

Article

Life Cycle Cost Assessment of Offshore Wind Farm: Kudat Malaysia Case

Shamsan Alsubal, Wesam Salah Alaloul * , Eu Lim Shawn, M. S. Liew, Pavitirakumar Palaniappan 
and Muhammad Ali Musarat 

Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS,
Bandar Seri Iskandar 32610, Malaysia; shamsan2040@gmail.com (S.A.); shawn.lim@utp.edu.my (E.L.S.);
shahir_liew@utp.edu.my (M.S.L.); p.kumar_1912@yahoo.com (P.P.);
muhammad_19000316@utp.edu.my (M.A.M.)

* Correspondence: wesam.alaloul@utp.edu.my

Abstract: The Government of Malaysia has set a striving target to achieve a higher usage of renewable energy (RE) in the energy mix which is currently around 2% of the country's electricity. Yet, the government intends to increase this ratio up to 20% by the year 2025. Most of the renewable energy in Malaysia comes from hydropower and biomass sources. Meanwhile, numerous studies have been conducted to determine the feasibility of wind energy in Malaysia. Several locations were reported to be economically viable for wind energy development such as Kudat, Mersing, and Kuala Terengganu. This study presents and discusses the whole life cycle cost analysis of an offshore wind farm in Kudat, Malaysia and determines the cost drivers of offshore wind energy developments. It covers the wind data collection and analysis, breakdown of whole life cycle cost structure, and calculation of the levelized cost of energy (LCOE). Results showed that almost 67% of the total cost was incurred by the capital expenditure (CAPEX), and around 26% by operation and maintenance costs (OPEX), while decommissioning costs (DECOM) reached up to 7% of the whole life cycle costs. The LCOE was calculated and determined to be USD 127.58/MWh.

Keywords: offshore wind energy; levelized cost of wind energy; Malaysian offshore wind energy; cost of wind energy; LCOE Malaysia



Citation: Alsubal, S.; Alaloul, W.S.; Shawn, E.L.; Liew, M.S.; Palaniappan, P.; Musarat, M.A. Life Cycle Cost Assessment of Offshore Wind Farm: Kudat Malaysia Case. *Sustainability* **2021**, *13*, 7943. <https://doi.org/10.3390/su13147943>

Academic Editor: Firoz Alam

Received: 13 April 2021

Accepted: 22 June 2021

Published: 16 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The power generation sector is deemed to be one of the core sources for emissions of greenhouse gases with 25% of the total emissions worldwide [1,2]. Renewable energy is the solution for this issue and is the priority for the countries in sustainable development [3,4]. Wind energy is one of the fast-developing renewable energy resources worldwide especially in the United States of America (USA), China and European countries [5]. Its capacity is rising rapidly within the last decades, where it reached 622 GW in 2019 and is expected to be 903 GW till 2023, with an average growth of 12% [5–8]. Offshore wind farms are given special attention due to the higher and steadier wind speed. Moreover, it is possible to locate wind farms near coastal cities where the energy demand is high and saves the cost of electrical transmission lines [9]. The technology of offshore wind turbines started in the 1990s, where the first offshore wind turbine was installed in 1990 in Sweden with a 220 kW capacity and 250 m far from the shoreline [10]. In 1991, the first offshore wind farm was installed in Denmark with 11 offshore wind turbines and a total capacity of 4.95 MW [10,11]. Most of the offshore wind turbines built within the period were bottom-fixed turbines except for some wind farms which are Hywind Tampen in Norway, WindFloat Atlantic in Portugal, and Fukushima in Japan [6,10].

Wind energy is readily accessible around the world and can lead to a reduction in the dependency on fossil fuel energy [12]. The productivity of wind energy has been improved in recent years and the unit cost of wind power has reduced which allows it to

be a sustainable alternative to other sources of energy [13,14]. To date, the production of wind energy has primarily occurred onshore, whereas offshore wind farms have a high energy density [15,16]. This may also be comparable in terms of output capability to traditional power stations. The wind on the sea surface is less disturbed by obstacles that cause turbulence in comparison with onshore surfaces. As a result, wind energy generation is more exploited [17,18]. Facing constraints of land availability and concerns related to noise and visual disturbances created by onshore wind farms, offshore wind farms are the best alternative to onshore wind farms [18]. The key inspiration for moving towards offshore energy is the minimal impact on human life, land resource and especially fossil fuels [19]. Despite the high net profits from offshore energy, the economic perspectives are counterbalanced by the higher capital, installation, and maintenance costs [20]. Whereas offshore wind turbines are much more complex than onshore projects to build and operate. However, offshore wind technology is developing at a rapid rate, which means that even larger systems developed for offshore use are required, which could potentially benefit from economies of scale which may result in a substantial cost reduction [21].

Malaysia has set up an auspicious plan for the development of renewable energy with its aim to reduce around 45% of greenhouse gas emissions by 2030 [22]. Conventional methods such as natural gas and coals are the main sources for power generation in Malaysia. The development of wind energy and LCOE, in particular, is still in its embryonic stage and no sufficient studies have been conducted. However, some researchers have carried out a few studies to evaluate the feasibility of wind power generation in Malaysia and determine the most suitable locations in Peninsular Malaysia, Sabah and Sarawak. According to the literature reviewed, most of the previous studies agreed on some offshore locations in Malaysia to be feasible for wind energy—Mersing, Kudat, and Kuala Terengganu [23–25].

Although there is no specific feed-in tariff (FiT) for wind energy in Malaysia, a few studies have been conducted to evaluate the economical aspect. The evaluation differs from one research to another according to the assumed FiT. Nor et al. [26] carried out a techno-economic study using a financial analysis method for a 1000 kW onshore wind turbine. It was found that the annual production of energy at Kudat is 3350 MW with a payback period of 4.95 years when considering the utility price of MYR 0.55/kWh. Mekhilef et al. [27] conducted a study to evaluate the potential locations for wind farming in Malaysia. It was reported that the sites facing the South China Sea are economically viable with a determined electricity price of MYR 0.4/kWh based on a 2 MW wind turbine evaluation. Another study was conducted by Ibrahim and Albani [28] to evaluate the wind energy at Kudat. It was found that the average capacity factor of wind energy is 10% to 11% with a payback period of less than 10 years.

