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Tech-Economic Assessment of Power Transmission Options for Large-Scale Offshore Wind Farms in China

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Abstract: China is taking initiative in energy transition to cope with the long-term controversy of its enormous energy consumption, aiming to use less carbon. Wind power, especially offshore wind energy, has become a prevailing alternative due to its low carbon emissions, renewability, competitiveness, and operation security. The layout of a transmission channel is a key consideration in marine project implementation. This paper investigates the technical characteristics, application status, and viable advantages of a conventional AC transmission, voltage source converter-based high-voltage direct current (VSC-HVDC) transmission, gas-insulated line (GIL) transmission, and hybrid HVDC transmission. A component-resolved evaluation model was proposed to estimate the costs to be incurred of four electrical transmission options for offshore wind power along the coast of Eastern China, with technical feasibility and economical considerations. Cost comparisons and component sensitivity analyses were developed with different transmission distances and capacities. Results suggest HVAC transmission and VSC-HVDC are the preferable solutions for present offshore wind farm development in Eastern China, and the economic potential of the hybrid HVDC makes it feasible for future deployment. Some conclusions can be applied in disparate regions across the globe.

Keywords: offshore wind; China; HVDC; opex; economic evaluation

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1. Introduction

Deployment of variable renewable energy resources are technical solutions driving global climate change. In order to sharply decrease the carbon emission and accelerate the global energy transition [1], wind power has experienced a rapid development in the last 20 years, which has become the mainstream renewable energy around the world now [2]. In 2019, China maintains the first place in terms of cumulative installed capacity of wind power and is vigorously promoting wind power on a priority basis [3]. Compared with onshore wind power, offshore wind farms have much less negative impacts on humankind as no land resource is needed, which also makes them usually have a larger scale and the offshore turbines have a larger capacity, which means a fall in the capital costs [4].

Because of the above advantages, plenty of studies have been conducted in the cost assessment area of the offshore wind farms (OWFs), which concentrates on the cost evaluation methodologies, potential economical technologies, and cost reduction. The infrastructure costs of OWFs are strongly related to the spatial condition [5,6]. Myhr et al. presented a cost sensitivity analysis and pointed out that the results suffer significant spatial bias and may differ in various countries [7], such as spatially-explicit assessment for the United Kingdom (UK) [8,9], Australia [10], Thailand [11], India [12], and Nigeria [13]. Thus, a Geographic Information System (GIS) makes costs and energy potential estimations possible based on spatially clustered data [14,15]. To obtain the cost reduction potential, the GIS-based levelized production cost (LPC) methodology is a common analysis model [16–18]. Furthermore, some assessments take the impacts of marine ecosystem and weather or climate variance into consideration [19,20].

The costs of the OWFs are more expensive than the onshore farms due to its complex foundation, installation, and submarine cabling; with the construction of the marine economy, the transmission vehicle becomes an important part [21]. Furthermore, the costs of different transmission methods are distance- and capacity-dependent functions [22], because the required diameter and number of cables are capacity-resolved, especially for projects with GWs capacity, and there exists a “breakeven” distance [23]. Two prevailing approaches are conventional: alternating current (AC) transmission, which is effective for near shore farms [24], and extensive voltage source converter-based high-voltage direct current (VSC-HVDC) transmission, which is the preferred solution for long-distance transmission. The HVDC transmission technology has many advantages, such as a fast power control speed [25] and oscillation damping control [26], and can be used in ultra-high-voltage occasions [27–29]. However, the HVDC implementation also has disadvantages. The first disadvantage compared to AC transmission is the cost, as the VSC is based on so many IGBT components that finally lead a relatively high investment. The second disadvantage is the stability problem, where the VSC often suffers from oscillation risk, especially when the power fluctuates. The third disadvantage is that the IGBT is very sensitive to the fault current, and it requires a fast protection scheme. However, the advantage of VSC makes it still be suitable for offshore wind farm integration. Offshore wind power is often located in the far sea area and the transmission cable also decreases the fault possibilities. The same as with HVDC transmission, a gas-insulated transmission Line (GIL) provides another way due to its advantage of considerably larger capacity, but its exaggerated expense makes it less competitive. Consequently, VSC-HVDC becomes more eye-catching for investors with predominant capability and desirable loss, which is suitable for crossing long-distance water transmission, such as in the North Sea of Germany [30]; but, the terminal converter stations are more expensive. However, the choice of electrical transmission ultimately depends on both technological potential and economic potential [31]. For future technical development of OWFs, there is another competitive option—hybrid VSC/LCC-HVDC technology—which is a novel form of HVDC transmission not widely applied, but it greatly decreases the costs and is planned for use China, possessing huge technological potential.

In China, there are many large-scale blocks with a capacity of more than hundreds of MW planned for OWFs [32]. The existing research has mostly focused on a single offshore wind farm project [33], lacking the overall research on regional offshore transmission systems [34]. There is a need to explore the optimal technical transmission method of the regional offshore transmission network for wind farms, which is conducive to wind energy utilization. This paper conducted regional cost analysis and economic feasibility comparisons of four electricity transmission options for offshore wind power in Guangdong Province using component-resolved evaluation models. Economic costs and sensitivity have been derived using the Discounted Cashflow Model (DCF). This contributes to determining the reasonable scope of technical and economic application of various transmission modes, giving perceptible information for stakeholders for offshore wind transmission infrastructure under indigenous development, economic perspective of relevant technologies, and possible potential to future deployment and implementation of marine projects.

To make clear the characteristics of the different wind power transmission technologies, this paper compares various offshore wind farms with the HVAC, HVDC, GIL, and hybrid HVDC output channels. The novelties of the paper are as follow.

(1) The evaluation models for different wind power integration technologies are investigated, and the techno-economic costs can be calculated according to the proposed method for different technologies.
(2) The economic characteristics of each technology are clarified based on the proposed analysis model, and the compositions of these various transmission solutions are studied and compared.
(3) The influence factors for the investment of different technologies are also investigated, and the suitable application situations are proposed for different wind power output solutions.

This paper is structured as follows: The study area and technical potentials of the four transmission methods are introduced in Section 2. Section 3 proposes specific evaluation models of the various transmission solutions. Then, the techno-economic costs and sensitivity to transmission distance and capacity analysis results are investigated using the DCF approach in Section 4. The conclusions and areas of further work are discussed in Section 5.

2. Study Area and Methodology

2.1. Study Area

Guangdong is located on the eastern coast of China, which is rich in offshore wind energy; it is also the core area of economic development in southern China. To reach the new goal of deployment of the Guangdong–Hong Kong—Macao Greater Bay area (GBA). It has made great efforts to develop offshore wind power, which is effective to adjust coastal resources in line with a prosperous economy. By 2030, more than 1000 km of transmission lines will be built for grid connections for offshore wind power. For this trend of future planning of OWFs in Guangdong, policymakers are concerned with the cost assessments of efficient electrical transmission options to transport large quantities of offshore energy across great distances.

