SCIREA Journal of Energy
http://www.scirea.org/journal/Energy
August 15, 2023
Volume 8, Issue 1, February 2023
https://doi.org/10.54647/energy480191

Techno- Economics of an Improved Hybrid Solar Wind Turbine

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Abstract
The design of an Improved Hybrid Solar Wind Turbine (IHSWT) is described in which solar and wind are combined and converted into a single energy source. It consists of installing solar panels on the south- facing façade of the wind turbine tower. To capture maximum sunlight, the solar panels below the turbine blade, are mounted on extended cantilever arms and arranged in a semi-circular skirt around the perimeter of the tower face. This is an improvement on the previous design as more panels can be installed allowing for greater capture of solar irradiance. Data of an NREL 8 MW reference wind turbine is used for comparison to evaluate the performance and cost of the proposed IHSWT. From the results it is clear that IHSWT offers a reduced levelized cost of energy (LCOE), even after allowing for shading losses from the turbine blade, and a much steadier production of energy. The introduction of IHSWT would help to make wind farms a more cost-effective and competitive source of clean energy.

Keywords: Improved hybrid solar wind turbine, solar panels, turbine blade, cost-effectiveness, LCOE. tower.

1 INTRODUCTION

The world is being increasingly threatened by the impacts of greenhouse gas (GHG) emissions-induced climate change. This is primarily due to the use of fossil fuels. Renewable energy technologies are thus being harnessed to address these challenges. Foremost among these is wind energy, which is increasingly forming part of the world's renewable energy mix. A report by [1] indicates that the total global installed capacity grew to 906 GW. With wind power moving out to sea, larger wind turbines in deeper depths of the ocean have been introduced. This has come at an increased cost of energy, with a challenge to make it competitive with fossil fuel energy sources. Offshore wind energy developers are now looking to solar technologies to enhance the reliability of their renewable energy projects. The integration of offshore floating solar into an offshore wind farm results in a more balanced production profile due to the complementary nature of wind and solar resources. An early attempt to combine solar and wind was made by Southwest Wind Power and Advanced Technology and Research Corps [2]. The hybrid solar-wind projects to date have had ground-mounted solar plants adjacent to the wind turbines [3]. These large-scale PV plants necessitate valuable land mass and hence the advent of floating solar plants. [4] have proposed placing a floating solar plant between the free spaces amongst the offshore wind turbines. A similar project by RWE and Solar Duck [5] is coming up in the North Sea. Figure.1 shows an illustration of a hybrid

Figure 1 Illustration of a combined wind and solar energy farm

floating solar and wind energy farm. [6] have stated that hybrid floating installations are more costly due to the harsh ocean environment requiring stringent module requirements. A more novel approach by [7] for an offshore energy farm called the Hybrid Photovoltaic Wind Turbine involved installing photovoltaic (PV) solar panels along the currently unproductive tower face to produce solar energy.