Malaysia is considered a low wind speed country. However, the high wind speed is blown from the Indian Ocean and the South China Sea, especially during monsoon seasons. Two monsoons in Malaysia come from the Southwest starting from May to September and the Northeast from November to March. The wind speed during the southwest monsoon is often less than 7 m/sec which reaches up to 15 m/s during the northeast monsoon on the east coast of Peninsular Malaysia. Therefore, this study aims to determine the whole life cycle costs of an offshore wind farm and evaluate the cost factors for its construction in Kudat, Malaysia. The study is limited to the evaluation of available wind energy at Kudat based on 19 years of a wind speed data record. The capacity of the evaluated offshore wind farm is 105 MW with 7 MW rated power of wind turbines. The challenges of the construction of wind turbines and foundations are not discussed in this research.

2. Methodology

The methodology of the cost assessment follows the breakdown of the life cycle cost structure and the levelized cost of the energy method. The evaluation of the life cycle cost consists of three elements, namely, *CAPEX*, *OPEX* and *DECOM* [29]. These elements are subdivided into five phases to represent an offshore wind turbine project starting from an idea to the decommissioning stage of the structure. The phases are predevelopment

and consenting, production and acquisition, installation and commissioning, operation and maintenance, and decommissioning and disposal [30]. The general expression of the life cycle costs or economic viability cost (EC_v) of the offshore wind turbine is given by Equation (1):

$$EC_v = \sum C_{CAPEX} + C_{OPEX} + C_{DECOM} \quad (1)$$

where EC_v is the total cost over a lifetime.

2.1. Breakdown of Life Cycle Cost Structure

Several models proposed by IEC 60300-3-3:2004 [29] were used to calculate the life cycle costs of an offshore wind turbine farm [30]. However, the costs in this study were calculated based on the phases of the wind turbines' life cycle which are capital expenditure (CAPEX), operational expenditure (OPEX), and decommissioning and disposal (DECOM). CAPEX is considered the initial investment cost which is spent at the early stages of the project development and construction. OPEX is the expenditure throughout the lifetime of the wind turbines for operations and maintenance, while DECOM is the cost of removing and disposing of the structures at the end of their lives. CAPEX consists of three phases which are predevelopment and consenting (P&C), production and acquisition (P&A), and installation and commissioning (I&C). The other two phases of the whole life cycle costs are operations and maintenance (O&M), and decommissioning and disposal (D&D).

Predevelopment and consenting (P&C): This is the first phase of the offshore wind farm project. It starts with an idea and ends with the commencement of the project. It is also subdivided into five categories that are: project management (C_{projM}), legal authorizing (C_{legal}), surveys ($C_{surveys}$), engineering activities (C_{eng}), and contingencies ($C_{contingency}$) [31]. Project management refers to feasibility studies, administrative works and arrangements with sub-contractors; it costs about 3% of the CAPEX [32]. C_{sur} is the costs of coastal, environmental, seabed, and metocean studies. The cost of the survey depends on the capacity of the offshore wind farm, except for metocean studies which remain constant. The cost of surveying is given by the following equations [33]:

$$C_{sur} = IC [\sum (C_{surc}, C_{sure}, C_{sur_s})] + C_{sur_m} \quad (2)$$

$$IC = PR \left[\sum_{i=1}^n N_{WTi} \right] \quad (3)$$

where IC , PR , and N_{WTi} are the installation capacity, power rating of the offshore wind turbines, and the summation of optimum power produced by the offshore wind turbines, respectively.

The cost of engineering is related to the main engineering activities ($C_{eng-main}$) and the critical verification ($C_{eng-verif}$) by the third party which can be given by Equation (4). The main engineering activities depend on the project size and can be expressed as a function of installed capacity [33]. Therefore, $C_{eng-main}$ equals the sum of a fixed base cost (C_{base}) and the cost of a unit term multiplied by its capacity ($C_{eng-unit}$).

$$C_{eng} = C_{base} + C_{eng-verif} + C_{eng-unit} \times IC \quad (4)$$

Contingency cost refers to the cost incurred by the replacement of the most important components subjected to catastrophic failure and it is estimated to be 10% of CAPEX costs [34,35].

Production and acquisition (P&A): This is the second phase and drives the highest share of life cycle costs. It includes all the costs related to the manufacturing and procurements of the support structures (C_{SS}), wind turbines (C_{WT}), power transmission systems (C_{PTS}), and monitoring systems ($C_{monitoring}$). The cost of foundations varies according to their type and the depth of water. The water depth taken in this study was 20 m while the foundation was assumed to be monopile. Hence, the cost of the foundation (C_{ss}) is assumed to be USD 500,000.00 per MW according to the costs driven by Bosch et al. [36].

The cost of wind turbine procurements is described as a function of the total number of wind turbines (N_{WT}) installed in the farm and can be given by the following equation:

$$C_{WT} = (C_{wt-mat} + C_{wt-trans}) \times N_{WT} \quad (5)$$

where C_{wt} is the total cost of wind turbines' components, C_{wt-mat} is the cost of wind turbines' materials including subsystems, $C_{wt-trans}$ is the cost of transportation from the place of the manufacturer and N_{WT} is the number of wind turbines.

The cost of wind turbine components depends on the rated power of the wind turbine (PR). Shafiee et al. [31] used a logarithmic regression model on a dataset containing prices of several turbines and modelled the cost of materials by Equation (6). A root mean square of error of about GBP 223,000 was considered in the regression model.

$$C_{wt-mat} = 3,000,000 \times \ln(PR) - 662,400 \quad (6)$$

The cost of transportation of the wind turbines depends on the number of days required times the daily rate of hiring a vessel. China is considered the manufacturer location for wind turbines due to the huge trade exchange between the countries and the close distance to Malaysia. The distance between the Kudat and Beijing harbor ports is 1170 nm. Assuming the vessel speed is 10 knots, the expected travel days are 4.9 days. The daily rate of a vessel considered in this study is about USD 150,000/day based on rates derived by Kaiser and Snyder [37].

The costs of the power transmission system (C_{PTS}) represents the cost of cables (C_{cables}), the cost of offshore substation ($C_{of-subs}$), and the cost of onshore substation ($C_{on-subs}$).

$$C_{PTS} = C_{cables} + C_{of-subs} + C_{on-subs} \quad (7)$$

The cost of the offshore substation is estimated based on linear regression model developed by Myhr et al. [38] as follows:

$$C_{of-subs} = 583,300 + 107,900 \times IC \quad (8)$$

The onshore substation was estimated to be half of the offshore substation cost [30,39], while the cost of transmission cables (C_{cables}) was calculated based on the price per unit length times the distance plus the protection seals. It was estimated to be USD 20,000/MW.