Offshore wind resources of Guangdong Province are in western and eastern Guangdong. Based on the Notice of Guangdong Development and Reform Commission on Guangdong offshore wind power development plan (2017–2030), 15 offshore wind farm sites are located in the offshore shallow water area, and 8 sites are in the offshore deep-water area. Yangjiang city is the closest with a stable wind power supply base in the west to the GBA. There are three regions for offshore wind farms in the plan: Nanpeng Island OWFs, Hailing Island OWFs, and Shapa OWFs. The total planned installed capacity of the renewable energy is about 36 GW, as indicated in Figure 1.

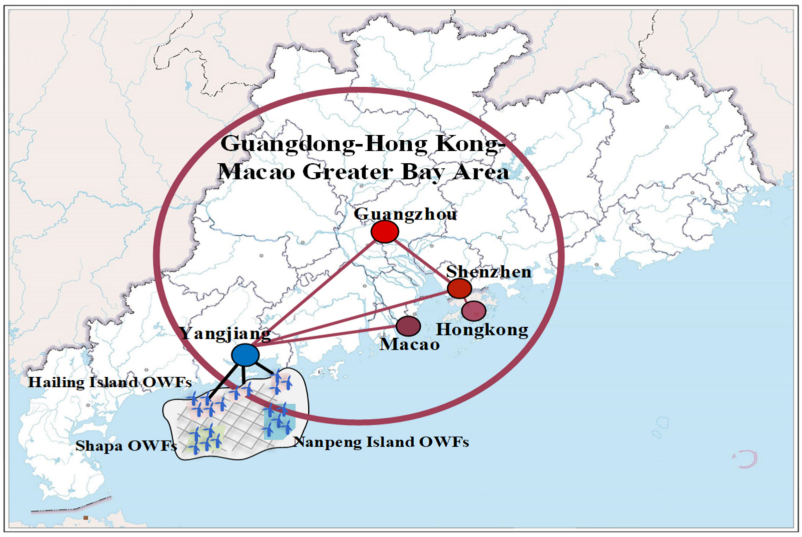

Figure 1. Overview of the study area.

2.2. Technical Evaluation of the Transmission Solutions

Four transmission solutions are studied in this paper, as shown in Figure 2. The offshore wind power from each farm is collected and transmitted to the offshore step-up transformer station. Then the voltage will be raised and the electrical power will be delivered to the onshore step-up transformer station via a submarine high-voltage transmission line (AC/DC cable or GIL line) and delivered to the onshore booster station.

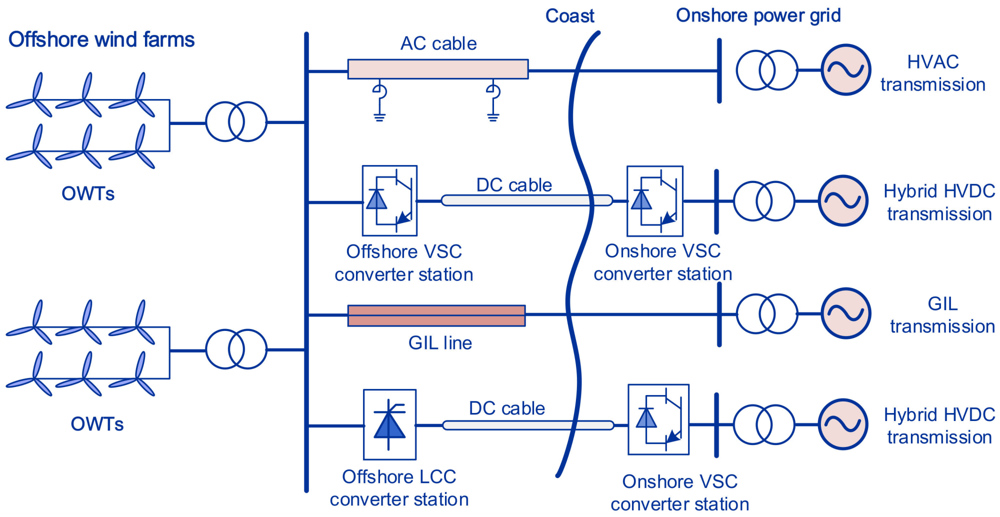

Figure 2. Structure of the four transmission methods for OWFs.

As mentioned above, AC transmission is widely used in near sea OWFs, compared with others. The distributed capacitance of the AC cable will become larger and larger, and the ampacity will decrease with the increase in length. This significantly reduces the transmission ability; also, multi lines are needed to transfer the large amount of wind power, which means more investment cots in the AC cable. In addition, due to the close electrical connection between the wind farm and the onshore power grid, the fault of either side will quickly spread to the other side; this will cause voltage oscillation and power instability, which reduces the power quality. It is necessary to install dynamic reactive power compensation devices to improve the stability and available transfer capability. A DC cable is cheaper and able to transfer more capacity with lower loss, which is popular in OWF transmission, but an offshore converter station needs to be assembled and a large DC platform should be built for it, which makes the economic investment of VSC-HVDC higher in the early infrastructure. However, it is convenient to build and expand by stages, and the asynchronous connection to onshore grid can suppress the synchronous transmission of faults.

With regard to GIL lines, as derived from GIS, GIL only needs to have basic electrical performance, such as insulation and dynamic thermal stability, and there is no switchgear; it thus has obvious reliability advantages over either AC/DC cable or overhead lines in long-distance and large-capacity power transmission. However, the high costs and high technical requirements of the construction design and the long project period are difficult problems for the actual project. In China, a new hybrid DC transmission mode combines the superior performance of LCC-HVDC and VSC-HVDC technologies and has a lower cost than current VSC-HVDC transmission. Yet, the available transmission power is determined by the VSC-HVDC side, and it is hard to realize power flow reversal due to the voltage polarity that needs to be changed in the LCC converter station. Still, it is a new trend of innovation and becomes an alternative for offshore wind power transmission though it has not been applied due to a lack of research, except in China. In summary, the technical potential of the four methods is in Table 1.

Table 1. Technical comparisons of the four transmission options.

Methods	Advantage	Restrictions	Potential
HVAC	Easy layout, High reliability, Rich experience	Large distributed capacitance, Additional reactive power compensation, Multi lines for larger capacity, Synchronous fault propagation	Popular for near sea OWFs
VSC-HVDC	Better stability, Low line cost and loss, Restrain fault propagation, Easy for construction and capacity expansion	Layout of converter station, Additional offshore platform	Developing rapidly Large-capacity transmission, and long-distance transmission
GIL	Best operation reliability, High ampacity, Large transmission capacity of single line and less loss	High cost, High technical requirements, Long project period	Limited application for large-capacity transmission
Hybrid HVDC	Better performance than VSC-HVDC or LCC-HVDC, Lower cost than VSC-HVDC	The available transmission power is determined by VSC side, Hard to power flow reversal, Lack research	New trend of transmission, Worth developing

3. Methodology

The costs evaluation can be broken down into multiple components, such as site-dependent variables, fixed water depth, the distance to grid connection point, and fixed costs [35]. Total investment cost equals the summation of the capital cost components, calculated as suggested by Dicorato et al. [35] and Hong and Möller [14,33].

The methodology establishes an empirical component-resolved evaluation model from an industry standard or outline to evaluate four electrical transmission concepts. The economic costs under each concept are intricate, so the main resolved components, including capital costs, OPEX, and loss costs, are considered and calculated in this paper.

