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# Economic Assessment of an Offshore HVDC Grid in North America

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## SUMMARY

During the last few years, integration of large scale offshore wind energy has been experiencing an increasing growth in many parts of the world. Also, in North America there is a strong government initiative to reduce the amount of greenhouse gas (GHG) emissions that can be accomplished in part by integration of offshore wind sources. This demand has created an interest in offshore transmission infrastructure, particularly the possibility of offshore HVDC grid applications. When compared with individual HVDC links, , an offshore HVDC grid will enable the aggregation and delivery of power from geographically distributed offshore wind farms, resulting in power generation profiles of lower variability and higher economic value. In addition, an offshore HVDC grid facilitates power exchange and trading between coast regional power grids.

This paper investigated the economic benefits of a visionary offshore HVDC grid in North America using a demonstration case located in the Mid-Atlantic region, a major resource for high quality wind energy. Integration of about 8 GW of offshore wind power is facilitated by various offshore converter stations that are located along the Atlantic coast. The interconnected converter stations constitute the HVDC grid that runs in the North-South direction and terminates at the onshore substation embodied in larger scale transmission grid (AC transmission grid). Here, an economic assessment methodology is presented and the benefits of HVDC grid is analyzed against that of individual HVDC links with direct connection between onshore and offshore stations. The demonstration case is modelled using industry recognized software program GridView™ for economic assessment.

The economic impact of integrated offshore HVDC grid is observed in conjunction with the onshore AC transmission grid. The onshore AC transmission grid incorporates detailed generation, demand, and transmission system models of NERC Eastern-Interconnection electricity market based on the year 2013. The wind farms are modeled based on hourly wind profiles representative of the offshore wind speeds in the targeted wind energy areas. The economic analysis is based on the simulation results of integrated model for one year in one-hour increments, to capture the seasonal variations of wind energy and the corresponding seasonal variations in the electrical loads. Key operational indicators such as generation dispatch from fossil fired units are then analyzed to evaluate the impact of the offshore wind on system costs and GHG emissions.

## KEYWORDS

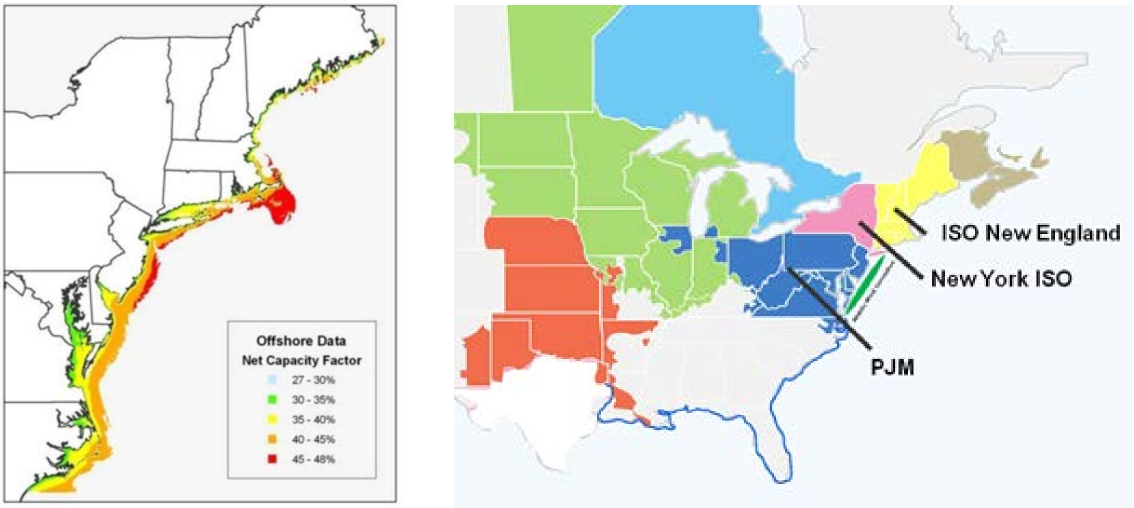
Offshore wind, HVDC Grid, Multi-Terminal HVDC, HVDC Link, Economic Assessment, GridView

# 1. INTRODUCTION

In North America, especially in the US there is strong government initiative to reduce the amount of greenhouse gas emissions and to reach power requirement of 20% wind by 2030, the cumulative installed offshore wind capacity in US is expected to be 60 GW [1]. Offshore wind has been identified as a viable energy source to meet this objective. The National Renewable Energy Lab has reported accessibility of close to 1,071 gigawatts of offshore wind generation resources for depths between 0 – 30 meters across the US shallow shores [2].