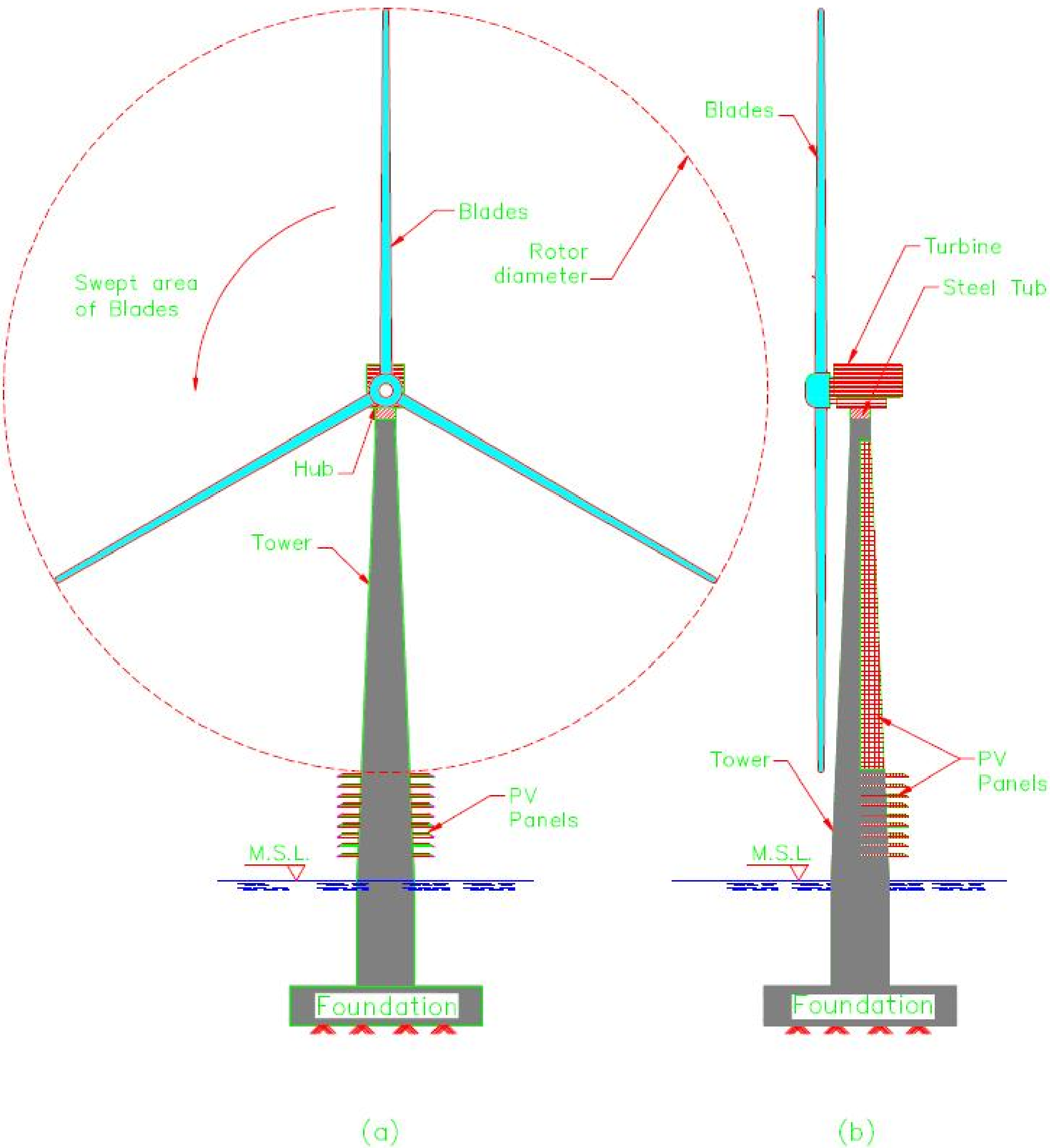

Figure 2 General view of IHSWT (a) Front view (b) Side view

The present concept was aimed at taking the developments of the latest offshore WTs, with the advances made in high-performance PV panels and integrating innovative technology to design an Improved Hybrid Solar PV–Wind Turbine (IHSWT). The innovation was in increasing the number of PV panels that could be accommodated on the tower by mounting the panels on an extended cantilever arm projecting from the tower face. see Figure.2 which illustrates the front view and side view of IHSWT. This combination of wind and solar power results in a single point of conversion, leading to reduced capital expenditure, and an increase in annual energy production. An analysis is made using a representative fixed-bottom offshore wind energy project installed in the US, North Atlantic. The WT is integrated with Solar panels to create a hybrid –solar-wind generation system. The present study estimates the Levelized Cost of Energy (LCOE} for land-based offshore WTs and their comparison with IHSWT to understand the potential impact on the LCOE for future wind farms. The primary analysis for the baseline comparison is NREL's 8 MW WT for a hypothetical offshore-based wind farm of 600 MW rated capacity [8]. For this analysis, the 8 MW WT is designed as an IHWT using 600 W photo- voltaic (PV) panels.