3.1. Costs Calculation of HVAC Cables Transmission

The HVAC cable transmission concept is a popular way for offshore wind farms, and the principal cost drivers include capital costs $C_{cap.AC}$, operation and maintenance costs $C_{opex.AC}$, and loss costs $C_{loss.AC}$. The calculation is given by

$$C_{AC} = C_{cap.AC} + C_{opex.AC} + C_{loss.AC} \tag{1}$$

3.1.1. Capital Costs

In the concept of HVAC cable transmission, $C_{cap.AC}$ covers the relative substation foundation costs $C_{station.AC}$, underwater cable foundation and installation costs $C_{cable.AC}$, and reactive power compensation foundation costs $C_{reacpc.AC}$, estimated by

$$C_{cap.AC} = C_{station.AC} + C_{cable.AC} + C_{reacpc.AC} \tag{2}$$

1. Substation foundation cost

Substation foundation cost in the HVAC transmission system is the total costs of each transformer substation capital expenditure, which is dependent on the infrastructure investment of the substation, expense of the transformer and the investment cost of auxiliary electrical equipment, including the reactive compensation capacitor and switchgear. Then the calculation of $C_{station}$ is based on cost C_{perMVA} and determined by the capacity of substation S.

$$C_{station.AC} = C_{perMVA} \cdot S \tag{3}$$

2. Cable foundation and installation cost

The underwater cable for offshore wind energy is utilized for the link between the transformer substation and offshore substation; hence, $C_{cable.AC}$ is estimated as a proportion of distance to station L.

$$C_{cable.AC} = 3(P_1 + P_2)L \tag{4}$$

where P_1 and P_2 are the expense and installation cost of one unit (length, km) of cable, respectively.

3. Reactive power compensation foundation cost

In the HVAC transmission system, the distributed capacitance of the cable is generally much larger than the overhead line, so a large capacitance current will be generated in the AC line, which significantly reduces the available transfer capability. Therefore, reactive power compensation devices should be installed on sides of the cable according to the actual operation. Thus, compared with the VSC-HVDC transmission method, the foundation cost of the reactive power compensation should be considered additionally, which mainly includes the cost of the shunt reactors. To calculate it, the reactive power Q_{reac} (MVAR) of the line capacitance is calculated.

$$Q_{reac} = 2\pi \times f \times c \times l \times {U_{cable}}^2 \tag{5}$$

where f is the operational frequency of system, c is the capacitance value per km of the cable, and U_{cable} is the voltage of AC cable.

The capacity of reactors $C_{reacpc.AC}$ can be determined by

$$C_{reacpc.AC} = P_3 \times Q_{reac} \tag{6}$$

where P_3 is the expense of the reactors.

3.1.2. Operation and Maintenance Costs

$C_{opex.AC}$ is usually estimated in the form of percentage A of the annual maintenance cost to total investment cost (excluding land occupation cost and offshore platform costs) or percentage A_1 of lifetime maintenance costs to total investment cost. The relation between A and A_1 is

$$A = A_1 \times \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

where i is the annual interest rate; n is the lifetime; Van Eeckhout gives the specific data of A equals to 1.2%, n is 20 years, i is 5% [36]. Then, $C_{opex.AC}$ is estimated:

$$C_{opex.AC} = C_{cap.AC} \cdot A \tag{8}$$

3.1.3. Costs of Loss

The loss costs $C_{loss.AC}$ comprise of substation loss $C_{sub.loss}$ and transmission line loss $C_{line.loss}$. $C_{sub.loss}$ is dependent on the substation loss rate $P_{sub.loss}$, as referred to in the literature [36]. The $P_{sub.loss}$ of two substations is 0.8%, that means the loss rate of each substation is 0.4%. $C_{line.loss}$ includes conductor losses $C_{con.loss}$ and losses of sheath and armor $C_{shar.loss}$. $C_{con.loss}$ can be formulated by the current I_{cable} of the copper conductor, which can be approximately calculated by

$$I_{cable} = \frac{P}{\sqrt{3}U_{cable}\cos\varphi} \tag{9}$$

where P is the active power; the power factor $\cos\varphi$ is 0.95.

Therefore, with the resistance of conductor R_{cu}, $C_{con.loss}$ is given by

$$C_{con.loss} = 3{I_{cable}}^2 \cdot R_{Cu} \tag{10}$$

The losses of sheath and armor $C_{shar.loss}$ is estimated.

$$\begin{bmatrix} \Delta U_C \\ \Delta U_S \\ \Delta U_A \end{bmatrix} = \begin{bmatrix} Z_1 & Z_2 & Z_3 \\ Z_4 & Z_5 & Z_6 \\ Z_7 & Z_8 & Z_9 \end{bmatrix} \begin{bmatrix} I_C \\ I_S \\ I_A \end{bmatrix} \tag{11}$$

where ΔU_c, ΔU_s, ΔU_A, I_c, I_s, I_A are the voltage and current of the copper core, sheath, and armor, respectively; Z_1–Z_9 are the matrix of parameters of the cable.

Moreover, since both ends of the sheath are grounded, the armor layer is linked with the sea, with the assumption of $U_s = U_A = 0$ and $I_c = I_{cable}$; so, $C_{shar.loss}$ can be given by the power loss $P_{ar} = 3{I_A}^2 \times R$, $P_{sh} = 3{I_S}^2 \times R$, and I_S and I_A are

$$\begin{cases} I_A = \left(Z_9 - Z_8 Z_5^{-1} Z_6\right)^{-1} \left(Z_8 Z_5^{-1} Z_4 - Z_7\right) I_C \\ I_S = -Z_5^{-1}(Z_4 I_C + Z_6 I_A) \end{cases} \tag{12}$$

The costs of C_{arsh} is dependent on the operation time of full generation per year T_f and the on-grid price of electricity $P_{on\text{-}grid}$, which are

$$C_{shar} = (P_{sh} + P_{ar}) \times T_f \times P_{on-grid} \tag{13}$$

The evaluation of $C_{loss.ac}$ is obtained by total C_{sh} and C_{ar}.

$$C_{loss.AC} = C_{sub.loss} + C_{shar} + C_{con.loss} \tag{14}$$

3.2. Costs Calculation of VSC-HVDC Transmission

As for the VSC-HVDC transmission concept, the total costs of C_{VSC} compose of capital costs $C_{cap.VSC}$, operation and maintenance costs $C_{opex.VSC}$, and loss costs $C_{loss.VSC}$.

$$C_{VSC} = C_{cap.VSC} + C_{opex.VSC} + C_{loss.VSC} \tag{15}$$

3.2.1. Capital Costs

$C_{cap.VSC}$ consists of the converter station foundation cost $C_{station.VSC}$, and the cable foundation and installation costs $C_{cable.VSC}$.

$$C_{cap.VSC} = C_{station.VSC} + C_{cable.VSC} \tag{16}$$

1. Converter station foundation cost

$C_{station.VSC}$ is the total infrastructure investment of each converter station. Furthermore, the additional costs of IGBT, converter controller and reactor, DC capacitor and AC filter, as well as the cost of civil construction of the offshore platform for converter station layout are estimated. Then $C_{station.VSC}$ is computed as a proportion of the capacity of per converter station P.

$$C_{station.VSC} = C_{perMW} \cdot 2P \tag{17}$$

2. Cable foundation and installation cost

Similar to HVAC cable, $C_{cable.VSC}$ of DC cable is calculated by the transmission distance.

$$C_{cable.VSC} = 2(P_1 + P_2)L \tag{18}$$

where P_1 and P_2 are the expense and installation costs of per km DC cable.