Integration of bulk renewable power generation, especially offshore wind farms, to existing AC power grids requires a massive new transmission network. Offshore wind farms close to major load centers have the unique advantage of delivering clean energy close to loads. A lot of load centers in North America face local transmission congestion due to unavailability of right of ways or environmental concerns against overhead lines. A number of these load centers are located close to shore Figure 1(a). Underground transmission is becoming a viable option for injecting power into load centers from the environmental perspective especially when constructed within existing rights of way. Submarine transmission is also getting more popular for connecting between major load centers. Wind farms that tie in to submarine transmission lines close to load centers are definitely attractive for environmental reasons.

An offshore HVDC grid, also called a multi-terminal Direct Current transmission system (MTDC) based on voltage source converters (VSCs) is now technically feasible [3], is considered more superior alternative to integrate and transport large renewable energy resources. To illustrate these benefits results are compared with individual HVDC links, also called point-to-point (PtP), with direct connection between onshore and offshore wind generation stations.



(a) (b)

Figure 1: (a) Locations of offshore sites in Eastern Interconnection [2] (b) Map of US-Eastern Interconnection electricity power market [6].

# 2. ECONOMIC ASSESSMENT METHODOLOGY AND APPROACH

The approach is an economic benefit calculation procedure that is based on simulating the economic operation of an integrated generation and transmission system down to the operational level of one-hour. We have used GridView [4], a software tool that is able to simulate operation of open electricity market by performing transmission security constrained unit commitment and economic dispatch. The tool incorporates detailed supply model, demand model, and transmission system model for large-scale transmission grid. The GridView solves an optimization problem subject to various aforementioned constraints. The objective function minimizes a generation production cost function that, in addition to the cost of serving the demand, also includes costs for unserved load and penalty cost for transmission limit violations. To build system model in GridView a lot of data has to be collected to cover generation, load, and transmission systems. For this study, we took advantage of the GridView Database for US-Eastern Interconnection regional power market based on the year 2013 as a base case and then expanded the model to build the study system. The base case has generation (fuel cost and scheduled maintenance), transmission line infrastructure, annual energy and load demand based on the 2013 and the regional load profiles are based on the year 2006.

The same tool also supports modeling the operation of the High Voltage Direct Current (HVDC) Grid delivery system. The HVDC Grid operational model determines hourly converter and cable loading with due respect to their capacity limits and thermal losses. The wind farms were modeled as hourly variable energy resources based on the hourly wind profiles representative of the offshore wind speeds in the target wind energy areas. The receiving generation-transmission system is composed of control areas within the Eastern United States which were modeled in detail in Gridview. The offshore wind and HVDC Grid delivery system model are then integrated with the receiving AC system resulting in our integrated model. One year simulation was performed, using a day-ahead market load forecast with one-hour increments, to capture the seasonal variations of wind energy and the corresponding seasonal variations in the electrical loads as well as the maintenance schedule of the generators in the system. Key operational indicators such as generation dispatch from fossil fired units were then saved and used to evaluate the impact of the offshore wind on the system costs and its greenhouse emissions.

## 3. SYSTEM MODELING

The test system contains one large AC system and one offshore HVDC grid in the Atlantic shore. Figure 2 shows the DC Grid superimposed on a map layer of the mid-Atlantic region. There are nine proposed points of interconnection (POI) into the AC grid, which are all onshore. The northernmost POIs are located in the New York area while the southernmost POIs are located in Virginia. Most of the POIs are located in the PJM control area.

