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RESEARCH ARTICLE

Optimal Design and Techno-Socio-Economic Analysis of Grid-Connected Hybrid Renewable System

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ABSTRACT The global shift towards clean and sustainable energy sources has prompted interest in repowering and optimizing existing wind farms through the use of new technology. In the early 2000s, multiple wind farms with capacities ranging from 200 kW to 800 kW were developed in India. As these wind farms near the end of their useful lives, there is an urgent need to investigate viable methods for exploiting the region's significant wind potential. This research focuses on the need to repower these aging wind farms with larger, more efficient turbines. Wind farms' lifespan is extended via repowering. The WAsP software is used to assess wind resources. Furthermore, by using photovoltaic (PV) panels, the study presents a new technique for maximizing wind farm space utilization. Land utilization is optimized and overall energy output capacity is boosted by installing PV panels in the gaps between wind turbines. This strategy takes advantage of underutilized areas in the wind farm to harness wind and solar energy, thus contributing to the shift to cleaner energy sources. In addition to the technical issues, an in-depth economic analysis is carried out to determine the financial feasibility and long-term benefits of repowering wind farms and incorporating solar panels.

INDEX TERMS Wind turbine, repowering, annual energy production (AEP), solar energy, power generation, WAsP, hybrid renewable system, economic analysis.

I. INTRODUCTION

Wind and solar energy have gained traction in India's quest for a clean, sustainable energy future. With a fast-expanding economy and rising energy demand, India has made significant investments in renewable energy sources in order to diversify its energy mix and lessen its reliance on fossil fuels.

The wind energy sector in India has grown dramatically, with a total installed capacity of 42.86 GW as of April 2023. Concurrently, India has seen a significant increase in solar energy deployment. As of April 2023, the country's installed solar capacity is 67.07 GW [1].

Wind turbines, the key technology for harvesting wind power, have advanced significantly, resulting in higher efficiency and power generation. Like any other technology, wind turbines degrade in performance over time, notably after the 20-year mark of their operating lifespan. This deterioration can result in decreased energy output and greater maintenance expenses, necessitating repowering. Repowering entails involves upgrading or replacing ageing wind turbines with newer, more modern models. Repowering provides various benefits, including increased power generation, enhanced operational efficiency, and an extended lifespan for wind farms, by adding larger turbines with higher capacity ratings and improved technological features. It provides a chance to improve the performance of current wind farms and make the best use of available wind resources [2].

Wind farms with capacities ranging from 200 kW to 800 kW were developed in the early 2000s, particularly in locations such as Tamil Nadu. However, these wind farms are

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nearing the end of their operating lifespans and will need to be repowered in order to continue contributing to the country's renewable energy ambitions [3].

Furthermore, the repowering procedure frequently results in large underutilised space between the turbines. This provides an excellent chance to include additional renewable energy technologies, such as PV, into the wind farm. A wind-solar hybrid plant can be built by merging wind and solar energy sources. The use of solar panels within the wind farm optimises land utilisation and increases the hybrid system's overall energy output capability. [4]

In the context of India, the integration of wind and solar energy technologies offers several benefits. Wind and solar resources work together to provide a more reliable and regular energy supply throughout the year. A wind-solar hybrid plant can take advantage of the synergies between these plentiful renewable resources, maximizing energy-generating potential and minimizing intermittency difficulties.

An in-depth economic analysis is required to examine the economic viability and long-term benefits of such hybrid renewable energy systems. This analysis considers capital investment, operational costs, revenue generation, and return on investment. Sensitivity analysis allows decision-makers to assess the hybrid system's resilience to market uncertainty and policy changes, assuring its long-term survival [5].

Numerous in-depth studies have been undertaken to investigate the viability and possible benefits of repowering wind farms and incorporating PV panels into existing infrastructure. These studies cover a broad range of topics and implications. For example, [6] discusses the repowering potential of several Indian states, whereas [7] dives into the technological consequences of real repowering projects, analysing their effects on energy production at the turbine level.

The environmental consequences and benefits of repowering wind farms are the topic of study in [8] while [9] discusses the uncertainties involved with wind power. Furthermore, economic concerns are widely examined, with studies such as [10], [11], and [12] investigating the economic feasibility and sensitivity of repowering, particularly in the instance of the Kayathar wind farm.

Additionally, the feasibility of incorporating PV panels within wind farms is explored in [13], and wind-solar hybrid power plants are thoroughly discussed in [14], [15], [16], and [17]. The innovative concept of constructing solar PV power plants in shadow-free unoccupied areas, in collaboration with wind turbine generators (WTGs) to mitigate power generation fluctuations, is meticulously examined in [18]. The feasibility of hybrid offshore plants is addressed in [19], and in-depth analyses of shadow patterns for wind turbines and capacity planning for PV integration within hybrid power plants are provided in [20], [21], and [22], with a specific focus on the Kayathar wind farm outlined in [3].

Financial factors from numerous sources ([19], [23], [24], [25], [26], [27]) have been taken into consideration for the economic analysis in this study. A techno-economic assessment of PV-wind farms is also carried out in citedbc and [29] and while [5] and [30] specifically cover the techno-economic analysis of PV-wind farms in the context of Kayathar. In the range of studies that have been reported, a thorough analysis that covers both the viability of a hybrid system combining PV components and an in-depth economic assessment is conspicuously absent.

This case study is proposed as a requirement to upgrade the older turbines in the Kayathar wind farm. The major objective of the study is to optimize the wind farm to extract more energy with PV panels. This paper fills a crucial gap by offering a thorough investigation of the viability of repowering, taking into consideration the inherent uncertainties in energy output, and a detailed sensitivity analysis of financial parameters.

The rest of the paper is organized as follows. The section II discusses site selection. The methodology followed in the study is given in section III. The repowering analysis is discussed in section IV. Section V discusses shadow analysis of wind turbine and hybrid plant electricity generation. Section VI deals with economic analysis. The sensitivity analysis of the hybrid plant is discussed in section VII. Discussions of the findings of the optimization, techno-economic analysis, sensitivity analysis, and environmental advantages are found in section VIII. Finally, section X concludes the paper.

II. SITE SELECTION

According to studies, around 10% of all wind turbines in India have a rating under 500 kW, which equals about 3,500 MW of total installed capacity. The three states of Tamil Nadu, Maharashtra, and Gujarat have the highest potential for repowering such projects with turbine sizes under 500 kW, with installed capacities of 1,744 MW, 302 MW, and 202 MW, respectively. The majority of these machines have been set up in Class I wind locations with significant wind power potential [6].