3.2.2. Operation and Maintenance Costs

$C_{opex.VSC}$ is obtained in Equation (8), and the A of the DC submarine cable equals to 0.5%, n is 20 years, and i is 5%, which were applied to this study.

3.2.3. Costs of Loss

The loss costs $C_{loss.VSC}$ consist of converter station loss $C_{sub.loss}$ and line loss $C_{line.loss}$. Converter station loss rate $P_{sub.loss}$ is the percentage of station power loss to the transmitted power. $P_{sub.loss}$ of two converter stations is 1.6–2.4%, and Zhen points out that $P_{sub.loss}$ is 1–2% [36]. The levelized loss rate of each substation is

$$P_{sub.loss} = (\frac{1.6\% + 2.4\%}{2} + \frac{1\% + 2\%}{2})/2 = 1.75\% \tag{19}$$

Meanwhile, the line losses $C_{line.loss}$ can be evaluated as

$$C_{line.loss} = (P/U_{DC})^2 \cdot R \cdot 2L \cdot T_f \cdot P_{on-gird} \tag{20}$$

where U_{DC} is the DC voltage; R is resistance.

The evaluation of $C_{loss.VSC}$ is described as

$$C_{loss.VSC} = P_{sub.loss} \cdot P \cdot P_{on-gird} + C_{line.loss} \tag{21}$$

3.3. Costs Calculation of GIL Transmission Concept

The GIL transmission concept is similar to the AC transmission concept, but there is no reactive power compensation costs.

$$C_{GIL} = C_{cap.GIL} + C_{opex.GIL} + C_{loss.GIL} \tag{22}$$

3.3.1. Capital Costs

The capital expenditure $C_{cap.GIL}$ is dependent on the transformer substation foundation cost $C_{station.GIL}$ and cable foundation and installation cost $C_{cable.GIL}$.

$$C_{cap.GIL} = C_{subfound.GIL} + C_{cable.GIL} \tag{23}$$

The foundation cost $C_{station.GIL}$ is similar to $C_{station.AC}$ in Equation (3); similarly, the calculation of $C_{cable.GIL}$ is as Equation (4).

3.3.2. Operation and Maintenance Costs

Based on the OPEX in HVAC transmission system, $C_{opex.GIL}$ is expressed by the percentage A as in Equation (7).

3.3.3. Costs of Loss

The loss costs $C_{loss.GIL}$ in the GIL transmission system comprises of $C_{sub.loss}$ and line loss $C_{line.loss}$ as well.

$$C_{loss.GIL} = C_{sub.loss} + C_{edcir} + C_{con.loss} \tag{24}$$

where $C_{sub.loss}$ is dependent on the $P_{sub.loss}$, $C_{line.loss}$ comprises of conductor losses $C_{con.loss}$, as computed by Equation (10), and the eddy current and circulating current loss $C_{edcir.loss}$ of the shell.

3.4. Costs Calculation of Hybrid HVDC Transmission

3.4.1. Capital Costs

Capital costs in the hybrid HVDC transmission $C_{cap.HybDC}$ covers the converter station foundation cost $C_{station.HybDC}$, cable foundation cost, and installation cost $C_{cable.HybDC}$.

$$C_{cap.HybDC} = C_{station.HybDC} + C_{cable.HybDC} \tag{25}$$

where $C_{station.HybDC}$ is dependent on the sum of the investment costs of the different types of converter stations on both sides.

3.4.2. Operation and Maintenance Costs

Since the OPEX in the hybrid HVDC transmission system is in the same way in the VSC-HVDC transmission system, $C_{opex.HybD}$ can be calculated by Equation (8).

3.4.3. Costs of Loss

Similarly, $C_{loss.HybDC}$ consists of substation loss $C_{sub.loss}$ and line loss $C_{line.loss}$. $C_{sub.loss}$ is dependent on the converter station loss rate $P_{sub.loss}$, which is 1.75% for VSC-HVDC and 0.8% for LCC-HVDC. The average value of $P_{sub.loss}$ is 1.275%. The transmission line loss $C_{line.loss}$ is the same as in Equation (20).

4. Results and Discussion

The empirical component-resolved evaluation models give a crucial message to stakeholders that the economic costs are sensitive to transmission distance and capacity. The cost comparisons of the four electrical transmission options for wind farms with different distances and transmitted power were carried out. The rated voltage is 220 kV, and the frequency is 50 Hz, and the operation hour of full capacity per year is 2500 h. If the capacity is 300 MW, 600 MW, and 900 MW, respectively, the economic evaluations from 25 km to 75 km were conducted.

4.1. Essential Evaluation Data

Based on the DCF model, the costs evaluation results can be converted to cash value. Unlike an onshore power grid, the specific environment and operational conditions of the offshore substation are more complicated; it is necessary to adopt more strict standards for long-term stability. For the AC cable, one line is needed for 300 MW, two lines for 600 MW, and three lines for 900 MW wind power. However, it is important to point out that in the GIL transmission concept, the rated current is 3.15 kA, so the transmission capacity of a single line is 1200 MVA, and there is no need to install additional lines with different capacity. The data are given in Table 2.

Table 2. Overview of basic data related to the economic evaluation of offshore wind farm transmission.

Components	Cost	HVAC	VSC-HVDC	GIL	Hybrid HVDC
		220 kV, 1200 mm^2 Singlecore Underwater AC Cable	**±200 kV, 500 mm^2 Core Optical DC Cable**	**220 kV GIL Line**	**±200 kV, 500 mm^2 Core Optical DC Cable**
Capital costs	Foundation costs of substation (converter station)	CNY 0.45 million/MVA [a]	CNY 1.1 million/MW [36]	CNY 0.45 million/MVA [a]	CNY 0.9621 million/MW [b]
	Expense for P_1	CNY 3.732 million/km [c]	CNY 1.077 million/km [b]	CNY 20 million/km [37]	CNY 1.077 million/km [b]
	Installation cost $P_2(P_3)$	CNY 0.30533 million/km [a,d]	CNY 0.3 million/km [a]	CNY 0.3 million/km [a]	CNY 0.3 million/km [b]
OPEX	Annual percentage A	1.2% [36]	0.5% [36]	0.5% [36]	0.5% [b]
Loss costs	Power loss of substation (converter station)	0.4% [36]	1.75% [36]	0.4% [36]	1.275% [b]
	Loss costs of cables	CNY 0.6145 million/km	CNY 0.0876 million/km [38]	CNY 0.077 million/km [37]	CNY 0.0876 million/km [b]

[a] Design Control Index of Power Grid Project in China (2014). [b] Presented in this paper considering both LCC-HVDC and VSC-HVDC cost. [c] Materials provided by Dongfang Cable Factory in Ningbo city, China. [d] Materials of the project of 66kV Xin-Guang underwater cable in Dalian city, China.

