J) as well as the need for congestion relief within Zone J. The light blue line, charting flows from OSW plants in Zone K to OSW plants in Zone J, indicates that this link is used most often to export power out of Zone J and into Zone K (as reflected by the negative Zone K-to-J flow values)—although these J-to-K flows rarely exceed 300 MW.

The data in Figure 4 implies that the optimal and most cost-effective transfer capability for the studies gen tie and POI combination may only be in the 300-400 MW range, but the specifics would need to be evaluated if and when implementing a meshed grid is considered in the future.

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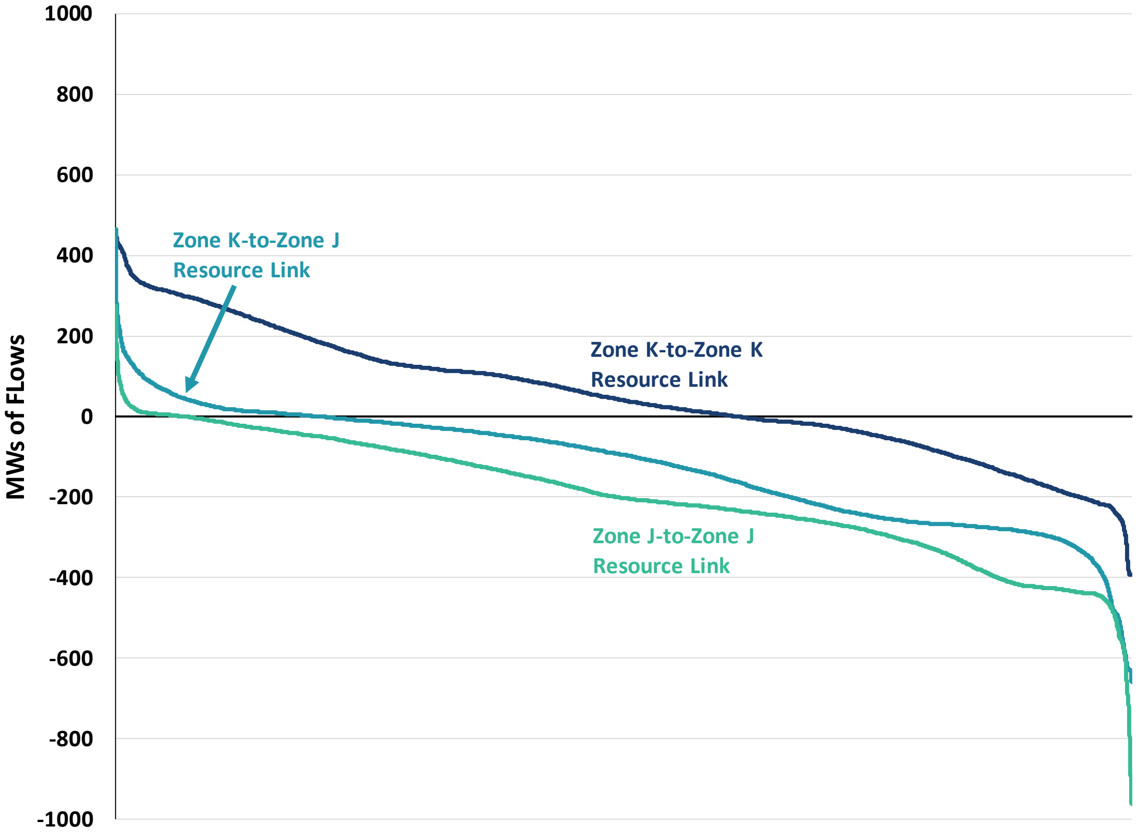
[9] The 1200 MW capacity of the offshore links was chosen, for the purpose of this illustrative analysis, to allow for power transfers between the onshore POIs in addition to re-routing OSW generation output (rather than limiting transfers to the size of the OSW plant or less).

FIGURE 4: FLOWS ON OFFSHORE LINKS OF THE MESHED GRID



It is important to note that standard production cost simulations, like the one used in this illustrative analysis, are known to underestimate the actual savings of new transmission infrastructure. This is because these simulations analyze only "normal" and fully predictable operating conditions. This leaves out a large portion of the value of transmission infrastructure that occurs during uncertain and stressed system conditions. For that reason, Potomac Economics, the Independent Market Monitor (IMM) for NYISO, has found that adding 40% to the simulated APC benefits of transmission infrastructure is appropriate (and recommended) to obtain more accurate estimates of production cost savings.[10] Adding the IMM-recommended

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[10] Potomac Economics, Market Monitoring Unit for the NYISO, "NYISO MMU Evaluation of the Proposed AC Public Policy Transmission Projects," February 2019, p. 16, stating the following:

> [A production cost simulation] model does not include transmission outages and unforeseen factors such as load forecast error that exacerbate congestion during actual market operations and, as such, does not fully capture the value of new transmission lines that may help mitigate the impact of such factors. Transmission outages drive a large share of congestion in market operations, especially in areas with renewable generation. For example, we have found that most export-congestion from the North Zone is caused by transmission outages. Moreover, in the AC Transmission Proceeding, the Brattle

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40% to the simulation results implies that the cost savings from the illustrative meshed grid configurations range from $55 to $60 million per year.

This estimate may still underestimate the total benefits. First, there are several plausible future scenarios where a meshed offshore grid would deliver larger production cost benefits. For example, the state of New Jersey is planning to add 7,500 MW of OSW resources, which would decrease the ability to export to PJM and increase curtailments in Zone J, making the meshed offshore grid between Zones J and K even more valuable. Similarly, additional OSW resources interconnecting in Zone J or additional upstate renewables delivered to Zone J (*e.g.*, through Clean Path New York) would increase the benefits from a meshed grid between Zones J and K.