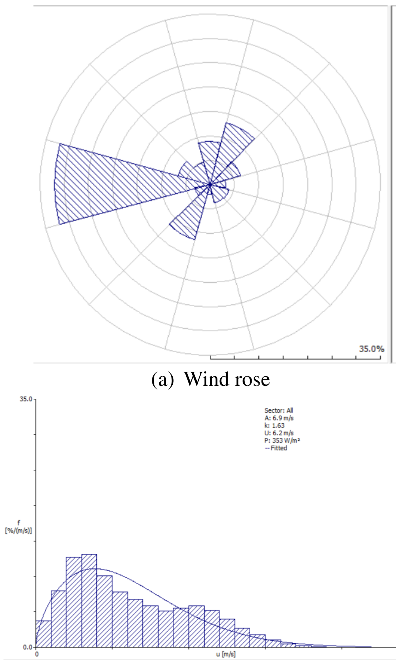
The research study location is one of Tamil Nadu's windiest places, and it has historic wind turbines that Tamil Nadu Energy Development Agency (TEDA) and NIWE own and operate. These historic turbines, which were among the first installations in the area, have been crucial in the development of wind energy [3]. The generation and capacity utilization of the existing wind farm for the period of 2016-2017 is shown in Table 1

A. SITE DESCRIPTION

Kayathar is located in the Tenkasi pass (Latitude: 08 57' 13.4'' N, Longitude: 77 43'12.5'' E) with an elevation of 93m above sea level. This region boasts a homogeneous landscape predominantly characterized by dense foliage comprised of small trees and shrubs. The Kayathar wind farm is spread over 100 acres. The wind data of the site is taken from NIWE for the period April 2010 – May 2011.

TABLE 1. Generation and CUF details of existing wind farm [3].

Month	Generation kWh	Total generation kWh	CUF%
April-16	0	3769080	7.97%
May-16	74650		
Jun-16	595940		
Jul-16	689398		
Aug-16	372900		
Sep-16	449664		
Oct-16	653108		
Nov-16	351584		
Dec-16	321064		
Jan-17	260772		
Feb-17	0		
Mar-17	0		



(a) Wind rose

(b) Weibull distribution

FIGURE 1. Wind rose and Weibull distribution at 70m hub height in Kayathar.

1) WIND CHARACTERISTICS OF THE SITE

The data consisted of wind speed, wind direction at 50 m and 70 m height. This data is used for the wind resource assessment in the site. The average wind speed in the investigated wind farm is 6.2 m/s, with the predominant wind direction being west. Fig. 1 shows the site's Wind Rose and Weibull distribution at 70m hub height. The wind power density in the site at 70m height is 352 W/m^2

2) WIND FARM LAYOUT

The wind farm comprises 32 wind turbines, including 30 Micon 200 kW turbines, one Suzlon 600 kW turbine, and one Senvion 2 MW turbine. Figure 2 shows the layout of the wind farm. Table 2 shows the specification of the turbines in the wind farm.

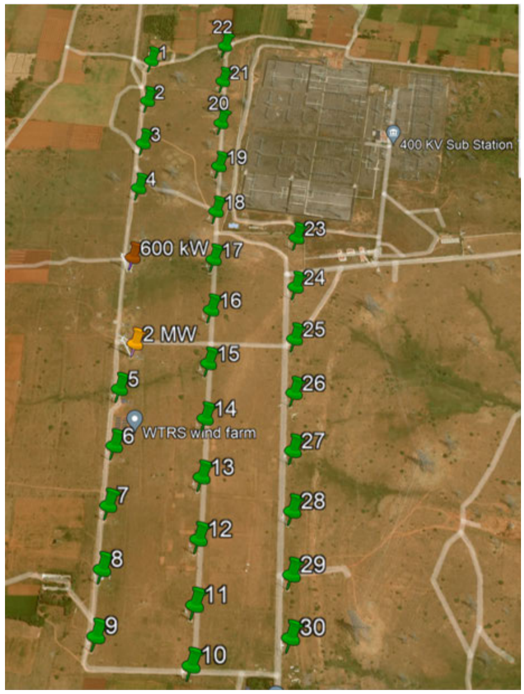


FIGURE 2. Layout of existing Kayathar wind farm.

TABLE 2. Specification of turbines used in the repowering analysis.

Capacity	Cut-in Speed (m\s)	Cut-out Speed (m\s)	Rated Speed (m\s)	Hub Height (m)	Rotor Diameter (m)
600 kW	4.5	25	13.5	68	50
1 MW	3	25	13	70	58
1.5 MW	3	25	13.5	67	66
2 MW	3	22	11	80	100
2.5 MW	3	25	14	100	100
3 MW	3	25	14	94	100.6

3) SOLAR CHARACTERISTICS OF THE SITE

According to NIWE measurements, the Kayathar region receives an average of 4.92-5.21 kWh/m^2/day of Global Horizontal Irradiance (GHI) per year. From March through September, strong sun irradiation is present at the site, giving the greatest energy for the PV system.

III. METHODOLOGY

Wind resource assessment is required to determine the wind potential at the location. WAsP is used for this. The energy production of the wind farm can be determined using WAsP. The viability of repowering the turbines using more powerful machinery is then investigated. The feasibility of integrating solar panels into the wind farm is then researched. The shadow of the wind turbine impacts the PV generation in the hybrid plant. As a result, shadow analysis is required.

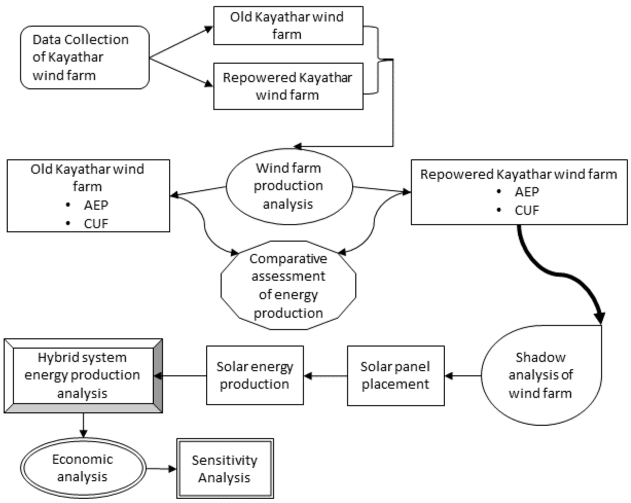


FIGURE 3. **Flowchart of Methodology.**

A mathematical formula is used to calculate the ground shadow cast by wind turbines, with tower height and sun angles as factors. The turbine's shadow region is discovered, and the remaining area is used to install the PV panels. After that, the energy produced by the solar panel is calculated using the PVSyst software. The economic and sensitivity analysis of the hybrid power plant is also performed. Figure 3 depicts the overall approach used in this study.