4.1.1. Capital Costs Evaluation

The $C_{station}$ of the AC cable varies among different projects. For example, according to the materials in Design Control Index of Power Grid Project (2014 standard) provided by the Electric Power Planning and Engineering Institute of China [39], the investment of the 220 kV Yucai substation project (indoor) is 0.303 million RMB per megavolt-ampere (MVA), and the cost of the 220 kV Pingli substation project (Laizhou, Shandong) is CNY 0.435 million/MVA. In this study, for 35 kV wind farms with a 220 kV single-core underwater cable, the foundation costs of substation C_{perMVA} is CNY 0.45 million/MVA. Procurement materials provided by Dongfang Cable Factory in Ningbo city indicates that the expense basis of a 220 kV single-core underwater cable with the 1200 mm^2 cross-sectional area of copper core is CNY 3.732 million/km. The installation costs refer to cable crossing barge, sea sweeping, and trench laying. The project of the 66 kV Xin-Guang submarine cable in Dalian city gives the cost P_2 around CNY 0.3 million/km. As for the reactive power compensation, the rated power of the AC cable is 427 MVA and the capacitance for the 1200 mm^2 cable is 0.179 μF/km. The maximum DC resistances of the 20 °C and AC resistance of 90 °C are 0.0151 Ω/km and 0.02 Ω/km, respectively.

Several studies provide various foundation costs for the converter station for reference. The costs of the traditional ±500 kV and ±800 kV LCC-HVDC converter stations are around CNY 0.52428 million/MW and CNY 0.56228 million/MW, respectively. There is a lack of reports on the cost of a VSC-HVDC converter station in China, which varies widely across the globe. Reference [36] applied the technical materials of ABB Ltd. to evaluate the costs of a VSC-HVDC station as CNY 1.155 to 1.343 million/MW, and the costs of the ±300 kV converter station are CNY 1.2 million/MW. Taking the development of offshore wind power technology into account, the standard of C_{perMW} is CNY 1.1 million/MW. According to the industry date provided by Dongfang Cable Factory, the expense the P_1 of XLPE-insulated DC submarine cable (Model: DC200 kV YJQ411 500 + 2 × 12 (core optical cable)) with a cross-sectional area of 500 mm^2 is CNY 1.077 million/km. Moreover, considering the difficulty of hybrid HVDC transmission technology, then C_{perMW} is CNY 0.9621 million/MW.

The expense of GIL P_1 is CNY 20 million/km. P_2 of the four transmission methods equals CNY 0.3 million/km. Thus, the capital costs under different capacity can be obtained.

4.1.2. Operation and Maintenance Costs Evaluation

The annual percentage A of the operation and maintenance cost of the AC submarine cable accounts for 1.2%, and 0.5% is adopted in the other three transmission methods.

4.1.3. Costs of Loss Evaluation

It is assumed that the operation hours are 2500 h per year, referred to in [37], and the on-grid price of offshore wind power is CNY 0.0085 million/MW·h [40]. The substation loss rate $P_{sub.loss}$ in AC cable and GIL transmission system is 0.4%. The apparent power is 427 MVA, based on Equation (9), and the current of copper core with I_{cable} is 0.8287 kA. R_{cu} is 0.006 Ω/km. Some industry gives I_s is 502.4 A and I_A is 313.2 A. The resistances of the sheath and armor are 0.21 Ω/km and 0.301 Ω/km. The eddy current loss $P_{ed.loss}$ and circulating current loss $P_{cir.loss}$ in the GIL lines are 0.0177 MW/km and 0.0062 MW/km, respectively.

For the XLPE-insulated DC submarine cable, the rated power is 324 MW and the DC resistance is 0.0366 Ω/km. Based on Equation (20), the conductor loss of 300 MW is 0.0412 MW/km, 0.0824 MW/km, and 0.1648 MW/km. The substation loss rate $P_{sub.loss}$ in the hybrid HVDC system is 1.275%.

4.2. Evaluation Results

It can be seen from the above analysis that offshore distance and capacity have an important impact on the capital costs of the four types of transmission. Based on the DCF model, the comparisons with different transmission distances and capacities were calculated, and the results shown in Table 3. Components analysis of the total costs was carried out to acquire an importance view for stakeholders, shown in Table 4. The gradual change in color from green to red represents an increase in costs.

Table 3. Economic costs comparisons of different P and different L.

P (MW)	L (km)	HVAC (CNY Million)	VSC-HVDC (CNY Million)	GIL (CNY Million)	Hybrid HVDC (CNY Million)
300	25	471.624	745.839	1686.1	659.657
	50	796.791	817.222	3218.2	731.04
	75	1121.96	888.605	4750.2	802.423
600	25	943.247	1491.68	1840.2	1250.12
	50	1593.58	1634.45	3372.2	1323.69
	75	2243.93	1777.21	4904.3	1397.26
900	25	1414.47	2237.52	1993.8	1840.58
	50	2389.99	2451.67	3525.9	1916.34
	75	3365.48	2665.82	5057.9	1992.1

Table 4. Economic costs comparisons of different P and different L.

Options	L (km)	C_{cap} (CNY Million)	C_{opex} (CNY Million)	C_{loss} (CNY Million)	C_{total} (CNY Million)
HVAC	25	448.33	5.38	17.914	471.624
	50	754.46	9.054	33.278	796.791
	75	1060.59	12.727	48.641	1121.958
VSC	25	728.85	3.644	13.345	745.839
	50	797.7	3.989	15.534	817.222
	75	866.55	4.332	17.723	888.605
GIL	25	1664.7	8.323	13.083	1686.11
	50	3187.2	15.936	15.009	3218.15
	75	4709.7	23.549	16.935	4750.18
Hybrid	25	646.11	3.231	10.317	659.657
	50	714.96	3.575	12.506	731.04
	75	783.81	3.919	14.694	802.423

4.3. Comparisons of Economic Evaluation

To obtain the best transmission method for Guangdong offshore wind power, the costs comparisons were calculated.

4.3.1. Total Costs Comparisons with Different L

According to the data in Table 2, the relationships between the total costs of transmission distance L from 25 km to 75 km are shown in Figure 3.

It is clear that the economic costs of the GIL electrical transmission concept are considerably much more than either the HVAC or HVDC transmission concept. When the transmission distance is not so long, such as 25 km, the costs of the GIL system is more than twice of that in other systems. In addition, the costs of the GIL changes great when L increases, which means it is most sensitive to transmission distance; it can even be four times that of the others at a distance of 75 km. On the other hand, the hybrid HVDC transmission concept has economic advantages to the VSC-HVDC system, and when the installed capacity increases, the preferred distance range under the hybrid HVDC technology becomes longer from 50 km (300 MW), 38.6 km (600 MW), to 36.4 km (900 Mw). It is feasible if the technology is developed widely in the future.