2 MATERIALS and METHODS

Hybrid systems are designed to combine two or more renewable energy sources. Solar and wind are generally merged in a hybrid system since they complement each other. This study aimed to design an IHSWT and investigate its techno-economic feasibility in comparison with a stand-alone WT. The present technology proposes providing cantilever arms projecting from the tower face to which is attached a semi-circular ring beam on which the solar panels are mounted in a semi-circular skirt around the perimeter of the tower face as illustrated in Figure.3

2.1 *Wind Energy*

WTs convert the kinetic energy of the wind to drive a generator that in turn produces energy. To take advantage of the strong winds over ocean surfaces, WTs are being manufactured with increasingly large swept areas, and taller towers, with installation in deeper water depths. An example is the Vestas 15 MW model [9]. The reference project considered for this study is a fixed bottom offshore wind system comprising an 8 MW rated WT forming part of a 600 MW wind farm in the US North Atlantic. NREL Report Study [8]. The key inputs are shown in Table 1. The WTs of this project are modified to IHSWTs, sharing an inverter and grid connection. The WT is supported on a 102 m prestressed concrete tower having a fixed bottom at a 30m depth of water. Technical details for this tower are taken from [10]. see Figure.3.

2.2 *Solar Energy*

Photovoltaic (PV} cells can convert the thermal energy from sunlight into direct current electricity.

Table 1 Reference Offshore Turbine Parameters

Turbine parameters			
Turbine rated power (MW)	8.0		
Number of turbines	75		
Wind plant capacity (MW)	600		
Turbine rotor diameter (m)	159		
Turbine hub height (m)	102		
Max. tip speed (m/sec)	81		
Power density (W/m^2)	315.8		
Annual avg. wind speed (m/sec)	*9.05*		

Conventional solar systems on land require valuable real estate. Floating solar parks adjacent to WTs require pontoons and a mooring system with the capability to survive the harsh ocean environment, adding substantially to their cost and thereby increasing the LCOE of the hybrid solar wind turbine system. In contrast, installing PV panels using the tower as a support base makes for a much more practical solution. There are limitations to this arrangement; a) the number of PV panels that can be installed is limited, b) the effect of shading on the panels due to rotation of the turbine blade needs to be accounted for, and c) erection/maintenance can pose a problem.

Flexible organic PV panel that use carbon instead of silicon are being developed for curved surfaces, although their efficiency is still below that of silicon modules, [11]. For this study the high-performance 610W Jinko Solar Tiger Neo N-Type 78 HLR- (V) Mono Facial module has been selected [12], technical details of which are given in Table 2. Its key features are; a) better light trapping; b) high salt mist and ammonia resistance; c) better reliability and; d) certified to withstand enhanced wind load and snow load.

2.2.1 *Tower and PV panel orientation*:

The tower selected for this design Figure 3, is a 102 m high prestressed concrete bi-linear tower having the indicative dimensions as tabulated in [10]. The south-facing façade of the tower is utilized for mounting the solar panels. To avoid interference with the turbine blade, panels for this portion are

Table 2 Parameters of PV module

Jinko Solar Module Tiger Neo N-type 78HLR-(V)	
Maximum power (W)	600
Maximum power voltage (V)	59.7
Maximum power current (A)	5.7
Open circuit voltage (V)	71
Maximum system voltage (V)	600
Module efficiency (%)	*20*
Module size (l x b x h) mm 2400 x 1350 x 30	

Source: www.jinkosolar.com

mounted vertically. Generally, the minimum operational blade tip clearance is kept at one-third of the static distance or a distance of one tower radius relative to the tower diameter at the same elevation, [13]. Panels located below the turbine blade do not have this limitation and can be mounted at an inclination to catch the maximum solar irradiance. To increase the amount of area required for these panels, and hence the amount of solar irradiance to be captured, they are mounted on a cantilever arm projecting from the tower face, Figure 3. The cantilever length is to be decided based on practical considerations, and the amount of solar energy required. The structural arrangement comprises five cantilever arms, connected by a semicircular ring beam. PV panels are attached to this beam with posts and rails. The nacelle of the WT rotates to absorb maximum wind energy. In this scenario, the rotor may be facing due north exposing the south-facing panels to direct sunlight, thus keeping them free from shading effect. The energy calculations are based on these two conditions.