The cost of a monitoring system ($C_{monitoring}$) is the cost of the supervisory control and data acquisition system (SCADA) and the cost of monitoring systems (CMSs).

Installation and commissioning (I&C): This is composed of the costs related to the activities of installation and construction of offshore wind turbines, support structures and electrical systems ($C_{I\&C-comm}$), ports charges (C_{port}), commissioning cost (C_{comm}), and insurance cost ($C_{I\&C-ins}$).

$$C_{I\&C} = C_{I\&C-comp} + C_{port} + C_{comm} + C_{I\&C-ins} \quad (9)$$

According to Kaiser and Snyder [37], the average time for the monopile foundation installation is 3.7 days and the average time for wind turbine installation is 4.1 days based on the average time for 18 cases. However, it took 1.5 days per nit for the installation in some cases, especially for the monopile foundation [37,40], while it takes 0.7 days/km to install transmission cables led by ROV. The minimum spread at the installation site was one main installation vessel, two crew boats, two tugs, and one other vessel. It was also reported that it takes almost four days for the installation of a substation [41]. The average days for the installation and minimum spread were considered in this study. The daily rates taken in this study were USD 150,000 for the main vessels, USD 35,000 for the cooperate vessels, USD 8000 for crew boats, USD 12,000 for the tugs and USD 8300 for ROV vehicles [37,40,42].

Ports usually charge for the use of their infrastructure's facilities, docking, quayside and cranes [43]. These charges must be paid to the local authorities annually (C_{port}). The commissioning cost (C_{comm}) is involved, in which the electrical system and wind turbine are tested to improve its reliability and detect early failures [44]. Insurance is important at this stage to reduce the impact of any accidental events that may take place; hence, the insurance cost ($C_{I\&C-ins}$) is added to the capital cost. The cost of insurance is taken based on the average global cost for installation insurance of the wind turbine, foundation and electrical systems including offshore and onshore electrical substations [37,40,41].

Operation and maintenance (O&M): This is related to the costs charged for the operation and maintenance of offshore wind turbines. Operations take into account the rent (C_{rent}) of the seabed and paid to the authorities or landlord, insurance ($C_{O\&M-ins}$) against collision damages and design faults, and transmission charges ($C_{transmission}$) to be paid to the national electrical grid [31]. Maintenance cost is divided into direct maintenance costs and indirect maintenance costs ($C_{M-indirect}$). Indirect maintenances are related to the activities involved in providing repair services, such as vessel rents, and operations associated to coordinate maintenance activities [45]. Direct maintenance consists of the costs involved with the transportation of failed components and maintenance technicians. It is divided into corrective maintenance (C_{CM}) which takes place after the failure of the component and proactive maintenance (C_{ProM}) which takes place before failure [46].

Operation and maintenance vary according to the depth of water, distance to the coast and the type of foundation [36]. The estimated OPEX cost in this study is USD 38,000/MW annually based on the findings reported by Bosch et al. [36]. O&M costs amount up to 30% of the total costs of the offshore wind farm [47].

Decommissioning and disposal (D&D): Also known as the life-ending phase, D&D is the final stage in which the offshore wind turbines with the supporting structures are removed and recycled. It includes the port charges ($C_{D\&Dport}$), removal costs (C_{remove}), waste management costs (C_{WM}), and post decommissioning monitoring activities costs (C_{postM}). The cost of port preparation is calculated based on the labor costs and the fees paid for the use of the port, which is around USD 1000 per vessel call in Malaysia. The cost of removal of a wind turbine and foundation ranges between 60–70% of the installation cost [48,49]. The removal of offshore wind farms includes the cutting and lifting of wind turbine and foundation components. In a study conducted by Adedipe and Shafiee [50], the time taken for the removal of a wind turbine foundation is 80% of its installation, while for the removal of a wind turbine it takes 90% of its installation time. The typical vessel used for the removal of a wind turbine and foundation is a jack-up vessel with an estimated day rate of USD 140,000. The main vessel for waste disposal and two tugs are required as well with a daily rate of USD 35,000 and USD 12,000 respectively. Whereas the vessels required for cable removal are an OSV and cable laying vessel with a daily rate of USD 8000 and 35,000, respectively. The time taken for the removal of a cable is 0.6 km per day [51].

Waste management strategies determine how the wind turbines are disposed of. Some options are available for disposal which are recycling, reusing, incineration with energy recovery and landfill disposal [31]. Waste management is calculated based on four factors which are processing of materials, transportation of waste materials, landfill charges and recycling benefits. The cost of waste processing depends on the total weight of materials. The average weight of a monopile is 455 tons (t) and it is considered due to the shallow water depth, where the total weight of a wind turbine is 943 tons. The cost of transportation is calculated based on the rates of the trucks and their capacities, while the cost of the solid waste landfill in Malaysia is determined to be USD 10/t [52]. The metal scrap and copper are recycled with a salvage value of USD 400/t, USD 3000/t and USD 1200/t for metal, copper and lead, respectively, based on rates in Malaysia for the year 2020. The average composition of metal and copper components in wind turbines is 93% and 1%, respectively [53,54]. However, the selling price of scrap metal is more likely to increase in the future.

Post-decommissioning monitoring activity charges are determined for the arising wastes after removal and to mitigate their risk, it is estimated to be 3% of decommissioning costs [50].

It is still difficult to predict the exact cost of decommissioning an offshore wind turbine platform in Malaysia as there is no practical record. However, the calculated costs are close to the costs reported by Topham and McMillan [49] and Topham et al. [54].

2.2. Site Selection

Based on previous studies [27,53,55–58], Kudat is one of the most likely locations for wind energy in Malaysia. Therefore, Kudat was chosen for the assessment of wind power and the evaluation of LCOE of the offshore wind farm. The site is about 17 km away from the shoreline with a 20 m water depth, as illustrated in Figure 1 [58].



Figure 1. Proposed location for offshore wind turbine installation.