Second, the above estimate is conservative because it does not include a quantification of several additional benefits that, as we understand, are important to New York State and the work of the state's Climate Action Council:

- Climate and health benefits due to reduced OSW curtailments and deeper offsets of thermal generation
- Improved onshore grid reliability and resiliency
- Ancillary services provided by the offshore grid
- Capacity value from increased transfer capabilities between Zones J and K

These benefits, not quantified above, would add additional value to a meshed offshore grid.

V. The Option Value of Procuring Mesh-Ready OSW Plants

Although current Commission Orders are limited to radial constructions, the Commission has the ability to preserve the option to build a meshed offshore network in the future through an improvement of the radial paradigm to include "mesh-ready" OSW substations. Fortunately, as the discussion below shows, the cost of preserving that option is low, and the potential future

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> Group report developed several ways of estimating how transmission outages and other unforeseen factors would affect actual market outcomes relative to what the…model would simulate, including one that would scale-up the production cost savings estimates by 40 percent. We accounted for this issue in our B/C ratio by incorporating the 40 percent adder.… [W]e recommend that future production cost simulations incorporate such factors.

benefits are large (as demonstrated by the list of benefits and illustrative simulations discussed above).

As the attached analysis by Hatch documents, the infrastructure needed to preserve the option to connect with a meshed grid in the future is limited with only minor incremental costs beyond a pure radial design. A new OSW project will need to include an offshore substation that can collect the output from the individual wind turbines and feed that generation to the gen tie line that connects the plant to the onshore grid. A platform, located near the offshore wind turbines (within the lease area for the project), hosts this offshore substation. To preserve the option to connect these offshore substations into a meshed offshore grid in the future would require the OSW developer to install some additional electrical and mechanical components—additional cable bays and shunt reactors. This would require a slightly larger platform to provide the space needed to host these additional components.

This additional infrastructure is relatively low cost and represents a small percentage of the overall cost of an OSW resource. Hatch evaluated several meshed grid design options and determined the incremental equipment and estimated cost necessary to develop a mesh-ready offshore substation for the recommended design. The recommended design links each OSW substation to two neighboring stations with three HVAC submarine cable links operated at the same 66kV voltage levels as the cables that connect modern large individual wind turbines to the substations. This design would allow for about 300 MW of transfer capability between two neighboring OSW plants. As explained in the Hatch Appendix, the proposed design is preferable to alternatives because it does not require additional voltage transformation at the OSW substation (which would add substantial cost)[11] nor does it rely on still-costly new HVDC technologies (for which there is currently very limited operational experience).

The Hatch analysis finds that the following physical equipment and costs are necessary to ensure the offshore substation is mesh ready for the recommended 66 kV design:

- **Six additional Gas-Insulated Switchgear (GIS) cable bays at the offshore substation:** needed to interconnect mesh links to each OSW substation. The mesh configuration analyzed by Hatch includes three 66 kV HVAC lines connecting neighboring offshore substations, which means six cable bays are needed at each substation (for three cables going in each direction to two neighboring stations). The cable bays will not be utilized until the HVAC links of the meshed grid are constructed in the future, but building them

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[11] Hatch estimates that the incremental cost of a mesh-ready OSW substation requiring voltage transformation to 230kV) would be approximately triple the incremental cost of the 66 kV mesh-ready design (that does not require transformation).

in the initial design is substantially more economical than modifying the offshore substations later. The estimated cost of each cable bay and switchgear is $900,000, for a total estimated cost of $5.6 million per offshore substation.

- **Six shunt reactors:** needed to compensate for AC cable charging. One shunt reactor is needed for each cable connecting at the offshore substation. The estimated charging capacity needed is 5.7 MVAR/mile (0.475 MVAR/mile per reactor times six), and the estimated cost of charging capacity is $30,000 per MVAR. The configuration studied by Hatch assumed 20 miles between each offshore substation, which implies a total cost for shunt reactors of $1.71 million per substation. Similar to the cable bays, it is more economical to install the shunt reactors at the time the substation is constructed.
- **Additional steel to build a larger platform:** the additional cable bays and shunt reactors will require a larger platform to host the offshore substation. The estimated additional steel needed to increase the size of the platform is 75 tons, costing $5,300/ton. The total estimated cost of additional steel is $400,000 per substation.
- **Mesh operating studies:** needed to ensure that the grid controls developed for and installed at each OSW plant are designed (at the outset) to be able to operate with meshed links. The estimated cost of these (one-time, up front) studies is $6-$8 million.

The total estimated incremental cost of the physical infrastructure needed to build a mesh-ready substation is $7.71 million with an additional $6–$8 million in operating studies. In comparison, the total estimated cost of a 1,000 MW OSW generating plant with its OSW substation and gen tie to its onshore POI is approximately $4 billion.[12] Therefore, the estimated cost of $7.71 million for physical infrastructure and $6–$8 million for studies represent between 0.34% and 0.39% of the total cost of each OSW plant.