It was recommended that, if it makes economic sense, to connect offshore stations together, instead of individually connecting the wind farms to onshore stations. Such strategy would allow the creation of an offshore backbone, or a direct interconnector, that could be utilized for increasing trade between the areas covered by the grid. This is evident in the single line diagram shown in Figure 2 where two DC cable backbones (Direct Interconnectors 1 & 2) run almost in a north to south direction, with wind farm tee-ins along the entire path.

Using the indicated topology, the developed DC Grid model thus has nine offshore converter stations, nine onshore converter stations and twenty-one cable circuits. The DC grid was assumed to operate at ±320 kV with VSC converters connected in a bipole configuration. The detailed system modeling is described in the following subsections.

### 3.1 AC System and Power Market Modeling

AC system is based on US-Eastern Interconnection regional power market, the system data base built in GridView is based on publicly available data sources and the system study period corresponds to the Year 2013 data base (including 2013 fuel pricing), the geographical scope of study system is shown in Figure 1(b). In the simulation set up the power market and power flow model simulates the operation of the power system based on a detailed set of Eastern Interconnection generation data including capacity and fuel costs, a detailed transmission grid model. Both conventional power plants and renewable generation are modelled.

The complete study area has more than 6,000 generators with diverse fuel types, 64,000 buses and around 83000 transmission branches. To reduce the simulation computation burden only the PJM, NYISO and NEISO regions were modeled as internal network with full details– the other regions were modeled as external network with generation and loads fixed at the initial values from the power flow case. It has a peak load and annual energy demand of 217 GW and 1176 TWh (terawatt-hour) respectively, approximating an annual load factor of 62% with a total generation capacity of 287 GW. To monitor a study system, Gridview fixes all power flows on crossing transmission lines connected between the study area and the external system. The annual average LMPs for the base case simulation model has 35 $/MWh, 46 $/MWh and 44 $/MWh for PJM, NYISO and NEISO regions respectively.