IV. REPOWERING ANALYSIS

Repowering of wind turbines is the process of replacing older lower-capacity turbines with newer, higher-capacity turbines. The turbines in the Kayathar wind farm has been running for more than 20 years. This provides a necessity for the repowering of the turbines. There are different turbines used for the repowering analysis The turbine details are shown in Table 2.

A. REPOWERING CASES

The thirty turbines of each 200 kW capacity is taken for the repowering study. The other two turbines in the site are not taken for the study as they are used as test machines in the site. In the initial stage, the wind farm is repowered with the same 200 kW turbines. This is taken as the base case for the comparison. In the subsequent cases, the thirty turbines are replaced with turbine capacities ranging from 600 kW to 3 MW. In all these cases the wind farm layout is changed and the number of turbines also decreases.

B. REPOWERING WIND FARM LAYOUT

During operation, it is important to consider turbine spacing since wind turbines create a conical wave in the downwind direction. Wind turbines positioned in this wake region tend to produce less electricity, hence optimal wind turbine arrangement is critical for the wind farm. On flat terrain, wind turbines are often placed at (5Dx7D) (5 times the rotor diameter in the same row and 7 times the turbine diameter in the next row) perpendicular to the prevalent wind direction.

For the first case, the layout of the wind farm is the same as the existing wind farm (Fig. 2). The layout of the other repowered wind farm is shown in Figure 4. The repowered wind farm with 2 MW, 2.5 MW, and 3 MW turbines are all the same, as the rotor diameter of the turbines chosen is almost the same. [3]

C. MICRO-SITING AND ENERGY ESITMATION

For the micro-siting analysis at the Kayathar wind farm, the WAsP model (version 12.7) is employed to assess optimal turbine placement and performance. Additionally, the Wind Atlas technique is utilized to create a detailed spatial representation of the wind patterns within the region. In order to generate accurate results, the software relies on specific information such as the wind resource characteristics unique to the location, topographical details, and the layout of the wind farm including the coordinates of the wind turbine generators (WTGs).

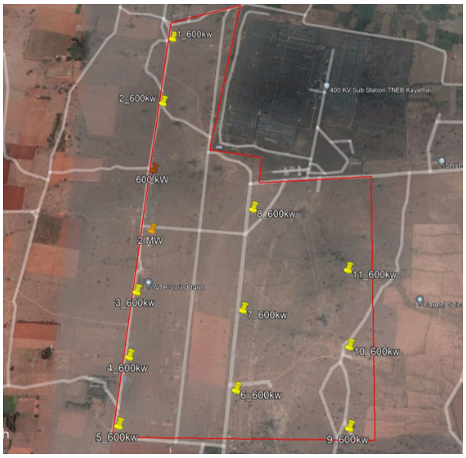
By analyzing the WTG locations, the software aims to optimize the existing wind farm layout, minimize the impact of wake losses, ensure the safety of nearby construction, and maximize the utilization of available grid and logistical infrastructure. Once the models are configured and the inputs are provided, the WAsP model enables the precise calculation of energy generation potential across different configurations, turbine sizes, and hub heights (as depicted in Figures 2 and 4). This integrated approach allows for informed decision-making and accurate assessment of energy generation capabilities at the Kayathar wind farm [3].

The wind resource assessment done using the WAsP software shows that the repowered existing wind farm layout (Fig. 2) has an Annual Energy Production (AEP) of 19.211 GWh and a Capacity Utilisation Factor (CUF) of 25.5%. The wind farm's projected wake loss is 2.45% (Table 3).

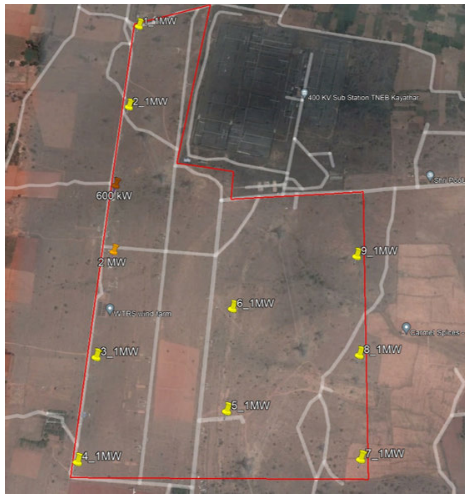
The different repowered wind farms are compared on the basis of repowering energy and capacity ratio. Repowering capacity and energy ratio are the ratios of new wind farm capacity and energy production relative to an existing wind farm with thirty-200 kW wind turbines.

When repowering the wind farm with eleven 600 kW turbines (Figure 4(a)), the wind farm's capacity increased by 1.1 times, which increased the generation by 1.61 times to 26.124 GWh with a CUF of 32.4% and an overall wake loss of the wind farm ins 1.64%. Repowering the wind farm with nine 1 MW turbines (Figure 4(b)), a 1.5 times increase in capacity addition also sees an increase in energy by 2.1 times. Table 3 shows the consolidated result of repowering existing wind farm with turbines of varying capacities.

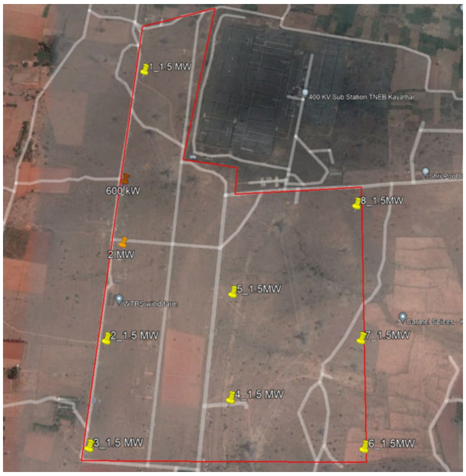
Among all the cases, the wind farm repowered with 2 MW turbines performs the best, delivering around 42 GWh of electricity at a CUF of 38.1%. Despite a 1.6 times increase in capacity, this represents a three-times increase in electricity production over the existing wind farm in Kayathar.