2.3. Collection of Wind Speed Data

The wind speed data were collected from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce [59]. Wind data such as daily mean wind speed and maximum wind speed for the past 19 years were collected at 5 m elevation. Then, the average wind speed was calculated statistically. As the wind speed in Malaysia has been stable for the past 19 years, it is assumed to be stable throughout the lifetime of the wind turbine (25 years). Figure 2 shows wind speed data collected with the average speed for the period 2002–2020.

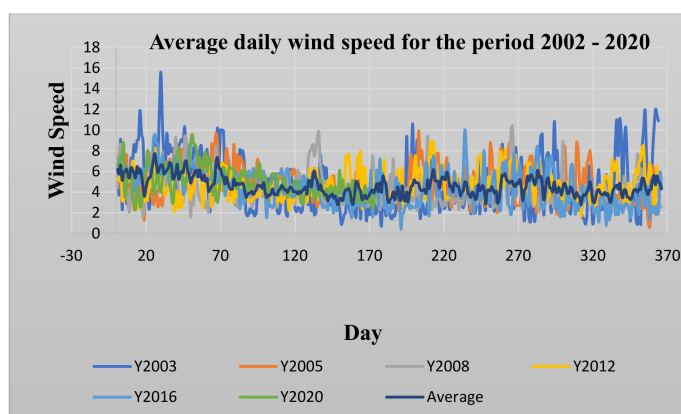


Figure 2. Sample of average wind speed for multiple years and the average wind speed for the period 2002–2020 in Kudat at elevation of 5 m.

2.4. Wind Resource Assessment

The SWT-7MW-154 wind turbine was selected for the wind energy assessment and wind data interpolation at hub height. The wind turbine has a swept area of 18,627 m² with

100 m hub height. The wind speed at the hub height ($Z_2 = 100$ m) was calculated using Equation (10), as the available data were taken at $Z_1 = 5$ m height. According to a study conducted by Albani and Ibrahim [57] based on data collected from wind measurement masts in Kudat, it was found that the wind speed rose at higher hub heights where it was 2.84 m/s at 10 m hub height and 5.91 m/sec at 70 m hub height. However, when the log-law was applied to determine the wind speed at 70 m based on the same data collected at 10 m, it gave a value of 3.21 m/sec which is less than 5.91 m/sec that was measured.

$$U_z = U_0 \times \left[1 + C \times \ln \left(\frac{Z_2}{Z_1} \right) \right] \quad (10)$$

where U_z is the wind speed at hub height and U_0 is the wind speed at 5 m, while C is the constant and can be given by Equation (11):

$$C = 5.73 \times 10^{-2} \times (1 + 0.15U_0)^{\frac{1}{2}} \quad (11)$$

Wind power depends on multiple factors, which are wind density, swept area of the rotor, wind velocity and power coefficient. Equation (12) was used to calculate the wind energy of the wind turbine. Wind speeds of below 4 m/s and above 25 m/s at 100 m elevation were removed as these are rated as cut-in and cut-off wind speeds of the chosen wind turbine, respectively.

$$P_{avail} = \frac{1}{2} \rho A (U_{(z)})^3 C_p \quad (12)$$

where ρ is the wind density, A is the swept area, $U_{(z)}$ is the wind speed at hub height and C_p is the power coefficient.

Wind turbines have a limit in extracting wind energy and this limit is called the power coefficient (C_p). It ranges between 35–45% of the wind energy based on the efficiency of the wind turbine. Considering the specifications of the chosen SWT-7MW-154 wind turbine, a power coefficient of 0.40 was determined for this wind turbine.

2.5. Levelized Cost of Offshore Wind Energy

The levelized cost of energy is defined as the present value of produced energy and can be given by the summation of costs within a lifetime of the wind farm over the summation of electricity produced during its lifetime [60,61]. It can be expressed by the net present value of costs over the net present value of energy produced as described in Equation (13):

$$LCOE = \frac{\sum_n \frac{C_n}{(1+r)^n}}{\sum_n \frac{E_n}{(1+r)^n}} \quad (13)$$

In a discounted cash-flow analysis, the net present value (NPV) of costs was determined using the discount rate as shown in Equation (14). REN21 gave a discount rate of 7.5% for the countries of the Organization for Economic Cooperation and Development (OECD) to measure the levelized cost of energy for wind energy, where only 10% is given to China and the rest of the world [62].

$$NPV_C = \frac{\sum C_{CAPEX} + C_{OPEX} + C_{DECOM}}{(1+r)^n} \quad (14)$$

where n is the number of years of wind turbine lifetime which was considered 25 years in this study, and r is the discount rate.

The average inflation rate for the past 20 years (2000–2019) in Malaysia is 2.16%. There are different ways to reflect the effect of the inflation rate [63]. In this study, the discount rate was adjusted to incorporate the effect of inflation rate as in Equation (15):

$$r = \frac{1+i}{1+e_a} - 1 \quad (15)$$

where i is the discount rate while e_a is the inflation rate.

3. Results and Discussion

3.1. Life Cycle Costs of Offshore Wind Turbine

The life cycle costs of the offshore wind farm were evaluated, and the high-cost components of the offshore wind farm development were identified. The cost components are divided into three categories, which include the capital expenditure (CAPEX), operation and maintenance (OPEX), and decommissioning and disposal (DECOM). Table 1 shows the whole life cycle costs of an offshore wind farm in Kudat, Malaysia. The foundations were assumed to be a monopile type while the wind turbine was selected to be the 7 MW (SWT-7MW-154).

Table 1. Breakdown of whole life cycle costs of an offshore wind turbine farm.