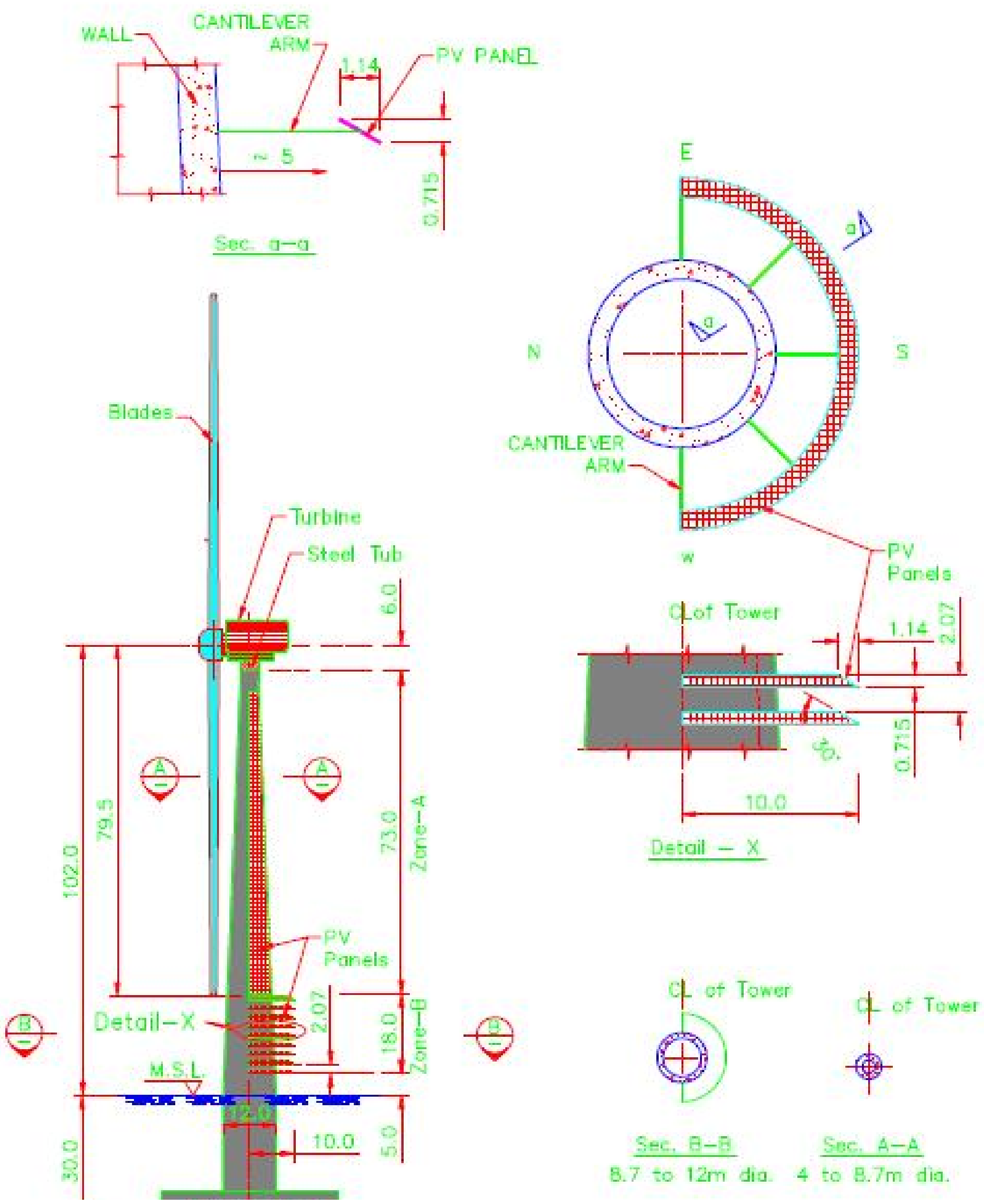

Figure 3 Detail of tower showing PV pane location

2.2.2 *Effect of Shading:*

Rotation of blades passing in front of the panels can cause reduced efficiency of the PV array. Bi-pass diodes, different stringing arrangements, and module-level power electronics are some of the methods being adapted to reduce these losses [14]. Further investigation on the effects of shading by WT is being investigated by a team that includes energy company Vattenfall, research organization TNO and E-mobility developer Heliox, [15].

Table 3 Solar data and Energy output at Reference site

Month	Solar Radiation (kWh/m^2/day)	AC Energy (kWh)
January	*4.53*	6,726
February	4.76	6,272
March	5.74	8,163
April	5.78	7,819
May	6.10	8,360
June	5.78	7,561
July	*5.85*	7,844
August	5.55	7,488
September	5.39	7,094
October	5.42	7,597
November	4.86	6,792
December	3.85	5,663
Annual	5.30	87,379

Source: NREL

Table 4 Comparison of the NREL 8.00 MW reference design to the combined wind and solar version of that design for the same site conditions

Condition: for no shading from blade

Items	8.0 MW WT	Solar (PV) 0.302 MW	WT + solar
CapEx ($/kW)	3871	919	4790
OpEx ($/kW/yr)	111	7	118
Fixed charge rate (%)	5.82	5.82	5.82
Net annual energy production(MWh/MW/yr)	4295	908	5203
Net capacity factor (%)	49.0	9.6 & 17	
Total LCOE ($/MWh)	*78*	57.7	75

2.2.3 *Panel installation*:

Inserts and racks used for fixing the panels are cast along with the shell elements of the tower. The Cantilever arm and ring beam are fabricated from hollow galvanized steel sections. They are pre-assembled at the site in sections, and solar panels are fitted on them. The individual segments