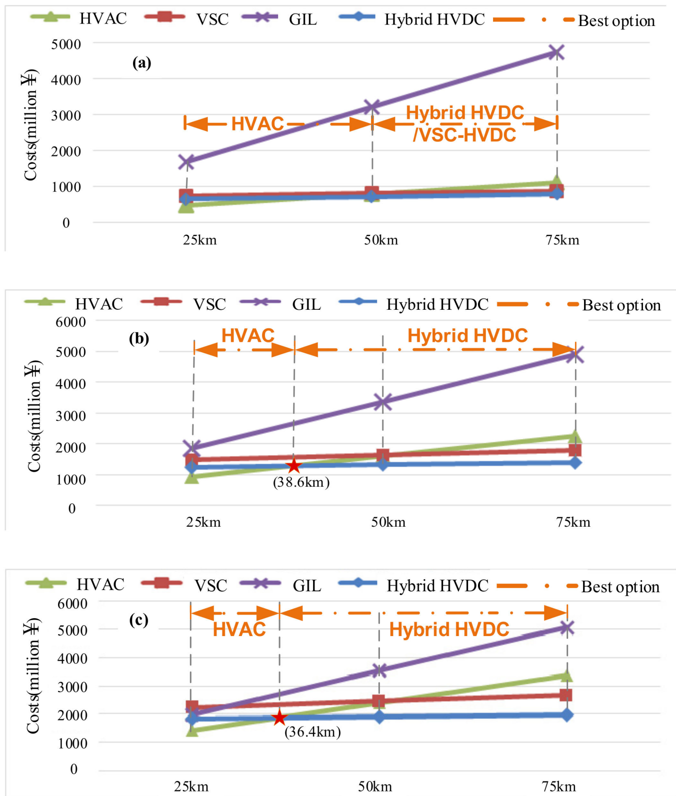

Figure 3. Total costs of different *L* of 300 MW, 600 MW, and 900 MW wind farms: (**a**) shows the 300 MW offshore wind farm total costs with different distances; (**b**) shows the 600 MW offshore wind farm total costs with different distances; (**c**) shows the 900 MW offshore wind farms total costs with different distances.

If the hybrid HVDC is not taken into present planning consideration due to its limited development, compared with VSC-HVDC electrical transmission, the HVAC concept is more superior when *L* is less than around 50 km in both 300 MW, 600 MW, and 900 MW wind farms. Otherwise, the HVDC transmission concept is preferable with a longer distance. HVDC is also less sensitive to transmission distance than the HVAC system.

4.3.2. Costs Components Comparisons with Different *L*

Taking 300 MW wind farms as an example, as Figure 4 shows, in the GIL and AC transmission system, the cable costs account for a large proportion of the total cost, especially the extravagant cable costs of the GIL transmission concept. That means the capital costs are the most important component to be considered, and the HVDC system has huge technological potential for offshore wind power transmission.

For the VSC-HVDC and hybrid HVDC transmission systems, cable costs are cheaper than for the AC transmission system. In turn, he costs of the converter station are much higher than that of the substation, as well as the costs of the converter station loss. It is important to notice that the capital costs in the AC system and GIL system increase greater than in HVDC systems.

4.3.3. Total Costs Comparisons with Different P

The economic costs of various transmission concepts are sensitive to transmission capacity, as shown in Figure 5. In near sea wind energy transmission, the economic costs of GIL transmission for 900 MW wind farms are even lower than that of VSC-HVDC transmission near sea wind farm transmission due to its advantages of large-capacity transmission. Thus, the GIL concept may be a better choice in the scenario under short distances with large-capacity transmission.

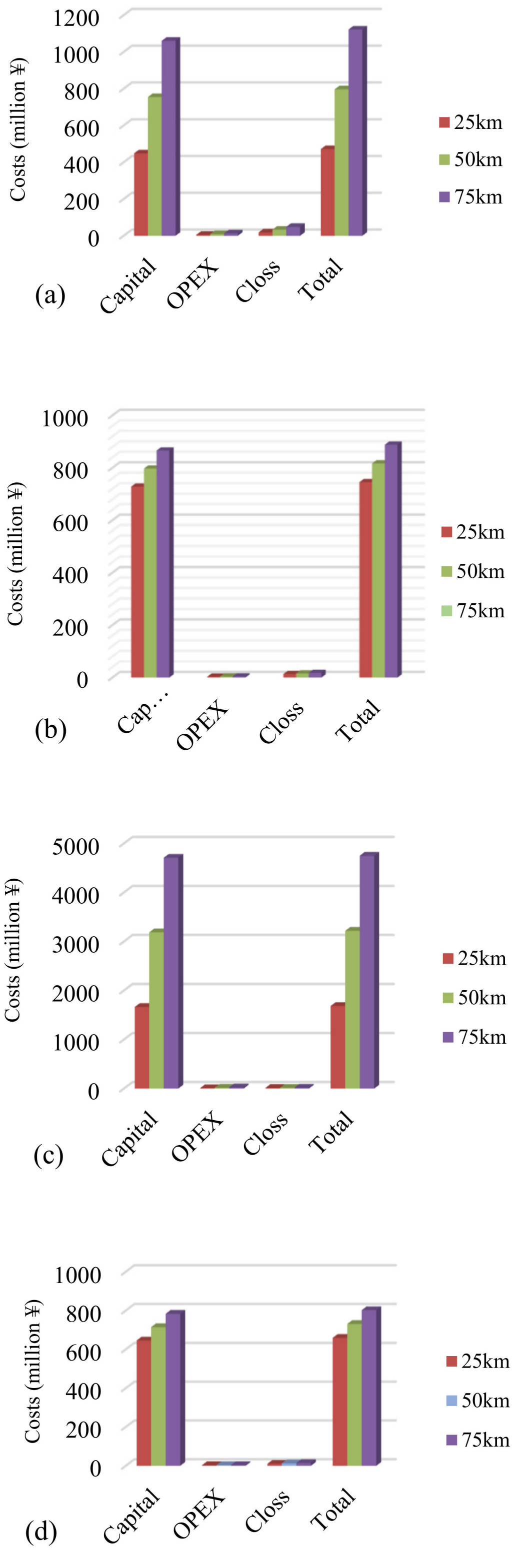

Figure 4. Cost component comparisons with different L (P is 300 MW): (**a**) shows the HVAC system; (**b**) shows the VSC-HVDC system; (**c**) shows the GIL system; (**d**) shows the Hybrid HVDC system.