Phase	Cost Element	Cost per MW Installed (USD/MW)	Contribution to CAPEX/OPEX/DECOM %	Contribution to the Whole Life Cycle Costs %
CAPEX	P&C			
	C _{projM}	90,000	3.74%	2.50%
	C _{legal}	7901	0.33%	0.22%
	C _{surveys}	30,066	1.25%	0.83%
	C _{eng}	2400	0.10%	0.07%
	C _{contingency}	251,565	10.46%	6.97%
	Total C_{P&C}	381,932	15.88%	10.59%
	P&A			
	C _{WT}	1,006,940	41.878%	27.92%
	C _{SS}	500,000	20.79%	13.86%
	C _{PTS}	190,599	7.93%	5.29%
	C _{monitoring}	5873	0.24%	0.16%
	Total C_{P&A}	1,703,412	70.84%	47.23%
	I&C			
	C _{port}	34,960	1.45%	0.97%
	C _{I&C-comp}	234,281	9.74%	6.50%
	C _{comm}	570	0.02%	0.02%
	C _{I&C-ins}	49,504	2.06%	1.37%
	Total C_{I&C}	319,315	13.278%	8.85%
OPEX	CAPEX	2,404,659		66.67%
	O&M			
	C _{rent}	23,370	2.46%	0.65%
	C _{O&M-ins}	87,305	9.19%	2.42%
	C _{transmission}	430,350	45.3%	11.93%
	C _{O&M-indirect}	60,325	6.35%	1.67%
	C _{ProM}	188,100	19.8%	5.22%
	C _{CM}	160,550	16.9%	4.45%
	OPEX	950,000		26.34%
	DECOM			
DECOM	D&D			
	C _{D&D-port}	49,639	16.82%	1.38%
	C _{remove}	236,850	80.35%	6.57%
	C _{WM}	−43,045	−14.59%	−1.19%
	C _{postM}	8589	2.91%	0.24%
	DECOM	252,033		6.99%

Table 1 shows the cost distribution of CAPEX, OPEX, and DECOM and their contribution to the whole life cycle costs of the offshore wind farm. It can be noticed that CAPEX incurred the largest proportion which amounted up to USD 2.4M/MW. Followed by OPEX with USD 0.95M/MW, while DECOM costs were the least with USD 0.25M/MW. The distribution of costs for each phase of the project development is presented in Figure 3. It is observed that around 47% of the total cost was incurred by the production and acquisition phase due to the procurement of wind turbines, foundations and electrical systems. It is followed by the operation and maintenance cost (O&M) with 26% of the whole life cycle costs. The predevelopment and consenting phase (P&C) costs were around 11% of the total costs, covering the cost of project management, surveying, engineering, legal authorization and contingency which takes the majority of the P&C costs. The cost of installation and commissioning (I&C) was 9% of the cost expenditure due to the type of foundation used. Moreover, the cost of transport was accounted for with the procurement of wind turbines. The decommissioning and disposal (D&D) costs were the lowest costs which are 7% of the total cost and is equivalent to 82% of the installation costs. The obtained costs were within the recommended range [48,49].

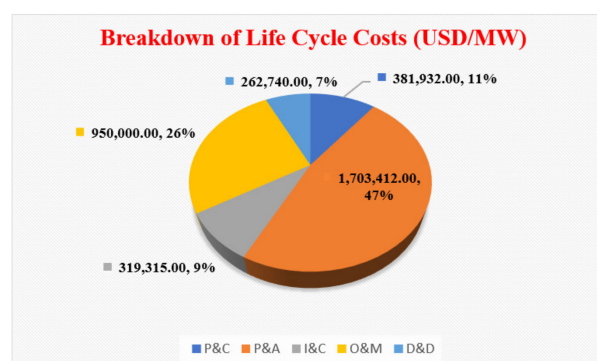


Figure 3. Cost distribution of the whole life cycle of an offshore wind turbine farm.

The initial capital expenditure costs (CAPEX) of the offshore wind turbine project are illustrated in Figure 4. The capital expenditure consists of the P&C, P&A, and I&C project phases, with an overall cost of about USD 2.41 M/MW. The result indicates that the key drivers of the capital costs were the wind turbine (42%), support structures (21%), contingency (11%), installation (10%) and power transmission system (8%). The procurement of the wind turbine cost around USD 1M/MW due to the transportation charges from China, followed by the cost of the monopile foundation which was estimated to be around USD 0.5M/MW. The installation cost was relatively less than the production cost, i.e., 10% of CAPEX costs. The other 9% of costs covered project management, engineering work, surveys, and other elements, where the highest cost among them was incurred by project management, i.e., 4% of CAPEX costs. The cost of production was close to the costs reported by the mentioned researchers [31,37,38], whereas the cost of installations was a close approximation to the values reported by the mentioned researchers [37,40,58].

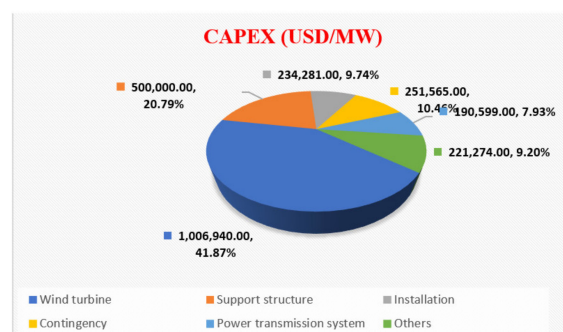


Figure 4. Distribution of initial capital expenditure cost (CAPEX) per MW.

Figure 5 illustrates a detailed distribution of costs incurred by the operation and maintenance phase. The results obtained show that almost 45% of the OPEX costs were driven by transmission charge costs, which are paid to the local authority in charge of the national electrical grid. The second cost driver was the direct maintenance which constitutes about 37% of total OPEX costs. The other cost drivers were insurance (9%), indirect maintenance (6%), and rent (3%). The costs' values obtained in this study were close to the values obtained by the mentioned studies [31,60].

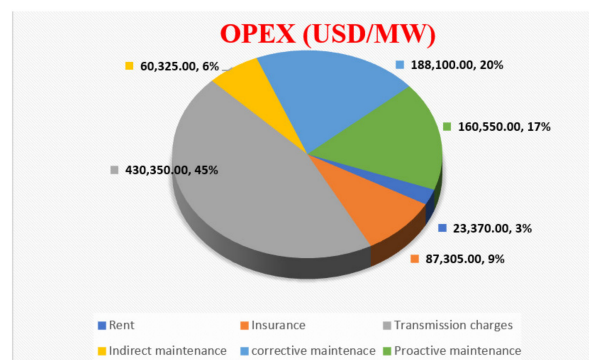


Figure 5. Distribution of operation and maintenance costs (OPEX) per MW.

3.2. Wind Resource Assessment

The wind speed data were collected at an elevation of 5 m only. Consequently, the wind speed at hub height (100 m) was calculated using Equation (10). The years that do not have complete data were not included in the calculation of the average wind speed at an elevation of 5 m. A sample of the calculation for 1-h mean wind speed $U_{(z)}$ (m/s) at level z (m) is given by Equation (16):

$$U_z = 6.2 \times \left[1 + C \times \ln \left(\frac{100}{5} \right) \right] \quad (16)$$

where $C = 0.0796$ as calculated by Equation (3). The wind speed at an elevation of 100 m equals 7.68 m/s.