The cost to exercise the option in the future and construct an offshore mesh by building the offshore transmission line(s) needed to connect the individual OSW plants is relatively inexpensive (compared to the potential benefits) for the recommended design. The only infrastructure necessary to exercise the option to link OSW plants in the future are the two sets of three 66 kV submarine cables. Hatch estimates that the cost of purchasing the 66 kV cable is about $1–$1.4 million/mile. Assuming the substations are 20 miles apart, the cost would be $20–$28 million per cable. The estimated cost of laying the cable is $0.72–$2.74 million/mile. Therefore, the total estimated cost of creating one link in the mesh grid (consisting of three 66 kV AC cables between two offshore substations) would be $120–$240 million. Compared to the

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[12] Based on NREL's estimate of the installed cost of offshore wind of $4,077/kW.

$55–60 million in potential annual benefits associated with a meshed grid (as estimated in the illustrative simulation analysis discussed above). Assuming most of this available value is concentrated in one 300 MW link, this means that it might take only several years to fully recover the cost of implementing the meshed grid—though a benefit-cost analysis for the specific scope and circumstances of a meshed grid would need to be undertaken at that point in time.

VI. Key Takeaways

Allowing NYSERDA to require OSW developers to make small incremental investments today to preserve the option to create the mesh offshore grid, gives the state time and flexibility on when and where to exercise that option in the future. The Commission can conduct, or order, future analysis of the costs and benefits of exercising the option to create an offshore grid. If the option is preserved today, that analysis can be conducted 5–10 years from now, based on the evolution of the transmission system, the resource mix, and the anticipated benefits of creating a meshed offshore grid at that point. The procurement of the meshed grid could even be part of a future PPTN conducted by the NYISO.

In short, procuring mesh-ready OSW plants creates a low-cost option to build a meshed-grid in the future. Once created, this option does not expire and the Commission will have increased flexibility over the next decades to exercise that option if or when it become valuable and, if benefits were to be informed further through an interregional study, the Commission could also potentially use this design framework for beneficial connections to OSW plants serving regions beyond the NYISO.

The proposal for meshed-readiness has the major benefit of continuing to support the pace of NYSERDA's competitive offshore solicitations, which is needed to meet CLCPA mandates. By integrating meshed-ready designs as an increment to the radial paradigms, NYSERDA can continue to procure OSW resources from the available lease areas without the need to first evaluate, procure, and construct other offshore grid alternatives. By continuing to rely on procuring OSW resources with their own gen ties (although high-capacity HVDC gen ties that better utilize the available cable corridors), this framework also continues to offer clarity to generators as to their project scope, thereby reducing project-on-project risk relative to a solution that entirely separates offshore transmission from OSW resource development (a concern that has previously been expressed on the Commission's docket).

The importance of acting now to create this option to build a meshed offshore grid in the future is made clear by the analysis above. It was recently highlighted by the New York Independent System Operation (NYISO),[13] which recommended that "the PSC must move quickly before the option [of a meshed offshore grid] is no longer viable," and that "a meshed network to connect offshore wind farms is best pursued as soon as possible before opportunities for an efficient design are foreclosed."[14]

As this report shows, the investment to preserve the option of creating a meshed offshore grid in the future is small (approximately 0.4% of the cost of an OSW plant) in comparison to potential future net benefits from implementing an offshore grid (estimated to potentially be of sufficient value to support simple payback of the cost of implementing the meshed links in only a few years). Procuring mesh-ready OSW plants now consequently provides the Commission with flexibility in making decision on future meshed-grid-implementation in the future. Therefore, it is beneficial to New York State customers and ratepayers for the Commission to allow NYSERDA to require OSW projects to make the investment in preserving the option to build a meshed offshore grid.

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[13] Case 20-E-0197, *Proceeding on Motion of the Commission to Implement Transmission Planning Pursuant to the Accelerating Renewable Energy Growth and Community Benefit Act*, Comments of the New York Independent System Operator, Inc. on Initial Report on the Power Grid Study and Department of Public Service Staff Questions (March 22, 2021).

[14] *Id.*, pp. 14–15.

APPENDIX
Hatch Offshore Wind Meshed Grid Design and Cost Analysis

Date: October 29, 2021

Appendix to Brattle Report:

Offshore Wind Meshed Grid Design and Cost Analysis

Table of Contents

1. Introduction

Brattle contracted Hatch to provide support in defining the technical requirements required in order to define an offshore transmission system to be “Mesh Ready”. This request is to address the State of New York future offshore wind development of 9000 MW by 2040. In this memo, Hatch has defined the technical requirements for a “Mesh Ready” system, the associated marginal cost estimates in terms of “Mesh Ready”, and “Mesh Implementation”, as well as electrical benefits that the meshed system provides to both the offshore and onshore systems.

2. Definition of a Meshed Grid

The rapid development of offshore generation requires a robust offshore network to maintain onshore system stability and security of supply, especially with systems with high penetration levels of renewable resources. Traditionally, each offshore project is connected to the onshore system through a radial connection using either HVDC or HVAC systems. Implementing a meshed grid provides a number of benefits to the grid, such as ease of operability, increased offshore network utilization, additional onshore system stability and security of power supply. Figure 1 below shows a proposed meshed offshore network.

Please note the definition of the meshed grid is being further developed under a separate contract with NYSERDA. In this context, a key enabler of a meshed grid system is the assumption that the radial connections from the off-shore wind to the on-shore points of interconnection will be HVDC.