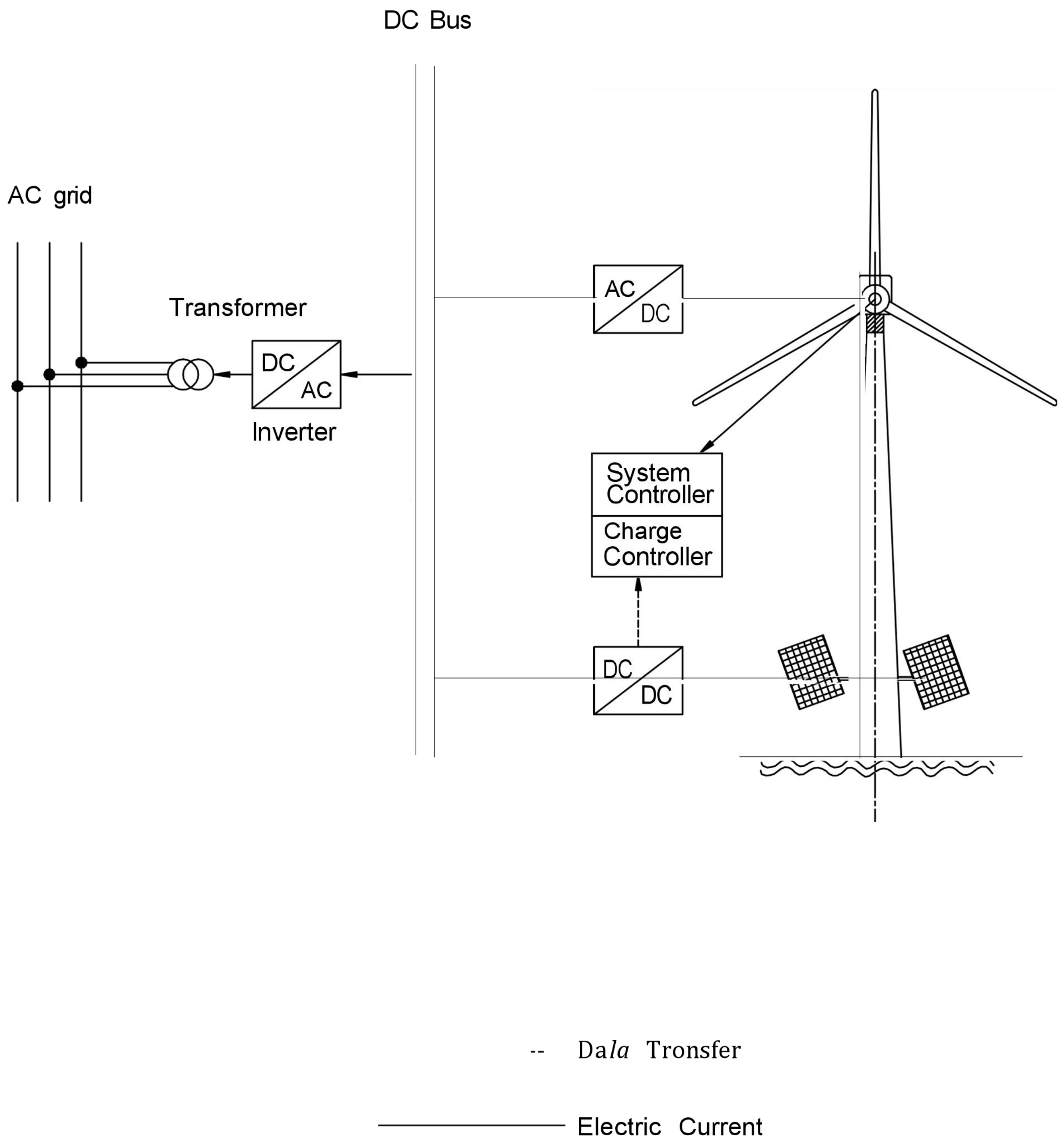

Figure 4 Diagram of an IHSWT energy system

comprising two cantilever arms, part of ring beam and solar panels is then lifted by cranes to the desired level. Workmen on a suspended platform make the bolted connection to the embedded inserts. Conduit pipes embedded in the wall allow for cable entry from solar panels. PV panels are periodically cleaned using water jets attached to drones.

2.2.4 *Solar-Wind hybrid integration*:

Electricity produced by the PV array and WT is inverted from DC to AC and then transmitted to the load bus through the cable bus for grid integration as shown in Figure.4. The regulation of the load and output from the solar panels and WT's is continuously monitored by the system controller [16].

3 RESULTS

3.1 ***Preliminary system description***.

Made as a practical design application, is a case study from a fixed-bottom offshore reference project comprising a 600 MW wind farm having 75 WTs of 8 MW rated capacity located offshore in the US North Atlantic, based on the NREL Technical Report [8]. Data and results are derived from 2021 commissioned plants. The WTs are sought to be hybridized with an array of solar panels, and the various technical and cost issues are discussed. A schematic configuration of the proposed design showing detail of the tower and solar panel locations is shown in Figure.3. The parameters for the target WT used as a baseline for comparison purposes are shown in Table 2. The additional weight and bending moment resulting from the addition of solar panels and supporting structure is negligible for this study.