3.3. Electrical Power Out (MW)

The average daily wind speed for 19 years back at hub height was calculated. Wind speed below 4 m/s and above 25 m/s were removed as they represent the cut-in and cut-out wind speed, respectively. After that, the wind energy was calculated for wind speed between 4–25 m/s on a daily basis using Equation (12). The total energy produced by the selected wind turbine over its lifetime was determined to be 197,884 MWh.

3.4. Levelized Costs of Energy

The levelized cost of energy is given by Equation (13) which equals the NPV of life cycle costs of a wind turbine farm over the NPV of the lifetime energy produced. The total life cycle cost of an offshore wind turbine farm is the summation of CAPEX, OPEX, and DECOM costs which amounted to USD 3,606,692 per MW. The whole life cycle cost of the 7 MW wind turbine amounted to USD 25,246,844, while it was USD 378,702,660 for the whole farm consisting of 15 wind turbines. The total energy produced by a 7 MW wind turbine over a lifetime was calculated using Equation (12) and by considering a power coefficient of 40%. The total energy produced over its expected lifetime was 197,884 MWh. The NPV of costs over a lifetime was calculated by considering a discount rate of 10% and an average inflation rate of 2.16%. By using Equation (13), the levelized cost of energy (LCOE) produced equals USD 127.58/MWh. The obtained value of LCOE fell within the range of LCOE conducted by the National Renewable Energy Laboratory [64] and was higher than the findings reported by Mekhilef et al. [27]. Likewise, it was higher than

the subsidized selling price of electricity for the industrial sector in the country, which is around USD 105.4/MWh [26]. The cost of energy obtained in this study makes it possible for the development of offshore wind farms in Malaysia by allocating a high FiT. In fact, the FiT for wind energy in Malaysia is not yet determined. However, it may not be less than the FiT for PV which starts from USD 124/MW since the year 2021. The levelized cost of energy was calculated with charges for the use of the country's infrastructure, such as the rent of ports and transmission charges paid to the national grid authority. However, if those charges are excluded, the LCOE drops to USD 108.54/MWh.

Levelized Cost of Energy Based on First-Of-A-Kind Scenario

The installation of offshore wind farms for the first time faces many challenges in construction, planning and procurement of components as well. Therefore, the costs rise over the expected or planned budgets. The challenges arise due to immature technology and experience in the country. Hence, the LCOE for the early projects may have a higher capital cost. According to Levitt et al. [29], the capital cost of offshore wind energy for the incipient development of offshore wind farms reaches up to USD 5750/kW. By considering this value as the capital costs, the levelized costs of energy produced equal to USD 195.35/MW. The calculated LCOE based on the first-of-a-kind scenario is very high compared to the selling price of electricity in the country. However, the governments' support for renewable energy makes it possible for the development of wind energy projects with a starting high FiT similar to PV energy which started at a rate of USD 275.3/MW in 2012.

4. Conclusions

Wind speed analysis in Kudat, Malaysia was conducted and assessed at 100 m elevation. The average daily wind speed was evaluated at the hub height of a 7 MW wind turbine and the projected wind energy produced was calculated on a daily basis as well. The assessment of wind speed was conducted 19 years back, while the future 25 years are expected to be the same as the wind speed has been stable over the past 19 years. The NPV of the energy produced over the lifetime of 7 MW wind was calculated by considering a 10% discount rate and a 2.16% of the inflation rate.

The breakdown of the life cycle costs structure was conducted, and the key cost drivers of offshore wind energy were identified. The calculated whole life cycle costs of the 105 MW offshore wind farm to be installed in Kudat, Malaysia was found to be USD 378.7M. It was noticed that the cost of production and acquisition (P&A) was the main cost driving component with a total cost of USD 1.7M per MW which is 47% of the whole life cycle costs. The cost of the wind turbine procurement incurred the highest proportion of the capital costs, with almost USD 1M per MW due to the cost of mobilization. The second cost driver was the operation and maintenance costs which amount up to USD 0.95M per MW with almost 26% of the total life cycle costs. Predevelopment and consenting, installation and commissioning, and decommissioning and disposal phases incurred about 11%, 9%, and 7%, respectively, of the whole life cycle costs. The cost of installation was relatively low as it is expected for the components to be transported from the manufacturer's country to the site. Hence, the transportation cost is calculated with the cost of procurement.

The calculated levelized cost of offshore wind energy (LCOE) is USD 127.58 per MWh. The obtained LCOE makes wind energy a promising sector of renewable energy in the country. However, the tariff for wind energy should be higher than USD 170/MWh in order to encourage investments in the wind energy sector.

Author Contributions: Conceptualization, S.A.; methodology, S.A. and W.S.A.; data curation, S.A. and P.P.; writing—original draft preparation, S.A. and W.S.A.; writing—review and editing, S.A., P.P. and M.A.M.; visualization, S.A.; supervision, M.S.L. and E.L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data are available within this manuscript.