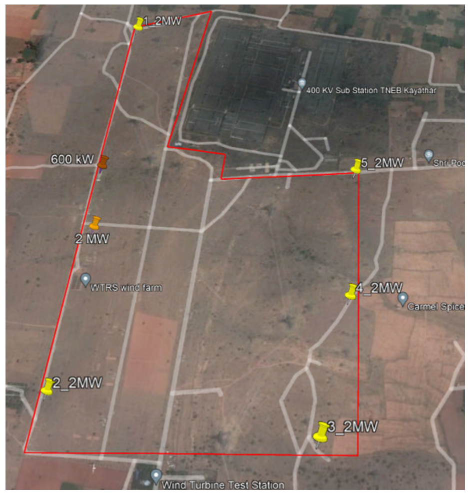
(a) Layout of repowered wind farm with eleven 600 kW turbines



(b) Layout of repowered wind farm with nine 1 MW turbines



(c) Layout of repowered wind farm with eight 1.5 MW turbines



(d) Layout of repowered wind farm with five 2 MW turbines

FIGURE 4. Layout of different repowered wind farm.

The repowered wind farm with 2 MW turbines (Figure 4(d)) specifically produces an output of 4.2 GWh of electricity per MW of installed capacity, which is the most favourable result among all scenarios. The repowered wind farm configuration with 600 kW turbines (Figure 4(a)), which produces 3.96 GWh of electricity for every MW of installed capacity, is the second best choice. In contrast, the repowered wind farm with 1.5 MW turbines (Figure 4(c)) has the worst performance, generating only 2.91 GWh of electricity for every MW of installed capacity.

Further improvements to boost energy generation and overall efficiency can be made by concentrating on these results and optimizing the layout of the wind farm in accordance.

V. PV INTEGRATION IN THE WIND FARM

To improve the layout and increase energy gathering, a solar plant is integrated into the repowered wind farms. When considering the installation of photovoltaic (PV) panels near wind turbines, the shadow of the wind turbine is a significant issue. Wind turbines can cast both tower and blade shadows, which can shade PV panels and significantly reduce their output power. To avoid this, shadow analysis is performed to evaluate the potential shadow impacts of wind turbines on PV panels and to arrange panel location accordingly. Shadow analysis ensures that the solar panels receive optimum sunlight while being shaded by the turbine blades.

Wind turbine shadow effects are affected by a variety of factors, including the turbine's size, height, location, and orientation, as well as the position and arrangement of the PV panels. The shadow analysis comprises simulating the shadow patterns of the wind turbine over the course of a day, week, and year utilizing the sun's location and angles. The shadow analysis assists designers in determining the best location and orientation for solar

TABLE 3. Result of repowering the Kayathar wind farm.

Wind farm layout	AEP (GWh)	Total wind farm wake loss (%)	CUF (%)	Repowering Capacity Ratio	Repowering Energy Ratio
Existing wind farm	19.211	2.45	25.5		
Repowered wind farm with 600 kW turbine	26.124	1.64	32.4	1.1	1.61
Repowered wind farm with 1 MW turbine	31.969	1.36	31.4	1.5	2.1
Repowered wind farm with 1.5 MW turbine	34.929	1.69	27.3	2	2.41
Repowered wind farm with 2 MW turbine	42.027	1.15	38.1	1.6	3.04
Repowered wind farm with 2.5 MW turbine	47.617	1.2	36	2.08	3.54
Repowered wind farm with 3 MW turbine	53.486	1.4	34.7	2.5	4.08

panels in order to minimize shade and optimize energy output.

Turbine shadow is of two types: Tower shadow, and flickering. The tower shadow is further divided into two types Tower invasion shadow, and Tower self-shadow. A mathematical formulation is done to identify the shadow regions caused by the turbine.

Three repowered wind farm layouts is chosen for assessment in order to assess the feasibility of PV installations within the wind farm. The comparison layouts comprise the existing wind farm layout, repowered wind farm with 600 kW turbines, and repowered wind farm with 2 MW turbines. Because of their greater energy generation per megawatt (MW) of added capacity, these repowered wind farm layouts are suitable for benchmarking against the existing wind farm layout.

A. MATHEMATICAL FORMULATION FOR SHADOW ANALYSIS

The shadow of a vertical tower can be found out using the solar equations. The shadow components of a pole of height H at the origin are shown in Figure 5. The sun is at azimuth γ and elevation angle α in relation to the south. The shadow length L on the ground is given by: [20]

$$L = H/\tan\alpha \tag{1}$$

The altitude angle is given by the equation

$$\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \tag{2}$$

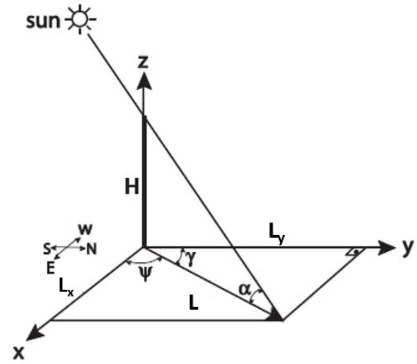


FIGURE 5. Shadow components of a vertical pole [20].

where ϕ is the latitude of the place, δ and ω are declination and hour angle given by the equations 3 and 4 respectively.

$$\delta = 23.45\sin\left[(284+n)\times\frac{360}{365}\right] \tag{3}$$

$$\omega = 15T - 180^\circ \tag{4}$$

The component of the east-west shadow is provided by: [20]

$$L_x = H\frac{\cos\delta\sin\omega}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega} \tag{5}$$

and the component of the north-south shadow is:

$$L_y = H\frac{\sin\phi\cos\delta\cos\omega - \cos\phi\cos\delta}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega} \tag{6}$$

B. SHADOW OF TURBINE TOWER

A turbine tower is a tall pole that, during the day, casts a shadow on the ground. This is the most noticeable shade. A turbine tower pole's shadow is normally a stationary shadow that travels with the sun throughout the day.

The tower height is proportional to the blade length or rotor radius R and can range between 1.5R and 2.5R. The turbine's overall height could be between 3R and 3.5R. In addition, the dimensions of the wind farm (the distance between the towers) are supplied in proportion to R using a grid-wise deployment that resembles an array (rows and columns). Figure 6 depicts a wind farm with a north-south spacing of 10R and an east-west spacing of 14R with a west-east wind direction. The average tower height H and width W are 2R and R/16, respectively.