3.2 ***Solar PV System***

3.2.1 *Requirement of PV panels*:

To estimate the number of PV panels that can be integrated with the WT, the tower is divided into two Zones A & B, Figure.3. Zone A coming under the influence of the turbine blade has the panels mounted vertically. The vertical height is taken as 73 m. The diameter of the tower varies from 4 m to 8.7 m, the average diameter is 6.35 m, and the half perimeter is 19.94 m. The area available for placing panels is 73 x 19.94 = 1455.6 m^2. The area of the panel is 2.4 x 1.35 = 3.24 m^2. Number of panels in Zone A that can be accommodated on the south side (S) = 1455/3.24 = 409. In Zone B, panels are provided in a fixed open rack system having a tilt of 32^o, with a row spacing of 2.07 m to prevent self-shading, Figure.3. The furthermost extent of the cantilever arm on which panels are supported is fixed uniformly at 10 m from the centre line of the tower, resulting in an approximate cantilever length of 5 m, depending upon the diameter of the tower at that location. Half perimeter = 2 x 3.14 x 10 x 0.5 = 31.4 m. Number of panels in a row = 31.4/ 2.4 == 12. Effective height = 18 m, Then no. of rows = 18/ 2.07 = 8, and. the number of panels in Zone B = 8 x 12 = 96.