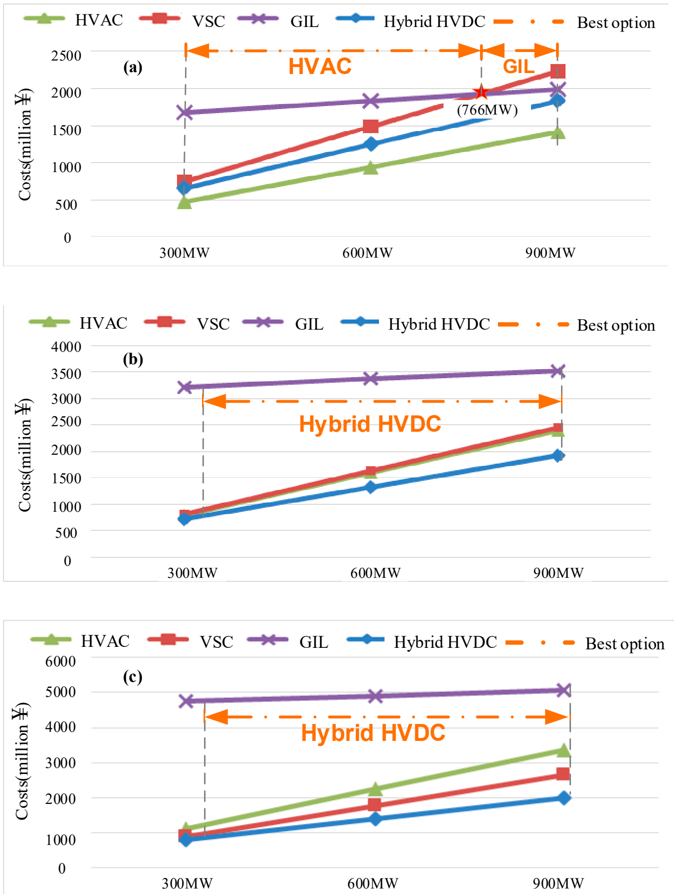

Figure 5. Total costs of different P of 25 km, 50 km, and 75 km wind farms: (**a**) shows the 25 km offshore wind farms total costs with different capacity; (**b**) shows the 50 km offshore wind farms total costs with different capacity; (**c**) shows the 75 km offshore wind farms total costs with different capacity.

Still, the lowest economic costs with different capacities are seen in the hybrid HVDC transmission concept, followed by HVAC electrical transmission and VSC-HVDC transmission. The GIL system increases significantly with a longer transmission distance; so, GIL is not recommended. Considering both economic and technical feasibility, for the offshore wind farms with different distances and transmission capacities, at present, HVAC transmission and VSC-HVDC transmission are selected according to the actual situation. The total costs are more sensitive to the distance than capacity. What is more, there is a need to notice that the hybrid HVDC transmission system is a preferred choice with the economic potential for either large-capacity or long-distance wind farms.

4.3.4. Costs Components Comparisons with Different P

Components comparisons of different *P* are carried out to acquire a view for investors. Taking the 25 km wind farms as an example, a sensitivity analysis was conducted, and the results shown in Figure 6.

It can be seen that there is an obvious advantage of the GIL system, as the capital costs of the GIL transmission system changed the least compared to the other systems, even when the capacity reached 900 MW. That means it is less sensitive to transmission capacity. However, the HVAC system and HVDC systems are so sensitive to capacity, which should be considered in OWF planning.

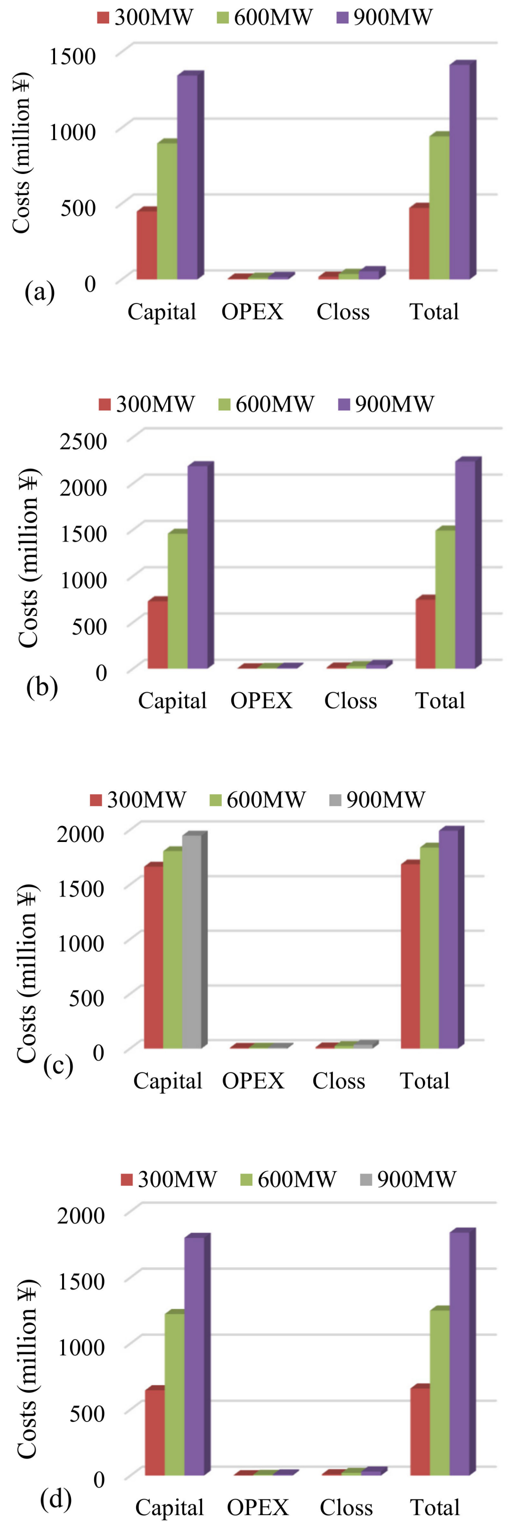

Figure 6. Costs components comparisons with different P (L is 25 km): (**a**) shows the HVAC system; (**b**) shows the VSC-HVDC system; (**c**) shows the GIL system; (**d**) shows the Hybrid HVDC system.

5. Conclusions

This paper investigates the four electrical transmission options for current and future Western Guangdong offshore wind farm implementation, including their technical characteristics, application status, and economic costs. Based on the component-resolved evaluation model, the capital costs, OPEX, and loss costs of four concepts of electrical transmission were studied, with the results showing that capital costs are the major component. The capital cost of the DC-type transmission technology is mainly related to the converter investment, while the cost of the AC type and GIL transmission technology is mainly related to the line and compensation cost. Meanwhile, the analysis also indicates that the offshore distance and capacity have an important impact on the capital costs of the four types of transmission. The sensitivity analysis of the four transmission solutions regarding transmission distance and capacity recommends the powerful competitive alternative of the HVAC transmission concept if the transmission system is less than 50.48 km for Yangjiang offshore wind farms, and VSC-HVDC and hybrid HVDC transmission for longer distances and larger capacities. For future planning, the GIL transmission system should be the preferred option in near sea and large-capacity wind farms, and the hybrid HVDC transmission possesses significant economic potential with a wide range of transmission distances and capacities.