The shadow length of the three different wind turbines is found using Eqn 1. The tower height of the 200 kW, 600 kW, and 2 MW turbines are 30m,68m, and 80m respectively. This height is taken as H in the equation. Figure 7 shows the shadow length of the 2 MW turbine on December 21st and on June 21st as they are the two solstices. The shadow length of the other turbines follows the same pattern throughout the day and month.

It is found that the shadow length on June 21st is comparatively lower than that of December 21st. Also, the shadow length of the pole peaks in the morning and in the

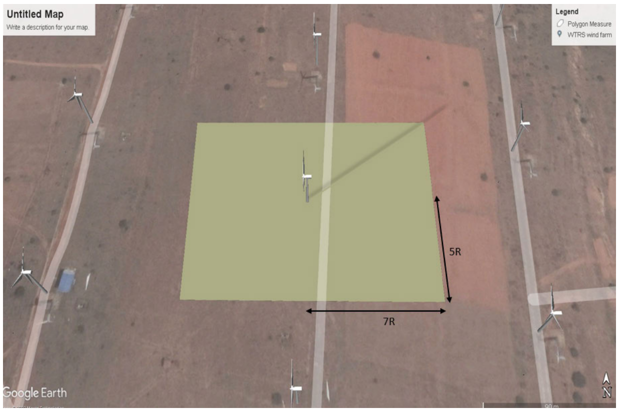


FIGURE 6. Wind farm layout.

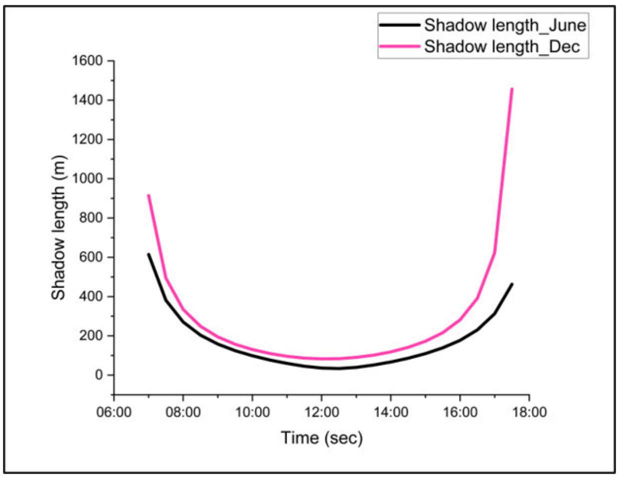


FIGURE 7. Shadow length of 2 MW turbine with height 80 m.

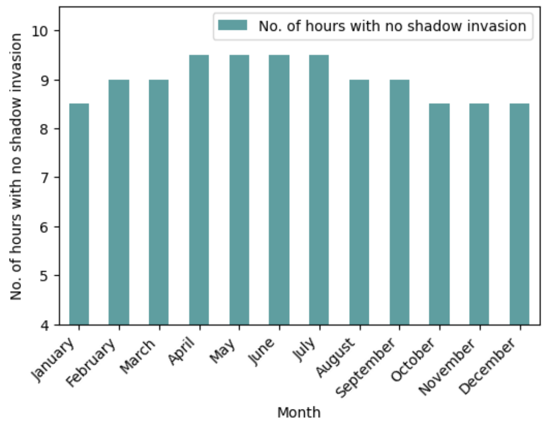


FIGURE 8. No. of hours with no shadow invasion on the neighboring turbine ground area.

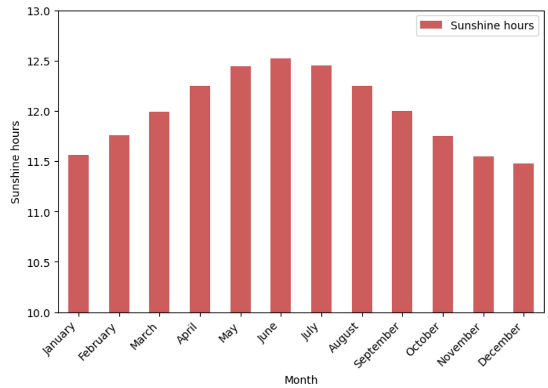


FIGURE 9. Average sunshine hours in a month.

afternoon it is at its lowest. According to this two types of tower shading can occur in the place: self-shading and invasion shading.

1) TOWER INVASION SHADOW

The tower of the turbine casts a shadow invading the neighboring tower ground. This type of shadow is more prevalent in the morning and evening when the sun is closer to the horizon. In the summer, the tower's shadow may invade the southern adjoining tower's area in the morning and after the afternoon. The shadow length for a tower of height $H = 2R$ is $(L/H) \times (2R)$. The shadow components obtained by equations 5 and 6 give the criteria for absence of the tower shadow into the nearby tower ground area (see Fig.6): [20]

$$(L_x/H) \times (2R) \leq 7R \tag{7}$$

$$(L_y/H) \times (2R) \leq 5R \tag{8}$$

The absence of shadow invasion into a nearby tower ground zone indicates that the tower shadow is only cast on the area of the tower in consideration. Since the goal is to calculate the number of hours a turbine tower casts a shadow on the tower ground area during the day, the shadow length from figure 7 and the conditions of equations 7 and 8 give the number of hours without shadow invasion for 21st of every month. Figure 8 shows the number of hours there is no invasion of shadow for the 2 MW turbine for 21st of every month. All the other turbines also has the same pattern.

There is no invasion of shadow for more than 8 hours during a day for all the turbines. In order to find the ratio of how many hours in a day the invasion shadow will not be there, the data in Figure 8 is divided by the total sunshine hours in a day (Figure 9). It is inferred that 70% of the time when the sun is available, the invasion shadow of the wind turbine does not occur.

C. TOWER SELF-SHADING

The turbine tower casts a shadow in the ground area belonging to the tower. This type of shadow can be more prevalent during the middle of the day when the sun is higher in the sky. When a wind turbine and a ground-mounted PV panel are near together, the tower shadowing effect can be more pronounced.