3.2.2 *Solar Resource and Annual Energy Production:*

The NREL model PV Watts Calculator [17] was used as the basis for obtaining the solar resource for the proposed location (Lat, Long 32.77, -79.98) in US North Atlantic, and to simulate the annual energy production (AEP). Typical values of monthly production of AEP for Zone B are shown in Table 3. The results give annual solar radiation as 5.3 kWh/m^2/day, based on 11% system losses, 96% inverter efficiency, and a DC-to-AC ratio of 1.2. Referring to Figure.3, AEP for IHSWT having panels at location S with WT rotor assumed facing north N, (condition for no shading from the blade). For Zone A, Watts available = 600 x 409 = 245,400 W. Then AEP from [17] assuming 90^o tilt, is 205,556 kWh/yr. For Zone B, Watts capacity = 600 x 96 = 57,600 W and AEP assuming 32^o tilt is 87,380 kWh//year. Then total for zones A & B; 205,556 + 87380 = 292,936 kWh/year. For PV panels at location S and WT rotor also at S (condition for panels under the influence of shading from the blade). Partial shading can cause reduced efficiency in the solar cell array[18]. To account for these generation losses, it is suggested to allow a 50% loss in production from the solar panels for the period the shading occurs [19].

Table 5 Comparison of the NREL 8.0 MW reference design to the combined wind and solar version of that design for the same site conditions

Condition: for shading from blade

Items	8.0 MW WT	Solar 0.270 MW	WT + solar
CapEx ($/kW)	3871	919	4790
OpEx ($/kW/yr)	111	7	118
Fixed charge rate (%)	5.82	5.82	5.82
Net annual energy production(MWh/MW/yr)	4295	879	5174
Net capacity factor (%)	49.0	9.6 &19.0	
Total LCOE ($/MWh)	*78*	67.6	75.2

3.2.3 *To calculate the effect of shading*

The maximum Chord (blade) width for the blade of Vestas V164- 8 MW WT is 5.4 m. Then area of blade = (5.4 + 0.4)/2 x 79.5 = 230.5 m^2. The effective area of the tower = 708 m^2.

Then shaded % = 230.5/708 = 0,22 or 22%. Panels under shading = in 0.22 x 409 = 89.98 say 90 no. Hence Watts capacity available for Zone A under the condition of shading = 0.5 x 90x 600 = 27,000 W. Balance 409 - 90= 319 number panels provide 319 x 600 = 191,400W. Then total = 27,000 + 191,400 = 218,400 W, and AEP from Watts calculator = 182,931 kWh/ yr. Then total for Zones A and B; 182,931 + 87379 = 270,1310 kWh/year.

3.2.4 *Costs and LCOE*

Costing is based on a rate of $\$0.87/W_{dc}$ from Utility Scale PV [20]. For condition under no shading:

PV panels 302600 W @ 0.87 $/W = $247,816

Steel structure 13,845 kg @ $ 2.2/kg = $30,460

Sub- total = $278,276

CaPex for PV panels = 278276/302 = 919.6 $/ kW

Capex for wind + solar = 3871 + 919 = 4790$/kW

Condition for no shading.

AEP for Zones A & B = 292,936 kWh/yr. This is for 302.6 kW. Then, AEP/kW = 292936/302.6 = 908 kWh /kW/yr = 908 MWh/MW/yr.

AEP_{net} for wind + solar = 4295 +908 = 5203 Mwh/MW/yr

To calculate LCOE, values of CaPex, FCR, OpEx and AEP_{net} are entered into the following equation, [8].