Acknowledgments: The authors would like to appreciate the YUTP-FRG project (cost center # 015LC0-088) awarded to Wesam Alaloul for the support.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Holmberg, K.; Erdemir, A. Influence of tribology on global energy consumption, costs and emissions. *Friction* **2017**, *5*, 263–284. [\[CrossRef\]](#)
- Alaloul, W.S.; Musarat, M.A. Impact of zero energy building: Sustainability perspective. In *Sustainable Sewage Sludge Management and Resource Efficiency*; IntechOpen: London, UK, 2020.
- Kucaj, E.; Susaj, E.; Qaja, B. Renewable energy—A great energizing potential that eliminates environmental pollution. *Eur. J. Econ. Bus. Stud.* **2017**, *3*, 40–45. [\[CrossRef\]](#)
- Rathi, R.; Prakash, C.; Singh, S.; Krolczyk, G.; Pruncu, C.I. Measurement and analysis of wind energy potential using fuzzy based hybrid MADM approach. *Energy Rep.* **2020**, *6*, 228–237. [\[CrossRef\]](#)
- Wang, C.; Utsunomiya, T.; Wee, S.; Choo, Y. Research on floating wind turbines: A literature survey. *IES J. Part A Civ. Struct. Eng.* **2010**, *3*, 267–277. [\[CrossRef\]](#)
- Hu, W. *Advanced Wind Turbine Technology*; Springer: Berlin/Heidelberg, Germany, 2018.
- International Renewable Energy Agency (IRENA). *Renewable Energy Target Setting*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2015.
- IRENA. *Renewable Capacity Statistics 2020*; IRENA: Abu Dhabi, United Arab Emirates, 2020.
- Perez, L.R. Design, Testing and Validation of a Scale Model Semisubmersible Offshore Wind Turbine Under Regular/Irregular Waves and Wind Loads. Master's Thesis, University of Strathclyde, Glasgow, UK, 2014.
- Anaya-Lara, O.; Tande, J.O.; Uhlen, K.; Merz, K. *Offshore Wind Energy Technology*; Wiley Online Library: Hoboken, NJ, USA, 2018.
- Tavner, P. *Offshore Wind Turbines: Reliability, Availability and Maintenance*; The Institution of Engineering and Technology: Stevenage, UK, 2012.
- Nelson, V.; Starcher, K. *Wind Energy: Renewable Energy and the Environment*; CRC Press: Boca Raton, FL, USA, 2018.
- Veers, P.; Dykes, K.; Lantz, E.; Barth, S.; Bottasso, C.L.; Carlson, O.; Clifton, A.; Green, J.; Green, P.; Holttinen, H. Grand challenges in the science of wind energy. *Science* **2019**, *366*, 6464. [\[CrossRef\]](#)
- Blaabjerg, F.; Ma, K. Wind energy systems. *Proc. IEEE* **2017**, *105*, 2116–2131.
- Rohe, S. The regional facet of a global innovation system: Exploring the spatiality of resource formation in the value chain for onshore wind energy. *Environ. Innov. Soc. Transit.* **2020**, *36*, 331–344. [\[CrossRef\]](#)
- Li, Y.; Huang, X.; Tee, K.F.; Li, Q.; Wu, X.-P. Comparative study of onshore and offshore wind characteristics and wind energy potentials: A case study for southeast coastal region of China. *Sustain. Energy Technol. Assess.* **2020**, *39*, 100711. [\[CrossRef\]](#)
- Emeis, S. *Wind Energy Meteorology: Atmospheric Physics for Wind Power Generation*; Springer: Berlin/Heidelberg, Germany, 2018.
- Kazak, J.; van Hoof, J.; Szewranski, S. Challenges in the wind turbines location process in Central Europe—The use of spatial decision support systems. *Renew. Sustain. Energy Rev.* **2017**, *76*, 425–433. [\[CrossRef\]](#)
- Moustakas, K.; Loizidou, M.; Rehan, M.; Nizami, A.S. *A Review of Recent Developments in Renewable and Sustainable Energy Systems: Key Challenges and Future Perspective*; Elsevier: Amsterdam, The Netherlands, 2020.
- Crivellari, A.; Cozzani, V. Offshore renewable energy exploitation strategies in remote areas by power-to-gas and power-to-liquid conversion. *Int. J. Hydrogen Energy* **2020**, *45*, 2936–2953. [\[CrossRef\]](#)
- Röckmann, C.; Lagerveld, S.; Stavenuiter, J. *Operation and Maintenance Costs of Offshore Wind Farms and Potential Multi-Use Platforms in the Dutch North Sea, in Aquaculture Perspective of Multi-Use Sites in the Open Ocean*; Springer: Cham, Switzerland, 2017; pp. 97–113.
- Zaman, A.A.A.; Hashim, F.E.; Yaakob, O. Satellite-based offshore wind energy resource mapping in Malaysia. *J. Mar. Sci. Appl.* **2019**, *18*, 114–121. [\[CrossRef\]](#)
- Masseran, N.; Razali, A.M.; Ibrahim, K. An analysis of wind power density derived from several wind speed density functions: The regional assessment on wind power in Malaysia. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6476–6487. [\[CrossRef\]](#)
- Hosseini, S.E.; Wahid, M.A. The role of renewable and sustainable energy in the energy mix of Malaysia: A review. *Int. J. Energy Res.* **2014**, *38*, 1769–1792. [\[CrossRef\]](#)
- Alsubal, S.; Liew, M.; Lim, E.; Harahap, I.S.; Nasser, A.M. The future of wind power in Malaysia: A review. In *Proceedings of the International Conference on Civil, Offshore and Environmental Engineering*, Kuching, Malaysia, 13–15 June 2021; Springer: Singapore, 2021.
- Nor, K.M.; Shaaban, M.; Rahman, H.A. Feasibility assessment of wind energy resources in Malaysia based on NWP models. *Renew. Energy* **2014**, *62*, 147–154. [\[CrossRef\]](#)
- Mekhilef, S.; Safari, A.; Chandrasegaran, D. Feasibility study of off-shore wind farms in Malaysia. *Energy Sci. Res.* **2012**, *28*, 877–888.