In this instance, the shadow length of the wind tower is calculated using the shadows during hours when there isn't an invasion shadow. The average shadow length for the day is

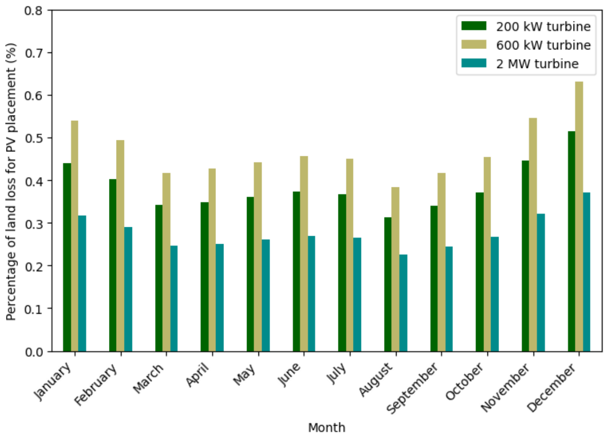


FIGURE 10. Percentage of area lost to wind turbine shadow by three different turbines.

calculated by averaging the shadow values for the entire day in this gap. This gives the value of $L_{average}$. The daily average tower shadowing area is now calculated by multiplying the length of shadow cast by the tower by the average tower width R/16: [20]

$$A_{average} = L_{average} \times (R/16) \tag{9}$$

The ratio of the average turbine shadow area ($A_{average}$) to the tower ground area (10R x 14R) can be used to calculate the percentage loss of the wind farm's ground area for photovoltaic energy. Figure 10 shows this for each month on the 21st day.

The graph reveals that the percentage loss of land to shadow is less than 1%. The most amount of area shadowed is by the 600 kW turbine this is because of the large height and small area of the 600 kW turbine. The 2 MW has the lowest area loss to shadow although it has the highest shadow length. This is because of the large area of the wind turbine.

D. SHADOW FLICKERS BY TURBINE BLADES

The rotating of turbine blades casts varying shadows on the ground during periods of bright sunlight, resulting in fluctuations in light intensity known as shadow flickers. These flickering shadows can induce fluctuations in the power output of photovoltaic (PV) panels on a regular basis. The frequency of these changes is proportional to the number of turbine blades.

Because of the whirling turbine blades, the PV panels' power output may oscillate and flicker, imitating cloud movement. As a result, the current-voltage (I-V) characteristic changes in many steps, with local maximum power points occurring as a result of alternating changes in light intensity. Inverters with dynamic maximum power point tracking (MPPT) capabilities have been developed to overcome this issue. These inverters are designed to respond to changes in irradiance, including those induced by clouds, shade, and obstructions. On a millisecond period, dynamic MPPT algorithms ensure accurate and speedy tracking of the optimal power point.

However, it should be noticed that the shadow cast by the turbine blades on the ground is significant. To simplify the study, it is assumed that a blade extends R units above the tower height. As a result, the total height considered for the shadow analysis is the sum of the tower height and the blade projection ($H + R$). The shadow analysis is then performed in the same manner as previously explained.

The average shadow length $L_{average}$ of the combined height is taken and multiplied with the width ($R/16$) to find the average area of shadow, $A_{average}$. With this the percentage loss in area is also found for each month. There is an overall increase of 0.1% in area loss by the three different turbines compared to the previous case (Section V-C). But still, the loss is below one percent.

E. POWER OUTPUT ESTIMATION OF HYBRID PLANT

Taking the average shadow length ($L_{average}$) as the radius of a circular area is found. (Fig. 7) This area is omitted for the purpose of PV panel placement. Since this area will have the most amount of shadow during the year. The total area of the shadow in the wind farm is found by adding the shadow area of all the wind turbines in the wind farm.

The existing wind farm layout has the lowest percentage of area loss due to shadows, with 30% of the overall wind farm area affected. Following closely after is the repowered wind farm configuration with 2 MW turbines, which has a shadow loss of 40% of the wind farm area. However, the repowered wind farm configuration with 600 kW turbines has the most shadow loss, with 44% of the area affected.

The wind farm has an area of 815,321 m^2. Out of this total area, the existing wind farm loses 243,410 m^2 to shadow, whereas the repowered wind farm with 600 kW and 2 MW turbines loses 356,874 m^2 and 325,415 m^2, respectively. As a result, there are 571,911 m^2 of open area for PV placement within the existing wind farm. There is 458,446 m^2 of a residual area in the repowered wind farm configuration with 600 kW turbines and 489,906 m^2 of available space for PV placement in the repowered wind farm layout with 2 MW turbines.

For the study, Vikram solar 370 W panels are used, and the PVsyst software is used to analyze the PV location, evaluate the capacity, and estimate the generation of the PV panels within these selected areas. The total installed capacity of solar panels and generation is shown in table 4.

Two key metrics are used to evaluate these plants: the capacity ratio and the energy ratio. The capacity ratio is the ratio of the total capacity of the hybrid plant to the capacity of the existing wind farm. The energy ratio is the ratio of total generation from the hybrid plant to the generation from the existing wind farm.

Notably, the existing wind farm has grown substantially, now boasting 13.65 times its previous capacity. However, even with this remarkable expansion, the available space for solar panels in shadow-free areas is more abundant than

TABLE 4. Hybrid power plant generation.

Wind farm	Shadow free area	Installable solar capacity (MW)	Installable wind capacity (MW)	Total Capacity (MW)	Capacity Ratio	Energy Generation from solar (GWh/yr)	Energy Generation from wind (GWh/yr)	Total Generation (GWh/yr)	Energy Ratio
Existing wind farm	571911	108.841	8.6	117.441	13.66	165.787	19.211	184.998	9.63
Wind farm with 600 kW turbine	458446	86.713	9.2	95.913	11.15	131.962	26.124	158.086	8.23
Wind farm with 2 MW turbine	489906	92.757	12.6	105.357	12.25	141.336	42.027	183.363	9.54

other options. Consequently, the capacity ratio aligns more closely with that of the repowered wind farm featuring 2 MW turbines, which stands at 12.25. In contrast, the wind farm equipped with 600 kW turbines lags behind with a capacity ratio of 11.15.

Turning our attention to energy generation, the existing wind farm maintains its dominance with an energy ratio of 9.63, marking the highest performance in this regard. The repowered farm featuring 2 MW turbines is not far behind, with an energy ratio of 9.54. Notably, the introduction of solar panels contributes significantly to the overall generation of the existing wind farm, elevating its energy ratio. Conversely, the wind farm employing 600 kW turbines exhibits the lowest energy ratio.

In light of these findings, the existing wind farm appears to be the preferable choice for PV installation due to its higher energy ratio. Nevertheless, the option of repowering the wind farm with 2 MW turbines and integrating PV panels also exhibits a substantial impact on the energy ratio. Consequently, conducting an economic assessment of these two scenarios is imperative to determine the most viable course of action.