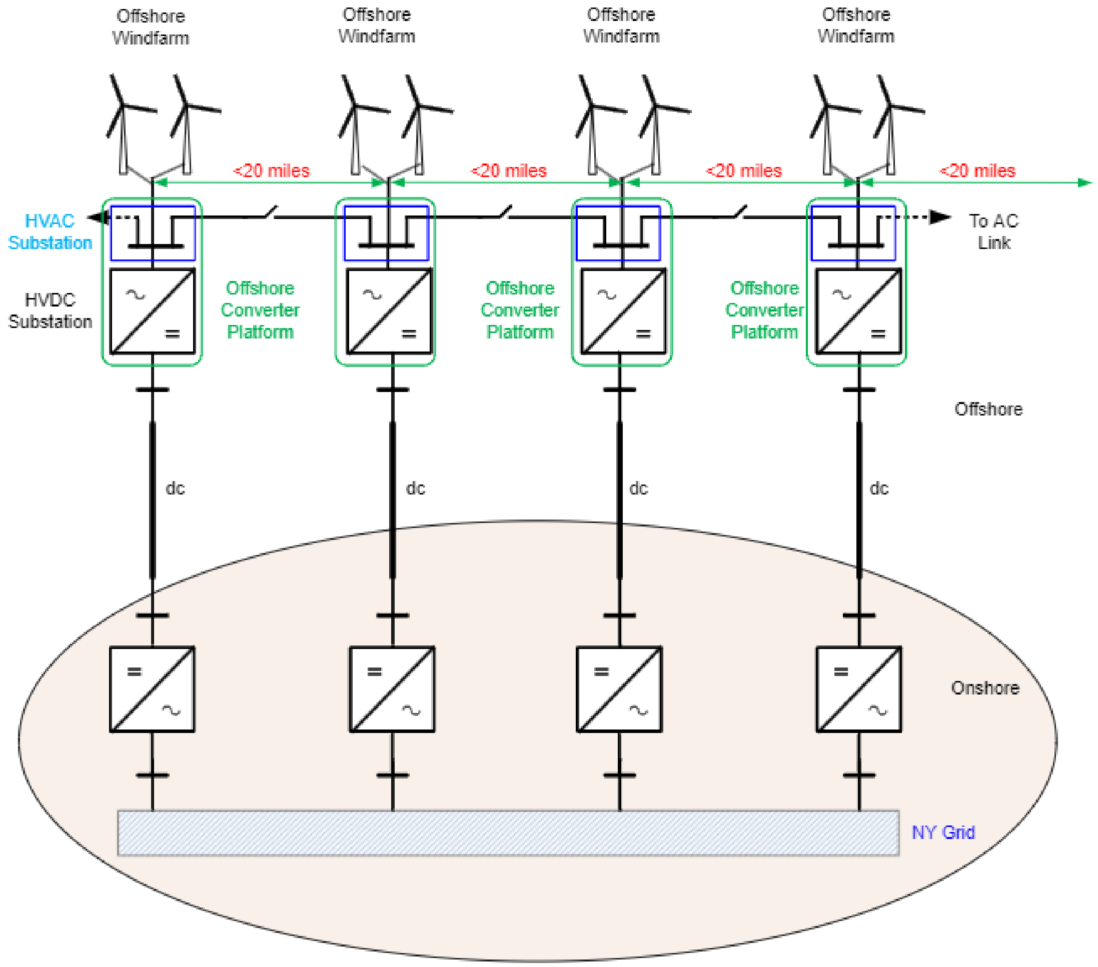

Figure 1: Meshed Grid

2.1 HVAC vs HVDC meshed Grid

To achieve the goal of implementing a meshed grid, various methods of interconnection were investigated. The two main categories of investigation revolved around interconnecting the grid on the HVAC side or the HVDC side of the off-shore converter station. Advantages, disadvantages and high level costs were looked at in order to make a determination of the best method for the meshed interconnection. Please note this analysis is only looking at the advantages of the meshed system, and assumes the connection to shore is HVDC.

2.1.1 *HVAC Interconnection*

The theory behind an HVAC interconnection is to mesh the grid before the energy is converted to HVDC by the offshore substation, as shown in Figure 2.

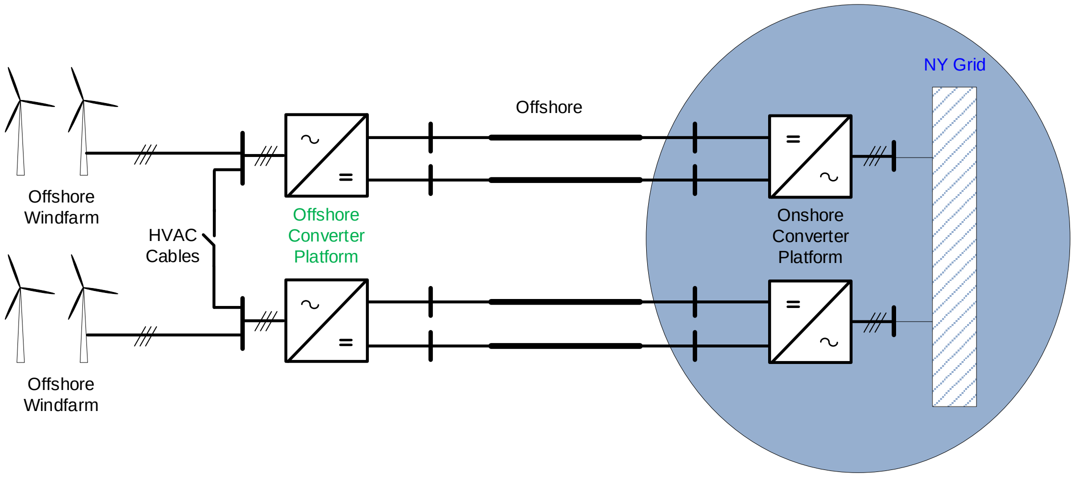

Figure 2: HVAC Meshed Connection

2.1.1.1 *Advantages of HVAC*

Lower Costs: The substations will already be equipped to consolidate the power from the various infield cables connecting the individual turbines to the offshore converter substation. By adding additional meshed cabling the marginal increase in costs will not be significant compared to the overall CAPEX. The meshed system will allow for redundancy of connection between platforms.