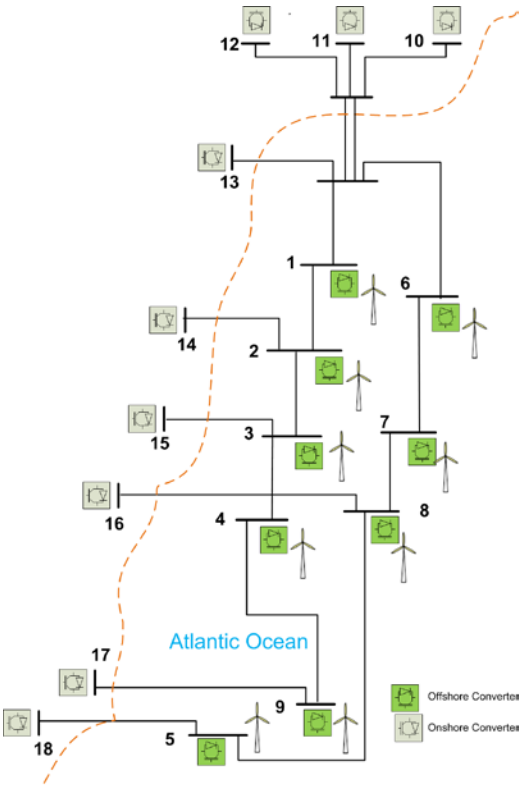


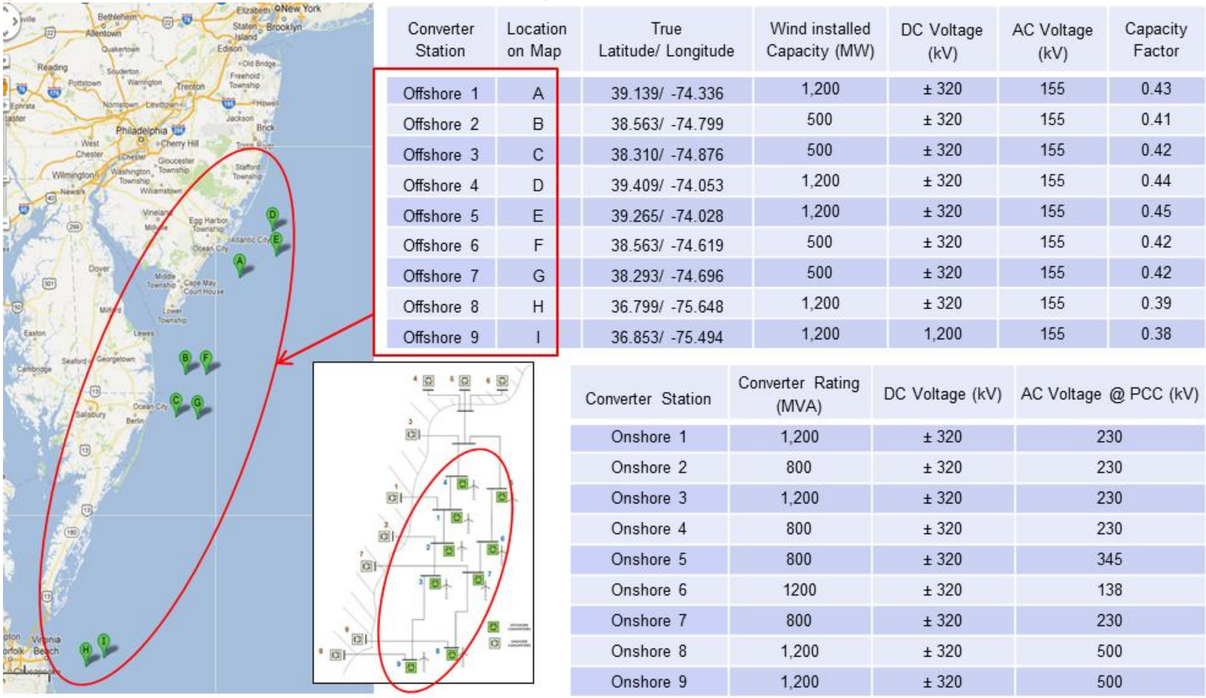
Figure 2 : HVDC Grid Design Strategy

### 3.2 Wind Resource Modeling

Each of the nine offshore wind platforms is modeled as a real power injection into the HVDC grid as an hourly time varying series. The resulting offshore generation power at given platform is an aggregation of the energy of the wind farms geographically situated around the platform. The majority of the sites currently being considered for offshore wind projects are situated close to the US east coast; this is in part due to the high cost of grid connection and limited grid availability.

Based on approximated site location of the offshore platforms, wind energy profiles were determined and then scaled up based on the intended size of the wind farms. Aggregation of wind power generation reflects the spatial distribution of the wind power stations in each region. The time series for the wind power production data which reflect both the temporal and geographical variability is available through NREL data base [2]. The obtained wind profiles are based on high-resolution simulations of the historical climate performed by a mesoscale numerical weather prediction (NWP) model. The NWP models are available for the years 2004, 2005 and 2006. For the execution of this study we considered wind resource database based on the year 2006 in order to be consistent with the system study period, which is also based on the year 2006.

The capacities of the wind power plant associated to an offshore wind platform are listed in Figure 3 with corresponding offshore converters. We assume that the wind farm will not contribute to the spinning reserve of the system. We also assume no production cost associated with wind generation, thus wind power generation dispatch has priority over other generation type. The simulation model also allows wind energy to be spilled due to system dispatch constraints associated with fossil generation commitment and transmission congestion. .



| Converter Station | Location on Map | True Latitude/ Longitude | Wind installed Capacity (MW) | DC Voltage (kV) | AC Voltage (kV) | Capacity Factor |
|---|---|---|---|---|---|---|
| Offshore 1 | A | 39.139/ -74.336 | 1,200 | ± 320 | 155 | 0.43 |
| Offshore 2 | B | 38.563/ -74.799 | 500 | ± 320 | 155 | 0.41 |
| Offshore 3 | C | 38.310/ -74.876 | 500 | ± 320 | 155 | 0.42 |
| Offshore 4 | D | 39.409/ -74.053 | 1,200 | ± 320 | 155 | 0.44 |
| Offshore 5 | E | 39.265/ -74.028 | 1,200 | ± 320 | 155 | 0.45 |
| Offshore 6 | F | 38.563/ -74.619 | 500 | ± 320 | 155 | 0.42 |
| Offshore 7 | G | 38.293/ -74.696 | 500 | ± 320 | 155 | 0.42 |
| Offshore 8 | H | 36.799/ -75.648 | 1,200 | ± 320 | 155 | 0.39 |
| Offshore 9 | I | 36.853/ -75.494 | 1,200 | 1,200 | 155 | 0.38 |