VI. ECONOMIC ANALYSIS OF HYBRID POWER PLANT

The economic analysis of a wind-solar power plant entails assessing the financial costs and benefits connected with the power plant's construction, operation, and maintenance. This analysis takes into account elements such as the initial capital expenditure, operational expenses, and revenue gained by selling the plant's power. This may entail analyzing the sensitivity of the project's financial performance to changing economic and market conditions.

A wind-solar hybrid power plant's economic analysis is critical for analyzing the project's cost-effectiveness, resource utilization, revenue generation, financing feasibility, and policy-making. It aids in determining the financial viability of investing in a hybrid power plant, optimizing the use of available resources, and determining the project's profitability. The analysis can help potential investors, lenders, and policymakers make educated decisions about boosting renewable energy technology and lowering carbon emissions.

The performance indices used for the study are Simple Payback, Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR), Net Present Value (NPV), and Discounted Payback. The parameters can be calculated using the formulas 10 -13

Simple Payback (SPB): Simple Payback is a financial statistic that calculates how long it takes for an investment to pay for itself. It is computed by dividing the investment's initial cost by the annual savings generated by the project

$$\text{Simple Payback} = \frac{\text{Initial Investment}}{\text{Savings}} \tag{10}$$

Levelized Cost of Electricity (LCOE): The levelized cost of electricity (LCOE) is a financial metric that evaluates the cost of generating power from a certain energy source across the project's lifetime. It considers the initial investment cost, the cost of operating and maintaining the equipment, and the project's estimated lifetime.

$$LCOE = \frac{\text{Sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=0}^{25} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=0}^{25} \frac{E_t}{(1+r)^t}} \tag{11}$$

where, I_t is the initial investment, M_t is annual maintenance cost, E_t is the annual energy production, r is the discount rate, t total life time of the project

Net Present Value (NPV): A financial metric called net present value (NPV) determines the present worth of anticipated cash inflows and outflows from an investment. It aids in deciding whether or not an investment is profitable by taking time value of money into account. An investment is presumed to be lucrative if the NPV is positive, as opposed to being unprofitable if the NPV is negative.

$$NPV = \sum_{t=0}^{25} \frac{C_t}{(1+r)^t} \tag{12}$$

where, C_t is the cash flow, r is the discount rate, t total lifetime of the project

Internal Rate of Return (IRR):An investment's profitability is measured using the financial term internal rate of return (IRR). It determines the discount rate at which the investment's cash inflows and outflows are both valued at their present values. Alternatively put, the discount rate (r) at which the NPV equals 0. The investment is considered to be more profitable the higher the IRR.

TABLE 5. Assumptions used for economic analysis.

Description	Value
Location of the project	Kayathar, Tamilnadu
TARIFF	
Wind power project	
Tariff period	25 Years
Energy selling price	₹3/kWh
Solar power project	
Tariff period	25 Years
Energy selling price	₹3/kWh
OPERATIONS	
Operational days in a year	365 days
Useful life (wind and solar)	25 Years
LOAN DETAILS	
Rate of interest	10.50%
Debt ratio	70%
Loan tenure	10 Years
ASSUMPTIONS—WIND	
Wind turbine cost	₹600 Lakhs per MW [6]
Turbine foundation cost	15% of turbine cost [24]
Decommissioning and miscellaneous costs	10% of the capital cost [25]
Scrap Value	10% of the capital cost [26]
Degradation factor	0.5% year on year [5]
O & M charges	1.1% on 85% of capital investment and 0.22% on 15% of the capital investment [27]
Escalation in O & M charges	5% yearly [27]
Wind turbine insurance	0.75% on 85% of the capital cost for the first year and to be reduced by 0.5% every year [27]
ASSUMPTIONS—SOLAR	
Solar panel price	₹28 per W [23]
Degradation factor	0.5% year on year [5]
Inverter cost	₹15 lakhs for one inverter [23]
O & M charges	1.5% of capital cost [28]

Discounted Payback (DPB): Discounted Payback is a financial metric that calculates the amount of time it takes for an investment to pay for itself, taking into account the time value of money.

$$Discounted\ Payback = No.\ of\ years\ before\ recovery + \frac{Remainin\ Cost}{Cash\ inflow\ in\ the\ following\ year} \tag{13}$$

There are some assumptions made for calculating the economic parameters. These assumptions are shown in Table 5.

These performance indices compare the existing wind farm layout with a solar panel to the repowered wind farm with 2 MW turbine layout with solar panels. In the initial stage, the economic analysis gives the P_{50} performance indices. P_{50} is the average annual energy yield predicted for a site - the annual energy output that is most likely to be achieved. The yearly wind and solar generation for the P_{50} are 19.211 GWh and 165.787 GWh respectively for the existing wind farm with solar panels. For the repowered wind farm with solar panels, 42.027 GWh and 141.336 GWh of electricity are produced by the wind and solar respectively. Table 6 shows the result of economic analysis for P_{50} confidence level.

TABLE 6. Economic analysis of the hybrid power plants (P_{50}).

	Existing wind farm with solar	Repowered wind farm with solar
Payback Period	4.70 Years	4.48 Years
IRR	13.30%	13.88%
LCOE	₹2.49/kWh	₹2.37/kWh
Discounted Payback	6.10 Years	6.05 Years
NPV	₹6707.49 Lakh	₹8136.03 Lakh

TABLE 7. Economic analysis of the hybrid power plants (P_{90}).

	Existing wind farm with solar	Repowered wind farm with solar
Payback Period	5.49 Years	5.23 Years
IRR	10.98%	11.74%
LCOE	₹2.86/kWh	₹2.72/kWh
Discounted Payback	7.07 Years	7.02 Years
NPV	₹2109.72 Lakh	₹3556.67 Lakh

A. UNCERTAINITY IN ENERGY PRODUCTION

The next step is to apply the method of exceedance probability estimate to the net AEP. The Physical Guarantee of the wind power generated must be calculated taking into account all sources of uncertainty in the project, so that the certified energy can bear a 90% probability, being attained or exceeded. This will reduce the risk that energy production will be less than the one on contract. This quantity is known as P_{90} [9]. P_{90}, is the energy yield that a wind turbine is 90% likely to produce over an average year. With the P_{50} value, total uncertainty of the project and the z value, through the equation 14 it is possible to calculate the value in net energy production for the desired probability of exceedance [9].

$$P_x = P_{50} \times (1 - z \times Uncertainity_{Total}) \tag{14}$$

where, P_x is the net energy production to desired probability of exceeded.