28. Ibrahim, M.; Albani, A. The potential of wind energy in Malaysian renewable energy policy: Case study in Kudat, Sabah. *Energy Environ.* **2014**, *25*, 881–898. [\[CrossRef\]](#)
29. Levitt, A.C.; Kempton, W.; Smith, A.; Musial, W.; Firestone, J. Pricing offshore wind power. *Energy Policy* **2011**, *39*, 6408–6421. [\[CrossRef\]](#)
30. Castro-Santos, L.; Diaz-Casas, V. *Floating Offshore Wind Farms*; Springer: New York, NY, USA, 2016.
31. Shafiee, M.; Brennan, F.; Espinosa, I.A. A parametric whole life cost model for offshore wind farms. *Int. J. Life Cycle Assess.* **2016**, *21*, 961–975. [\[CrossRef\]](#)
32. Bjerkseter, C.; Ågotnes, A. *Levelised Costs of Energy for Offshore Floating Wind Turbine Concepts*; Norwegian University of Life Sciences: Ås, Norway, 2013.
33. Laura, C.-S.; Vicente, D.-C. Life-cycle cost analysis of floating offshore wind farms. *Renew. Energy* **2014**, *66*, 41–48. [\[CrossRef\]](#)
34. Howard, R. *Offshore Wind Cost Reduction Pathways Project—Simple Levelised Cost of Energy Model*; The Crown Estate: London, UK, 2012.
35. Bahar, M.; Kamu, A.; Jantan, N.; Gabda, D. Analysis of wage distribution in Malaysia. *J. Phys. Conf. Ser.* **2020**, *1489*, 012031. [\[CrossRef\]](#)
36. Bosch, J.; Staffell, I.; Hawkes, A.D. Global levelised cost of electricity from offshore wind. *Energy* **2019**, *189*, 116357. [\[CrossRef\]](#)
37. Kaiser, M.J.; Snyder, B. *Offshore Wind Energy Cost Modeling: Installation and Decommissioning*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2012; Volume 85.
38. 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. [\[CrossRef\]](#)
39. Estate, C. *A Guide to an Offshore Wind Farm*; Report; BVG Associates: Swindon, UK, 2010; pp. 1–70.
40. Ahn, D.; Shin, S.-C.; Kim, S.-Y.; Kharoufi, H.; Kim, H.-C. Comparative evaluation of different offshore wind turbine installation vessels for Korean west–south wind farm. *Int. J. Nav. Archit. Ocean Eng.* **2017**, *9*, 45–54. [\[CrossRef\]](#)
41. Kaiser, M.J.; Snyder, B. *Offshore Wind Energy Installation and Decommissioning Cost Estimation in the US Outer Continental Shelf*; US Department of the Interior, Bureau of Ocean Energy Management, Regulation and Enforcement, Herndon, VA TA&R: Washington, DC, USA, 2010; Volume 648.
42. Dalgic, Y.; Lazakis, I.; Turan, O. *Vessel Charter Rate Estimation for Offshore Wind O&M Activities*; International Maritime Association of Mediterranean IMAM: London, UK, 2013.
43. Maples, B.; Saur, G.; Hand, M.; van de Pietermen, R.; Obdam, T. *Installation, Operation, and Maintenance Strategies to Reduce the Cost of Offshore Wind Energy*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2013.
44. Dinmohammadi, F.; Shafiee, M. A fuzzy-FMEA risk assessment approach for offshore wind turbines. *Int. J. Progn. Health Manag.* **2013**, *4*, 59–68.
45. Hassan, G.G. *A Guide to UK Offshore Wind Operations and Maintenance*; Scottish Enterprise and The Crown Estate: Edinburgh, UK, 2013; Volume 21.
46. Shafiee, M. Maintenance strategy selection problem: An MCDM overview. *J. Qual. Maint. Eng.* **2015**, *21*, 378–402. [\[CrossRef\]](#)
47. Maienza, C.; Avossa, A.; Ricciardelli, F.; Coiro, D.; Troise, G.; Georgakis, C.T. A life cycle cost model for floating offshore wind farms. *Appl. Energy* **2020**, *266*, 114716. [\[CrossRef\]](#)
48. Smith, G.; Garrett, C.; Gibberd, G. Logistics and cost reduction of decommissioning offshore wind farms. *Presented EWEA Offshore* **2015**, *2015*, 10–12.
49. Topham, E.; McMillan, D. Sustainable decommissioning of an offshore wind farm. *Renew. Energy* **2017**, *102*, 470–480. [\[CrossRef\]](#)
50. Adedipe, T.; Shafiee, M. An economic assessment framework for decommissioning of offshore wind farms using a cost breakdown structure. *Int. J. Life Cycle Assess.* **2021**, *26*, 344–370. [\[CrossRef\]](#)
51. PCCI, INC. *Decommissioning Cost Estimation for the Cape Wind Energy Project*; PCCI Inc.: Alexandria, VA, USA, 2014.
52. Sabeen, A.; Ngadi, N.; Noor, Z.Z. Minimizing the cost of municipal solid waste management in Pasir Gudang Johor Malaysia. *J. Mater. Environ. Sci.* **2016**, *7*, 1819–1834.
53. Tambi, N.H.M.; Afrouzi, H.N.; Mehrazamir, K.; Ahmed, J. A review of available hybrid renewable energy systems in Malaysia. *Int. J. Power Electron. Drive Syst.* **2020**, *11*, 433–441. [\[CrossRef\]](#)
54. Topham, E.; McMillan, D.; Bradley, S.; Hart, E. Recycling offshore wind farms at decommissioning stage. *Energy Policy* **2019**, *129*, 698–709. [\[CrossRef\]](#)
55. Sanusi, N.; Zaharim, A.; Mat, S.; Sopian, K. Bivariate probability model for wind power density analysis: Case study. *ARPN J. Eng. Appl. Sci.* **2006**.
56. Sharuddin, N.N.S.; Ng, C.Y.; Tuhaijan, S.N.A.; John, K.V.; Wong, L.W. An evaluation of offshore wind renewable energy performance in Malaysia. *Int. J. Biomass Renew.* **2019**, *8*, 25–33.
57. Albani, A.; Ibrahim, M.Z. Wind energy potential and power law indexes assessment for selected near-coastal sites in Malaysia. *Energies* **2017**, *10*, 307. [\[CrossRef\]](#)
58. Mekhilef, S.; Chandrasegaran, D. Assessment of off-shore wind farms in Malaysia. In Proceedings of the TENCON 2011–2011 IEEE Region 10 Conference, Bali, Indonesia, 21–24 November 2011; IEEE: New York, NY, USA, 2011.
59. NOAA USA. *National Oceanic and Atmospheric Administration*; NOAA USA: Boulder, CO, USA, 2009.
60. Effiom, S.; Nwankwojike, B.; Abam, F. Economic cost evaluation on the viability of offshore wind turbine farms in Nigeria. *Energy Rep.* **2016**, *2*, 48–53. [\[CrossRef\]](#)

-
61. Bruck, M.; Sandborn, P.; Goudarzi, N. A Levelized Cost of Energy (LCOE) model for wind farms that include Power Purchase Agreements (PPAs). *Renew. Energy* **2018**, *122*, 131–139. [[CrossRef](#)]
 62. Raturi, A.K. *Renewables 2016 Global Status Report*; REN21 Community: Bonn, Germany, 2016.
 63. Mathew, S. *Wind Energy: Fundamentals, Resource Analysis and Economics*; Springer: Berlin/Heidelberg, Germany, 2006.
 64. Lee, N.; Flores-Espino, F.; de Oliveira, R.C.; Roberts, B.J.; Brown, T.; Katz, J.R. *Exploring Renewable Energy Opportunities in Select Southeast Asian Countries: A Geospatial Analysis of the Levelized Cost of Energy of Utility-Scale Wind and Solar Photovoltaics*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2019.