| Converter Station | Converter Rating (MVA) | DC Voltage (kV) | AC Voltage @ PCC (kV) |
|---|---|---|---|
| Onshore 1 | 1,200 | ± 320 | 230 |
| Onshore 2 | 800 | ± 320 | 230 |
| Onshore 3 | 1,200 | ± 320 | 230 |
| Onshore 4 | 800 | ± 320 | 230 |
| Onshore 5 | 800 | ± 320 | 345 |
| Onshore 6 | 1200 | ± 320 | 138 |
| Onshore 7 | 800 | ± 320 | 230 |
| Onshore 8 | 1,200 | ± 320 | 500 |
| Onshore 9 | 1,200 | ± 320 | 500 |

Figure 3 : Modeling details of HVDC Grid and Offshore-wind

### 3.3 Offshore HVDC Grid Modeling

An HVDC grid model has been implemented in the GridView program to simulate its operation and quantify economic benefits. The program optimizes converter control to minimize the overall system production cost to meet loads and losses, subject to DC network constraints, AC networks constraints, and generating resource characteristics. HVDC grid topology is shown in Figure 2, which involves integration of eight gigawatts name plate capacity of offshore wind. There are nine onshore converter stations acting as points of interconnection (POI) into the AC grid. The HVDC grid connects nine offshore converter stations together by connecting the wind farms and then to onshore stations. Such strategy would allow the creation of an offshore backbone or a direct interconnector: 1) to increase the HVDC grid utilization when the wind power is below its rated capacity, 2) to contribute increased market trading between the AC grid onshore POIs, 3) to relieve transmission bottlenecks that may occur between various onshore regions. The offshore DC grid has two cable direct interconnectors run north-south terminated by converter stations on both ends. Offshore wind platforms tee-in to several points along both interconnectors, to facilitate long length connection between offshore and onshore. In the same tee-in locations, cable direct connectors run to various onshore converter stations. The HVDC grid was modeled to be a ±320 kV Voltage Source Converter bipole configuration, the positive and negative pole circuits are balanced at base case, that is, the flows in the positive pole circuits is equivalent to the flows in the negative pole circuits. The capacities of onshore and offshore converters of the HVDC Grid are summarized in Figure 3. Depending on the direction of power flow, the converter station can be operated as rectifier (AC→DC) or inverter (DC→AC) within its rated capacity. The losses of the HVDC converters have two parts: constant losses and usage losses as quadratic function of current or power. The converter losses are modeled as equivalent resistances – a shunt resistance for the constant losses and an equivalent series resistance for the variable losses.

## 4. RESULTS

A key driver for offshore wind is energy independence and security for North America. A one year simulation was performed in Gridview without the offshore wind farm and its HVDC grid. The GridView market simulation results are based on constrained unit commitment with day-ahead load forecast and transmission constraints including all defined interfaces (a total of 137 interfaces are defined in the system area) and individual circuits of 230kV and above (a total of 2838).

With the installed name plate capacity of 8 GB and forecasted capacity factors at the wind farms as shown in Figure 3, it is estimated that a total of 735 TWh of wind power can be generated for a period of 25 years. Based on regional prices of the study region the revenue of this wind energy could range from 28 BUSD to 56 BUSD for the lifetime of the wind farms. The estimate is based on 2013 whole sale electricity marginal prices in the study area [5]-[7]. If the cost of CO2 is factored into the equation, the clean wind energy will have displaced 750 million tons of CO2 emissions and at an assumed price of 20 USD per ton, this could easily add 15 BUSD to the total value of the wind energy.