Simplicity: Experience with HVAC technology is much more prevalent than the HVDC technology that would be required to mesh the system on the DC side of the converters. HVAC requires a limited amount of controls to mesh when compared to the HVDC- system and the HVDC control systems can be easily configured to accommodate this. Furthermore, it de-risks the requirement for different HVDC vendors to provide inter-operability between their HVDC controls. This in return reduces the time to develop and test sophisticated control algorithms that are required for linking HVDC systems, and hence speed up the time to implement the meshed grid system.

Reliability: When developing the meshed grid, one of the major drivers is the overall meshed grid reliability. By developing the meshed grid on the AC side of the offshore converter platforms, one can increase the system reliability of the various HVDC systems without increasing the complexity of the point-to-point HVDC systems (which could lead to a decreased reliability). When using DC-side links, this increased complexity would be driven by the requirement for enhanced inter-operability between different OEM’s systems and the introduction of technology that has not been deployed commercially to-date (such as DC circuit breakers). In contrast, when creating a meshed system on the AC side, each HVDC system is utilizing controls that are already inherent to the radial HVDC system (with some slight modifications), for an over-all more reliable system.

2.1.1.2 Disadvantages of HVAC

Interconnection Distance/Power Transfer limit: HVAC transmission efficiency drops off over long distances, and requires additional compensation for cable charging in order to connect over long(er) distances. Figure 3 below shows HVAC submarine cable transmission capacity decline over distance, considering different voltage levels.

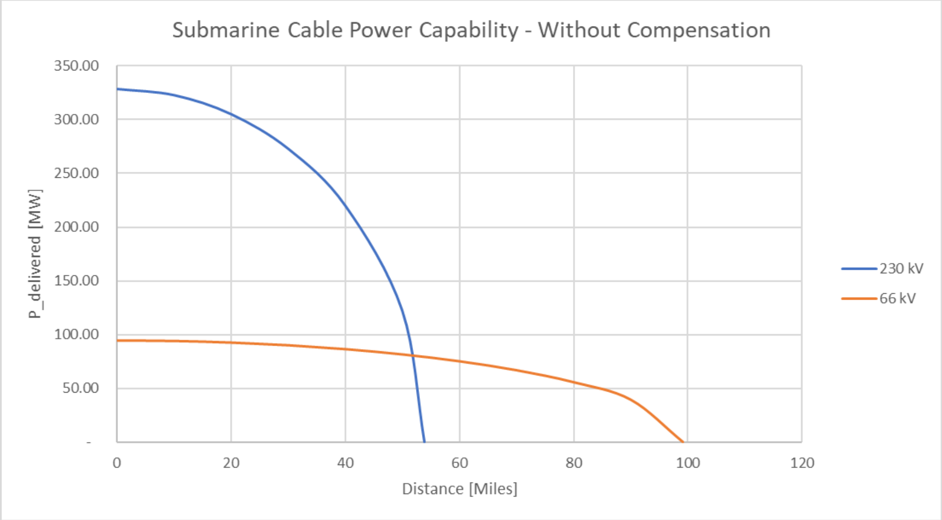

Figure 3: HVAC Submarine Cable Transfer Capacity in terms of distance

2.1.2 HVDC Interconnection

An HVDC interconnection would mesh the grid with connections to each of the HVDC radial links as shown below in Figure 4.

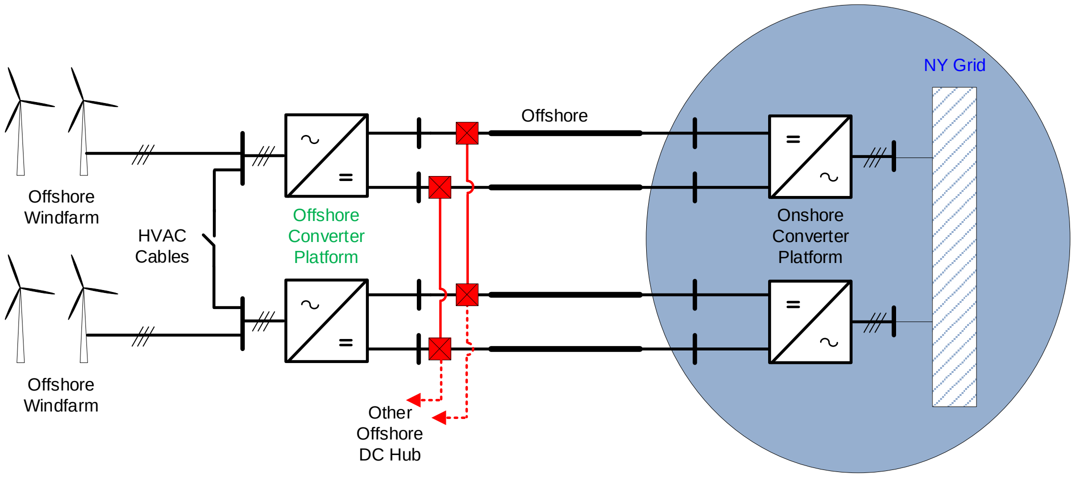

Figure 4: HVDC Meshed Connection

2.1.2.1 Advantages of HVDC

Longer Connection Capability: When utilizing subsea cables, HVDC lines have no distance limitations when connecting. This would allow an HVDC mesh to connect projects at much further distances than its HVAC counterpart, as there is a practical limit one can connect using AC cables as previously mentioned.