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References

1. Snyder, B.; Kaiser, M.J. Ecological and economic cost-benefit analysis of offshore wind energy. *Renew. Energy* **2009**, *34*, 1567–1578. [CrossRef]
2. IRENA. *Global Renewables Outlook: Energy Transformation 2050*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020.
3. GWEC. *Global Wind Report 2019*; Global Wind Energy Council: Brussels, Belgium, 2020.
4. IEA. *Offshore Wind Outlook 2019*; International Energy Agency: Paris, France, 2019.
5. BNEF. *Offshore Wind Energy Market Outlook 2017*; Bloomberg New Energy Finance: Shanghai, China, 2017.
6. Sachs, J.; Moya, D.; Giarola, S.; Hawkes, A. Clustered spatially and temporally resolved global heat and cooling energy demand in the residential sector. *Appl. Energy* **2019**, *250*, 48–62. [CrossRef]
7. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [CrossRef]
8. Myhr, A.; Bjerkseter, C.; Ågotnes, A.; Nygaard, T.A. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renew. Energy* **2014**, *66*, 714–728. [CrossRef]
9. Cavazzi, S.; Dutton, A.G. An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential. *Renew. Energy* **2016**, *87*, 212–228. [CrossRef]
10. Hdidouan, D.; Staffell, I. The impact of climate change on the levelised cost of wind energy. *Renew. Energy* **2017**, *101*, 575–592. [CrossRef]
11. Hearps, P.; McConnell, D. *Renewable Energy Technology Cost Review*; Melbourne Energy Institute: Melbourne, Australia, 2011.
12. Waewsak, J.; Landry, M.; Gagnon, Y. Offshore wind power potential of the Gulf of Thailand. *Renew. Energy* **2015**, *81*, 609–626. [CrossRef]
13. Nagababu, G.; Kachhwaha, S.S.; Savsani, V. Estimation of technical and economic potential of offshore wind along the coast of India. *Energy* **2017**, *138*, 79–91. [CrossRef]
14. Effiom, S.O.; Nwankwojike, B.N.; Abam, F.I. Economic cost evaluation on the viability of offshore wind turbine farms in Nigeria. *Energy Rep.* **2016**, *2*, 48–53. [CrossRef]
15. Möller, B.; Hong, L.; Lonsing, R.; Hvelplund, F. Evaluation of offshore wind resources scale of development. *Energy* **2012**, *48*, 314–322. [CrossRef]
16. Yamaguchi, A.; Ishihara, T. Assessment of offshore wind energy potential using mesoscale model and geographic information system. *Renew. Energy* **2014**, *69*, 506–515. [CrossRef]
17. Abdelhady, S.; Borello, D.; Shaban, A. Assessment of levelized cost of electricity of offshore wind energy in Egypt. *Wind. Eng.* **2017**, *41*, 160–173. [CrossRef]
18. Bosch, J.; Staffell, I.; Hawkes, A.D. Global levelised cost of electricity from offshore wind. *Energy* **2019**, *189*, 116357. [CrossRef]

19. Ebenhoch, R.; Matha, D.; Marathe, S.; Muñoz, P.C.; Molins, C. Comparative Levelized Cost of Energy Analysis. *Energy Procedia* **2015**, *80*, 108–122. [CrossRef]
20. Nagababu, G.; Kachhwaha, S.S.; Naidu, N.K.; Savsani, V. Application of reanalysis data to estimate offshore wind potential in EEZ of India based on marine ecosystem considerations. *Energy* **2017**, *118*, 622–631. [CrossRef]
21. Papathanasopoulou, E.; Beaumont, N.; Hooper, T.; Nunes, J.; Queirós, A.M. Energy systems and their impacts on marine ecosystem services. *Renew. Sustain. Energy Rev.* **2015**, *52*, 917–926. [CrossRef]
22. Kim, J.Y.; Oh, K.Y.; Kang, K.S.; Lee, J.S. Site selection of offshore wind farms around the Korean Peninsula through economic evaluation. *Renew. Energy* **2012**, *54*, 189–195. [CrossRef]
23. Pacheco, A.; Gorbeña, E.; Sequeira, C.; Jerez, S. An evaluation of offshore wind power production by floatable systems: A case study from SW Portugal. *Energy* **2017**, *131*, 239–250. [CrossRef]
24. Elliott, D.; Bell, K.R.; Finney, S.J.; Adapa, R.; Brozio, C.; Yu, J.; Hussain, K. A comparison of AC and HVDC options for the connection of offshore wind generation in Great Britain. *IEEE Trans. Power Deliv.* **2016**, *31*, 798–809. [CrossRef]
25. Cui, Y.; Song, X.; Zhao, L.; Yuan, H.; Wu, G.; Wang, C. WSN-Based Measurement of Ion-Current Density Under High-Voltage Direct Current Transmission Lines. *IEEE Access* **2019**, *7*, 10947–10955. [CrossRef]
26. Kimura, N.; Funaki, T.; Matsu-ura, K. Damping of current oscillation in superconductive line applied for high voltage direct current transmission system. *IEEE Trans. Appl. Supercond.* **1993**, *3*, 223–225. [CrossRef]
27. Lu, T.; Feng, H.; Zhao, Z.; Cui, X. Analysis of the Electric Field and Ion Current Density Under Ultra High-Voltage Direct-Current Transmission Lines Based on Finite Element Method. *IEEE Trans. Magn.* **2007**, *43*, 1221–1224. [CrossRef]
28. Jacobs, K.; Heinig, S.; Johannesson, D.; Norrga, S.; Nee, H.-P. Comparative Evaluation of Voltage Source Converters with Silicon Carbide Semiconductor Devices for High-Voltage Direct Current Transmission. *IEEE Trans. Power Electron.* **2021**, *36*, 8887–8906. [CrossRef]
29. Yuan, H.; Yang, Q.; Liu, Y.; Lu, J.; Akhtar, S.A. Development and Application of High-Frequency Sensor for Corona Current Measurement under Ultra High-Voltage Direct-Current Environment. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 1064–1071. [CrossRef]
30. Blanco, M.I. The economics of wind energy. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1372–1382. [CrossRef]
31. ABB. *World's First Power-from-Shore Dynamic ac Cable—Gjoa Floating Oil and Gas Platform*; North Sea: Zurich, Switzerland, 2015.
32. Schell, K.R.; Claro, J.; Guikema, S.D. Probabilistic cost prediction for submarine power cable projects. *Int. J. Electr. Power Energy Syst.* **2017**, *90*, 1–9. [CrossRef]
33. Wu, J.; Wang, J.; Chi, D. Wind energy potential assessment for the site of Inner Mongolia in China. *Renew. Sustain. Energy Rev.* **2013**, *21*, 215–228. [CrossRef]
34. Hong, L.; Möller, B. Offshore wind energy potential in China: Under technical, spatial and economic constraints. *Energy* **2011**, *36*, 4482–4491. [CrossRef]
35. Da, Z.; Xiliang, Z.; Jiankun, H.; Qimin, C. Offshore wind energy development in China: Current status and future perspective. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4673–4684. [CrossRef]
36. *2014 Standard*; Design Control Index of Power Grid Project. Electric Power Planning and Engineering Institute of China: Beijin, China, 2014.
37. Dicorato, M.; Forte, G.; Pisani, M.; Trovato, M. Guidelines for assessment of investment cost for offshore wind generation. *Renew. Energy* **2011**, *36*, 2043–2051. [CrossRef]
38. Eeckhout, B.V. *The Economic Value of VSC-HVDC Compared to HVAC for Offshore Wind Farms*; Katholieke Universiteit Leuven: Leuven, Belgian, 2008.
39. Guozhen, X.; Yonggang, G. Analysis and estimation of circulation and loss of GIS and Gil shells. *High Volt. Technol.* **2009**, *35*, 247–249.
40. National Development and Reform Commission of the People's Republic of China. *Yi Kang, Notice of the National Development and Reform Commission on the on Grid Tariff Policy of Offshore Wind Power*; National Development and Reform Commission of the People's Republic of China: Beijing, China, 2014.