Another benefit of the offshore DC grid is to provide dynamic DC backbone when the wind power is below its rated capacity. Under this condition, the available transfer capacity in the DC grid will be utilized to transfer cheap power to the high cost region. The shaded area in Figure 4 below illustrates the maximum available energy that can be transferred. The actual transfer will be less for various reasons such as during low load time period when the huge marginal price difference between the onshore stations does not exist. The margin for transmission access is estimated using Gridview simulation results that it would allow 6.8TWh more energy during the study year which accounts for around 170TWh excess transmission energy over 25 years.

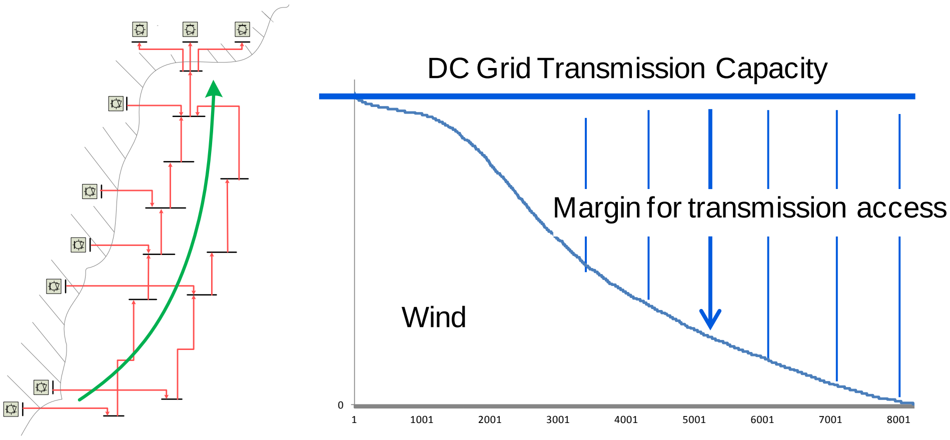
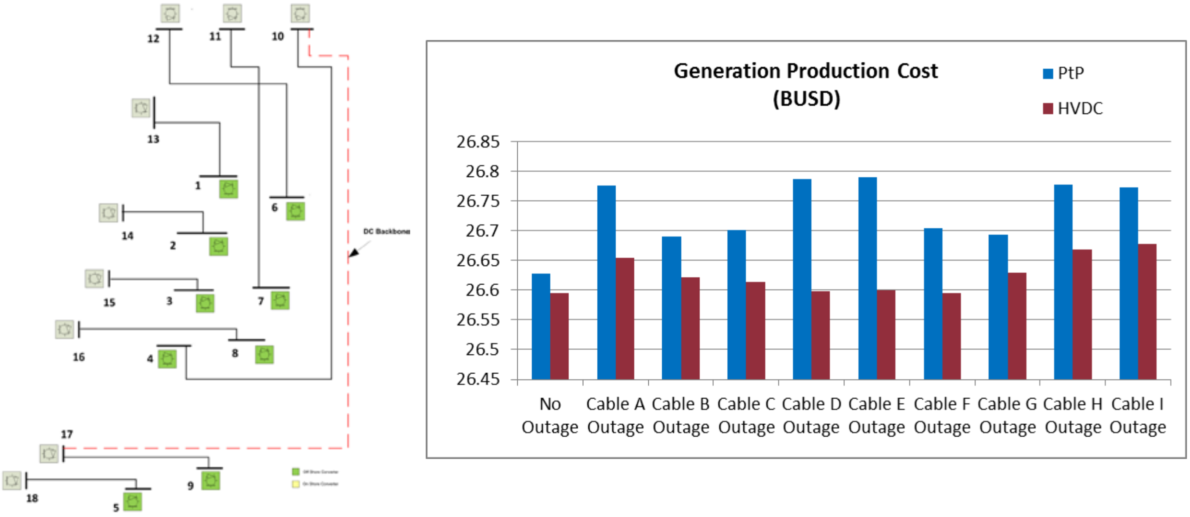