Optimize Power Flow: HVDC interconnection allow for very precise controllability of power between offshore platforms by controlling the scheduled power to shore on each link, thereby increasing offshore network utilization during unbalanced power generation condition from offshore platforms. HVDC interconnection can also provide a fast and tailored response during transient events compared to HVAC interconnections. HVDC systems can also provide the following ancillary services:

- Primary frequency Control
- Fault Ride Through capability
- Black-start capability
- Power flow optimization on the offshore grid

2.1.2.2 Disadvantages of HVDC

Costly: In comparison to HVAC, the size and cost of implementing the HVDC meshed network would be greater due to increased equipment cost required to interface on the DC side of the bus at the full HVDC voltage which is anticipated to be 320kV to 525kV. This includes all main circuit equipment (such as the DC bus, DC breaker and switches) and cabling, opposed to the lower cost 66kVac cables being proposed for the meshed grid.

DC Circuit Breakers: A failure event along any of the meshed lines would cause the entire meshed system to have to be shut down in order to clear the fault. To prevent this a HVDC circuit breaker would need to be installed on each platform. The technology for HVDC circuit breakers is in its relative infancy.

2.2 HVAC Design Selection

After a careful review of both the HVAC and HVDC meshed systems it was determined that and HVAC mesh design would provide the best technological solution that cost-effectively meets the goals of New York and NYSERDA of creating a meshed offshore grid option.

The main drivers for this was the relative close proximity of many of the offshore wind lease areas, which means the distance constraints associated with HVAC will not be an issue. Most lease areas up for auction are within 20 miles from each other. At this distance HVAC is a much more suitable option. HVAC also allows for less expensive upfront costs and technology risks to developers, which will enable higher degrees of cooperation and acceptance of a meshed solution.

While HVDC technology is advancing, it is most cost effective for long distances with commercial experience mostly for point-to-point (but not multi-terminal meshed) systems. If in the future it is deemed crucial to link projects that are not practical with AC, a HVDC link could be added to select projects to enable this. It was deemed too costly to expect all offshore wind developments to have to incorporate HVDC connection capabilities when a HVAC connections would be suitable and more cost effective in most situations.

2.3 Assumptions for Creating a Meshed Grid with HVAC Links

The following assumptions were made to help define the parameters that would allow a system to be considered mesh ready.

- The radial connections from the off-shore wind to the on-shore points of interconnection will be HVDC.
- The meshed grid will be designed to optimize the utilization of the offshore system, it will not increase to total capacity that it is capable of delivering to shore. I.e. the size of the DC connections to shore will not change under a mesh ready system.
- The links for creating a meshed grid will be constructed after the completion of the individual offshore wind projects and their HVDC gen ties. Each individual project will have its own radial HVDC line that will transmit power to shore. The implementation of a meshed grid will not increase the total capacity of delivering offshore wind generation to the onshore grid, but it will increase the operability of the network and provide a means for power to be directed where it is most needed or most valuable.
- The offshore stations must design their offshore substations with the capability to be mesh ready.
- All significant hardware, with the exception of the cables are assumed to be installed during the onshore fabrication of the off-shore substation. Installing the large components at the offshore state later would significantly increase the cost of the entire system due to the complexities regarding retrofitting equipment in an offshore environment. (due to additional costs for vessels, installation tools, permitting, and testing requirements)
- Each substation will be able to be linked with two neighboring off-shore substations.
- Each meshed connection will be an HVAC connection and will be able to transmit at least 300 MW of power throughout the meshed system at a distance of at least 20 miles from the offshore station to another meshed offshore station.
- The meshed system is to transmit the energy at a voltage level of 66kV, which the voltage level now used to interconnect modern offshore wind turbines (of 12-15 MW

each) to the offshore platform. Each cable is expected to transmit approximately 100MW of power, therefore a total of 3 3-phase cables will be needed to generate the mesh.[1]

- Projects that are meshed are all to be connected to the NY grid. Meshing to POIs in other power markets is not being investigated in this study effort but would be enabled through the NYS meshed-readiness.
- All dollars are in Real 2021 USD unless explicitly stated.

3. Cost of an Offshore Wind Project

The capital expenditure of off-shore wind projects have been decreasing in price over the recent years due to larger turbines and more efficient manufacturing and installation methods. The CAPEX of an offshore wind project according to the National Renewable Energy Laboratory (NREL) estimates that projects executed in 2019 the cost of offshore wind was $4,077/kW of installed capacity [1]. A project with nameplate capacity of 1GW[2] would then likely have a CAPEX of approximately $4 Billion USD, though costs of OSW generation continues to decline.

For an offshore wind project, the electrical infrastructure, which includes the onshore and offshore HV substations. For a HVDC project, the HVDC substation can make up for a significant portion of the electrical costs. The cost of a pair of offshore and onshore HVDC converter substations capable of transmitting over 1GW to shore is approximately between $600 and $850 million USD [2], which does not include the cable costs.

4. Meshed Grid Costs

The implementation of a meshed grid between projects would come in two phases, the first phase would ensure that all projects are “mesh ready” whereby they are designed with the capabilities to integrate with other projects. This includes the basic design and controls are ready to be meshed with other systems. The second phase is the mesh implementation phase whereby the projects, once already commissioned, would integrate with one another. The goal of the two phased approach is to limit upfront costs while preserving the option to create a meshed grid in the future, and maximize the efficiency of the meshed system.