LCOE = (CaPEx x FCR)/ (AEP_{net}/1000) + OpEx/ (AEP_{net}/1000) …

(1) where; LCOE = levelized cost of energy ($/ MWh}; FCR= fixed charge rate taken as 5.8 %, based on 25 year plant design life and discount rate of 5.29% [8]; CaPex = capital expenditure ($/kW); OpEx = operational expenditures ($/ kW/ yr); AEP_{net} = net annual energy produced (MWh/MW/yr).

Then for condition under no shading for Wind and Solar combined see Table 4;

LCOE = (4790 x 0.058)/5203/1000) + 118/5.2 = 52.4 + 22.08 = 75 $/MWh

Calculating similarly for Condition under shading; Note that Watts produced is less but number of panels is same. CaPex for wind + solar = 3871 + 919 = 4790 $/kW ; and AEP/kW for shading = 270310/276 = 879.38 MWh/MW/yr; AEP_{net} for wind + solar = 4295 + 879 = 5174 MWh/MW/yr. and LCOE from and Eq.1 = 75.2 $/ MWh See Table 5.

4 DISCUSSIONS

4.1 *Comparative Analysis:*

The present study estimates the LCOE for land-based offshore WTs and their comparison with IHSWT. LCOE is a useful metric to assess the cost of electricity generation, and its impact on power plants from technology design changes. The LCOE values for the 2021 fixed bottom wind plant for the baseline WT, and the converted IHSWT for no shade condition are shown in Table 5. It indicates that the LCOE of 75 $/MWh for the IHSWT is less than the LCOE of 78 $/ MWh of the reference WT. Similarly, from Table 6 it is noted that even for the shaded condition, the LCOE of 75.2 $/MWh is less than that of 78 $/ MWh for the baseline WT. The values obtained for LCOEs should be considered solely illustrative, as many of the elements such as wind resource, solar irradiance etc. are site-specific.
In another comparison, data of LCOEs from Hybrid Wind-Solar power systems in Japan, [21]al 2020) have shown that the cheapest WT system, the cheapest solar system, the cheapest hybrid wind-solar system and the most expensive hybrid have a price per kWh of energy, $0.294, $ 0.349, $ 0.339, and $ 0.526.

4.2 *Checking revenue from Wind Farm:*

There are 75 WT.s in the reference wind farm, and all are assumed to be converted to IHSWTs. The net energy gain from addition of PV panels;;
Condition for no shading,
There is a 21% increase in energy produced per WT. Energy generated by PV panels over 25 year lifetime of the project; E = 75 x 25 x 292.936 = 549,255,000 kWh. Additional revenue earned @ 0.106 $/kWh = $ 58.22 million.
Condition for shading;
Additional energy generated by WT is 20.5%. Energy generated by PV panels = 75 x 25 x 270,310 = 506,831,000 kWh and revenue earned @ 0.106 $/kWh = $53.72 million.
Future gains can be manifold considering that by 2050, onshore wind is set to increase to 5044 GW, and Offshore Wind by 1000 GW, [22]. Solar power is also unlimited with a yearly PV potential of 737 to 2337 kWh/W, [23](Global Solar Atlas 2021).

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5 CONCLUSIONS

In this paper, an analysis has been carried out to assess the technical feasibility and economic viability of an offshore fixed-bottom IHSWT. The LCOE metric has been used to compare the baseline WT with the converted IHSWT. Both the shaded and non-shaded conditions have been considered. A net reduction in LCOE of about 3% for the IHSWT is observed. To put it in context, the high prices of fossil gas prices in 2022 of 0.27 $/kWh [24] will make it about three times higher than the new improved hybrid solar and offshore wind turbine. It can be further concluded that the ability to produce more power from a single turbine means fewer turbines need to be installed at each wind farm. In addition to less capital expenditure, this also simplifies operations and maintenance. In conclusion, this turbine description will provide a reference for research and development actives in the offshore wind energy industry.

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