Figure 4 : Available Transmission margin in the DC Grid

To illustrate the benefits of having an offshore DC grid for connecting offshore wind farms the results are compared to individually connecting them to shore. A “point to point system” was composed with individual connections of wind farms and a direct interconnector from ‘onshore 10’ station to ‘onshore 17’ station to simulate the dynamic DC backbone. The backbone was necessary to make sure that the comparison for both topologies is even in terms of transmission capacity to transmit power into the AC grid. The single line diagram of this reference case is shown in Figure 5 (a), converter capacities and cable ratings are similar to DC grid, this is allowed us to have comparable overall economic dispatch of land based generators across the study region. The difference between the two configurations is significant under the conditions of VSC-HVDC link outages. In Point to Point (PtP) connections the VSC-HVDC link will force the wind generation to be disconnected from the system resulting in spillage, whereas in the DC grid scenario the wind generation is always connected to the system. Figure 5 (b) illustrates the impact of VSC-HVDC link outages on the study system production cost for both connections (DC Grid vs. PtP) where the outage corresponds to double pole outages over a period of one year.

To quantify the benefits of a DC grid over point to point systems an availability analysis is performed on both the system [10]. To make analysis simple only the radial VSC-HVDC links connecting onshore stations are considered for the both systems. Availability analysis together with the production costs, obtained from GridView, is used to determine the production cost benefit of one system over



(a) (b)

Figure 5 : (a) Individual wind farm connection with DC Backbone. (b) Impact of HVDC-link Outage on study system production cost

another. The expected production cost of the system can be defined as the weighted average of system production cost when all HVDC links are available and when each one is unavailable. Mathematically, this is expressed as

$$E(P_c) = p(0)P_c^0 + p(x_1)P_c^{x1} + p(x_{12})P_c^{x2} + \ldots. \qquad (1)$$

where $E(P_c)$ is the expected production cost; this is calculated for the grid and the PtP connection options, $P_c^{xj}$ is the system production cost when HVDC link $x_j$ is not in service (unavailable), $p(0)$ is the probability that all HVDC links are in service (available) and it is defined as 1 minus the sum of the unavailability of the other components in the list, i.e.

$$p(0) = 1 - p(x_1) - p(x_2) - \cdots.. \qquad (2)$$

where, $p(x_j)$ is the unavailability of HVDC link$x_j$.In theory unavailability for an individual VSC-HVDC link is derived from outage results of individual component of the link i.e. the unavailability of AC transformer, the cable, the DC breaker, the AC breaker, or the converter [10]-[12]. Each component was assigned a failure frequency and an estimated downtime in case of failure of the component and the effect of a component failure to the overall HVDC-link outage was determined. Here, for the both scheme's an average unavailability of 3.8% is assumed for individual VSC-HVDC link. This will result in HVDC Grid scheme having a lower annual production cost as compared to PtP scheme and for assumed lifetime of twenty five year this results in expected production cost savings of 1.6 BUSD.

## 5. CONCLUSION

This paper has analyzed the economic benefits of a representative offshore DC Grid in North America. A demonstration case was built consisting of nine offshore converter stations and 20 cable circuits covering a distance of 1075 kilometers to provide transmission access to offshore wind farms totaling 8 GW off the coast of the Mid-Atlantic region. The offshore converter stations are connected to an HVDC grid that runs in the North-South direction and terminating at select onshore substations. Economic benefit calculation software, GridView, was used to simulate system operations to the hourly level to capture the day-to-day operations of the receiving power system in terms of unit commitment and economic dispatch as well as transmission constraints. This software simulation tool was enhanced with a HVDC Grid function capability. For the assumed lifetime of twenty five (25) years the wind farms were forecasted to generate an estimated 735 TWh. During this period, the HVDC grid is also expected to provide transmission access to an additional 170 TWh energy transfer from low cost to high cost regions for land based generators in the host AC grid. Using current production costs in the study area, the wind energy was valued at a minimum of 28 BUSD (billion US Dollars). By factoring in the cost of carbon into the equation, the value of this wind energy goes up to an additional fifteen (15) BUSD depending on carbon emission price. The DC Grid was observed to perform more economically against PtP interconnection option. The analysis determined that opting for an HVDC grid lowers production cost of the overall system by 1.6 BUSD compared to connecting wind farms individually to shore.

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