4.1 Mesh-Ready Costs

For a station to be mesh ready, additional electrical components, mechanical components will need to be procured and additional studies must be performed in order to define the requirements. The preliminary list of equipment is:

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[1] 66kV was chosen as it appears that the collector lines will feed the offshore substation at 66kV then be transferred directly to HVDC. Transmitting at a higher voltage level would require a transformer which would greatly increase the costs and space needed on the substation. The new turbines of 12+MW scale are expected to transmit at 66kV, and this voltage level is expected to be the new standard for offshore wind infield transmission moving forward.

[2] The 1GW reference project was chosen, as it is estimated that the new lease areas have a projected capacity of approximately 1GW.

GIS Switchgear Cable Bays: A typical off-shore HVDC substation could have between 12 to 18 66kV bays, each connected to a string of offshore turbines. Additional cable bays will be needed to allow for the meshed system. An estimated 6 additional bays will be needed as it will require three 66kV cables to be able to transmit the required power[3] to each other substation. Each cable bay has an estimated cost of $900,000 for the cable bay and GIS switchgear. A total cost of $5.6 Million will be needed for these cable bays.

Shunt Reactors: To be able to transmit the energy through these cables, shunt reactors must be added to compensate for AC cable charging. 6 shunt reactors will need to be installed, one for each cable. Each shunt reactor will compensate 30-40% of its respective line, with the other 30-40% being compensated by the substation on the other end. Based on preliminary calculations it is that expected total charging capacity of 5.7 MVAR/mile will be needed (0.475MVAR/mile required per reactor), at an assumed cost of $30,000 per MVAR of charging capacity, a total cost of $85,500 per cable mile of shunt reactors are to be expected ($14,250 per mile of cable per reactor). With an assumed 20 mile distance between platforms a cost of $1.71 million of charging compensation will need to be installed.

Transformer (if required): The current assumption states that the meshed grid would be at the same voltage level as the infield cables. By meshing in this way a transformer would not be necessary. Should the mesh occur at a higher voltage, to allow for higher capacities over longer distances with larger cables, a transformer would be required. The cost of a 300MVA transformer capable of converting the power would be approximately $6 million. Two of these transformers would need to be installed (one for each 300 MW meshed link), for a total cost of $12 million. In addition to the cost of the physical transformer, additional offshore space for these 175 ton pieces of equipment would need to be allotted. Overall, the total costs of increasing the voltage level could be $20-$30 million per substation.

Additional Steel: In order to house the additional cable bays and shunt reactors, the size of the platform must also increase. The total additional steel that would be added to the structure is estimated to be 75 tons. The steel required for an additional bay is relatively small in comparison to the size of the entire structure, which is likely to weigh over 10,000 tons. It is unlikely that the addition of the switchgear would impact the substructure or structural design. A total cost for the additional space would be approximately $400,000 USD.

Mesh-Ready Studies: In order to be mesh ready, additional studies and control systems must be implemented for each OSW plant. These studies, among other things, will ensure that adding the meshed lines to the network, and the corresponding increase in the overall current of the system can be controlled. These items do not have a significant material cost, as the measures taken would not increase the amount of hardware offshore. They do however require simulation time and person hours to ensure that the HVDC system of each OSW plant is capable of handling the operational requirements of the meshed system. Further more specific studies would need to be performed once the meshed system is under construction and the offshore interconnection parameters are known. It is expected that the various studies could take up to 6-8 months to complete, with an approximate cost of $6-8

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[3] Each 66kV cable is expected to be able to transmit approximately 100MW of power

million added to the design work of OSW plant controls. With proper planning these studies have the potential to be done in parallel with the other studies that must be performed by the developer for their normal operations to reduce the overall scheduling increase.

The total cost for a station to become mesh ready is illustrated in the table below and is expected to be $15.7 million.

Table 1: Mesh Ready Costs -- 66kV Design

Item	Cost Per Item ($USD/item)	Quantity	Total Cost ($USD)
GIS Switchgear	900,000	6	5,600,000
Shunt Reactors	285,000	6	1,710,000
Additional Steel	5300	75 tons	400,000
Studies and engineering	8,000,000	All Studies	8,000,000
Total	**-**	**-**	**15,710,000**

The major cost of a project becoming mesh ready is in the studies and engineering required and the additional switchgear needed. With a total cost of the 1GW OSW farm expected to be approximately $4 billion, the incremental cost increase of creating a mesh-ready OSW substation capable of connecting two 300 MW mesh links is approximately 0.4% of the total cost of the OSW balance of plant.

If a decision were to be made to increase the voltage level from 66kV to 230kV through the addition of two offshore transformers (one for each link) to achieve the same 300 MW of transfer capability per link, the costs would be broken down as seen in Table 2.

Table 2: Mesh Ready Costs for 230 kV (including Transformation)

Item	Cost Per Item ($USD/item)	Quantity	Total Cost ($USD)
GIS Switchgear	2,500,000	2	5,000,000
Shunt Reactors	1,850,000	2	3,700,000
Additional Steel	5300	375 tons	2,000,000
Studies and engineering	10,000,000	All Studies	10,000,000
Transformer	6,000,000	2	12,000,000
Additional Electronics	-	-	8,000,000
Total	**-**	**-**	**40,700,000**

The addition of the two transformers would significantly increase the upfront cost of the offshore substation. The transformers would require additional space, increase the total weight of the structure and increase the complexity of the system as a whole. A total cost of over $40 million could be expected for this type of meshed solution, increasing the cost-adder of creating a mesh-ready OSW substation to 1% of total OSW plant cost. Increasing the transfer capacity of each of the links to values higher than 300 MW per link will require larger transformers, shunt reactors, and more switchgear, thereby further increasing costs.

4.2 Meshed-Built Implementation Costs

The following are the key costs that would be incurred when actually constructing the meshed system.

66kV Cables: The cost of a 66kV cable is between $1 and $1.4 million per mile. For a 20 mile connection a cost between $20 and $28 million would be needed to purchase each cable.

Cable Laying: The cost of laying cables can also vary depending on the cables, vessel and subsea conditions. However a range of $0.72 and $2.74 million per mile of cable laid can be expected. It is unlikely that all three cables could be laid simultaneously, as has been assumed that each cable would be laid separately.

Mesh-Built Studies/Commissioning: Once the various projects that are to be meshed together are selected, a set of studies will need to be performed to ensure that the proper controls and communication between the specific components are met and then the system commissioned. The total cost of these studies would be in the range of approximately $5 - $7 million.

Total Costs: The total cost of purchasing, laying and connecting a 66kV cable is expected to be $2.2–$4.4 million per mile of cable. A total of 3 cables over 20 miles must be installed in order to mesh the system, this gives a total project cost of $120-$240 million for the implementation of a single “link” (to connect two substations with three cables) of the meshed grid.

With an expected project CAPEX of $4 billion, the implementation of a the meshed system would correspond to a 3% to 6% increase to the overall project. There is potential for these costs to be reduced by implementing multiple meshed grids at the same time. Projects located closer than 20 miles would also reduce the cost of installation as the costs are very dependent on the distance between substations.

5. Electrical Benefits of a Meshed Grid Design

Meshing the offshore grid provides a number of benefits that can help to increase the reliability, efficiency and resiliency of the grid. The following sections illustrate these benefits.

5.1 Redistribution of Energy

By implementing a mesh between offshore projects, the offshore grid will become much more flexible in the way the power is able to be distributed. The impact of outages on any single HVDC line can be reduced by transmitting some of the power that would have been lost to surrounding projects. Under our assumption of a 300MW mesh, a total of 600MW of power could be recuperated by transmitting the energy to two neighboring facilities, provided the neighboring facilities have the available capacity.

The ability to redistribute the energy between platforms also allows for the injection of power to the optimal POI. It is likely that the offshore locations will have POI’s at varying locations onshore. By adding an offshore meshed system additional power can be transferred to POI’s with higher demand.

5.2 Increased Efficiency of Energy Transfer

The overall energy transfer to shore can also be optimized through a meshed system. Power generated from offshore wind is inherently variable according to the wind conditions offshore. One project may be operating at maximum capacity, while a neighboring project could be operating at a lower capacity. In the event that two or more meshed wind farms are operating at varying levels of capacity the meshed system can help balance the energy transfer to shore in order to reduce the losses in the system.

5.3 Increased Utilization of HVDC lines

Meshed networks can also allow increased utilization of HVDC lines. This is evident when an offshore project is experiencing a sudden surplus of energy, due to wind gusts. This surplus can then be rerouted to the nearest underutilized converter platform through the HVAC submarine cables, and exported to the shore through HVDC lines, thereby increasing HVDC lines utilization during different wind conditions and reducing offshore generation curtailments. This feature can be employed by developing the converter controls for grid forming, with one hub considered as “leader” and the rest of wind projects as the “followers”. In order to prepare the existing offshore system to be “Mesh Ready”, different system studies need to be performed to assess the offshore system response, and tune control parameters for a satisfactory response based on offshore system equipment limits, and onshore system normal and emergency limits.

5.4 Power Wheeling Between POIs

In the event of low wind generation, the offshore meshed grid can be used to help the onshore transmission network redistribute power to other POIs, this procedure is referred to as Power Wheeling. This feature will help alleviate any thermal congestions seen on the onshore transmission system, during critical system events. Excess power near one of the onshore POIs can be transferred to another onshore POI through the offshore grid, thereby bypassing any limited onshore transmission facilities during periods of network congestion.

5.5 Voltage Support and Black Start Capability

VSC-based HVDC systems (now the standard technology utilized for off-shore HVDC) can offer voltage support and black start capabilities. HVDC converters can independently control the injection of real and reactive power, which allows them to provide voltage support to the onshore grid at the POI (irrespective of whether the HVDC lines are meshed). During a black start, energized converters connected to their respective 66 kV offshore wind collector system can be linked together through the HVAC mesh on the AC side of the offshore substations, thereby synchronizing all of the meshed offshore HVDC converter substations, before energizing the rest of the onshore system. This added capability will help with onshore system stability performance during black start sequence.

5.6 Overall Grid Stability

Due to all of the reasons mentioned in this section, the grid is more stable with an HVDC cables linked through an offshore mesh, allowing for minimized impacts of faults, optimization of power distribution and control of the system.

6. References

[1] Stehly, Tyler, and Philipp Beiter. 2019 Cost of Wind Energy Review. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-74598.

[2] Sembcorp Marine, GE Firm Up $826M Sofia Offshore Wind Farm Contract, Offshore Engineer, 2021.

[3] A. J. Beddard, "Factors Affecting the Reliability of VSC-HVDC for the Connection of Offshore Windfarms," University of Manchester, Manchester, UK, 2014.

[4] M.Callavik, A. Blomberg, J.Hafner, B.Jacobson, "The Hybrid HVDC Breaker an Innovation breakthrough enabling reliable HVDC grids", ABB Grid Systems, Technical Paper, 2012.

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Attachment(s)/Enclosure