$Uncertainity_{Total}$ is the total project uncertainty.

z is the value found in the normal distribution table of specific probabilities.

Table 7 shows the economic performance indices for P_{90} confidence level.

There is a considerable change in the economic parameters in the P_{90} confidence interval. The NPV has been reduced by more than half. The IRR had reduced by almost 2% in all the cases. The payback has increased by one year. The LCOE of all the cases also increased.

Taking these values as the base scenario the sensitivity analysis is done. This is done to study the parameters under varying conditions.

VII. SENSITIVITY ANALYSIS

The goal of sensitivity analysis is to investigate the impact of input variables on the output and economy of a system.

TABLE 8. Sensitivity analysis on initial investment in the case: existing wind farm with solar panels.

Existing wind farm with solar				
Parameters	Initial investment variation			
	+10%	-10%	+5%	-5%
Payback	5.98	4.92	5.71	5.19
IRR	9.95%	12.55%	10.52%	11.81%
LCOE	₹3.11/kWh	₹2.61/kWh	₹2.98/kWh	₹2.73/kWh
Discounted payback	8.01	6.12	7.10	7.02
NPV (in Lakhs)	- ₹108.79	₹5005.84	₹1169.87	₹3727.19

It is not, however, confined to unknown input variables. The process of analysing how changes in one or more input variables impact the output of a system or model is known as sensitivity analysis. This study is carried out by experimenting with different values or scenarios for each input variable and monitoring how the system or model's output changes in response.

The goal of sensitivity analysis is to find the most critical input variables or factors that influence the system's output. Decision-makers can then concentrate their efforts on the most crucial variables and devise strategies to mitigate risks and optimise performance.

In this study, the input variables being examined are investment, operation and maintenance cost, and grid feed-in tariff. They are varied by +/- 10% and +/- 5%. The study examines the effect of these variations on the Payback, IRR, NPV, and LCOE. By examining how changes in input variables impact the system's output and economy, sensitivity analysis can help identify key drivers of a project's profitability and viability.

A. SENSITIVITY ANALYSIS ON INITIAL INVESTMENT

The initial investment (I_t) of existing wind farm with solar panels is ₹352.45 crores and that of the repowered wind farm with solar panels is ₹334.12 crores. These values are changed by +/- 10% and +/- 5% keeping other parameters such as O&M cost, insurance, and feed-in tariff constant.

Table 8 shows the changes of financial parameters with the variation in initial investment in the case of existing wind farm with solar panels.

The initial investment has a substantial impact on the system's NPV. The increase of 10% in the initial investment take the NPV to negative. The NPV becomes -₹108.79 Lakh and the LCOE increases above ₹3 /kWh This means that in this scenario the increase in initial investment will not make the project profitable.

Table 9 shows the changes of financial parameters with the variation in initial investment in the case of repowered wind farm with solar panels.

In comparison to the other cases, this has a better result. The LCOE does not increase above ₹3 /kWh and the NPV of the project when the initial investment is increased by 10% decreases only by 68%. This makes the project much more feasible economically.

TABLE 9. Sensitivity analysis on initial investment in the case: repowered wind farm with solar panels.

Repowered wind farm with solar				
Parameters	Initial investment variation			
	+10%	-10%	+5%	-5%
Payback	5.73	4.72	5.48	4.98
IRR	10.51%	13.20%	11.10%	12.44%
LCOE	₹2.96/kWh	₹2.48/kWh	₹2.84/kWh	₹2.60/kWh
Discounted payback	7.09	6.09	7.06	6.13
NPV (in Lakhs)	₹1,138.17	₹5,975.17	₹2,347.42	₹4,765.92

TABLE 10. Sensitivity analysis on O&M Cost in the case: existing wind farm with solar panels.

Existing wind farm with solar				
Parameters	O&M variation			
	+10%	-10%	+5%	-5%
Payback	5.59	5.40	5.54	5.45
IRR	10.82%	11.13%	10.90%	11.06%
LCOE	₹2.89/kWh	₹2.82/kWh	₹2.88/kWh	₹2.84/kWh
Discounted payback	7.08	7.07	7.07	7.07
NPV (in Lakhs)	₹1,764.89	₹2,454.54	₹1,937.30	₹2,282.13

TABLE 11. Sensitivity analysis on O&M Cost in the case: repowered wind farm with solar panels.

Repowered wind farm with solar				
Parameters	O&M variation			
	+10%	-10%	+5%	-5%
Payback	5.31	5.15	5.27	5.19
IRR	11.59%	11.88%	11.67%	11.81%
LCOE	₹2.76/kWh	₹2.69/kWh	₹2.74/kWh	₹2.71/kWh
Discounted payback	7.03	7.02	7.03	7.02
NPV (in Lakhs)	₹3,239.26	₹3,874.08	₹3,397.96	₹3,715.37

To sum up, the increase in initial investment will increase the payback and LCOE of the project and lowers the NPV and IRR of the project. The NPV of the project is affected by this change. On the other hand, the decrease in initial investment will increase the NPV considerably making the project more profitable. This also lowers the LCOE and payback of the project with an increase in IRR. Thus a decrease in capital expenditure will make the project more feasible.

B. SENSITIVITY ANALYSIS ON OPERATION AND MAINTENANCE COST

The existing wind farm has an Operation and Maintenance (O&M) cost of ₹ 34.85 Lakhs for wind and ₹ 3.81 crores for solar yearly. For the repowered wind farm wtih solar panels the O&M cost for wind is ₹ 58.08 Lakhs and for Solar in ₹ 3.25 crores. These values are changed by +/- 10% and +/- 5% keeping other parameters such as initial investment, insurance, and feed-in tariff constant

Table 10 shows the variation in the economic parameters in the case of existing wind farm with solar panels. Table 11 shows the variation in the economic parameters in the case of repowered wind farm with solar panels.

Unlike the sensitivity analysis on the initial investment, the variation in O&M cost does not affect the economic parameters much. From the base scenario of P_{90}, increasing

TABLE 12. Sensitivity analysis on feed-in tariff in the case: existing wind farm with solar panels.

Existing wind farm with solar				
Parameters	**Feed-in tariff variation**			
	+10%	-10%	+5%	-5%
Payback	4.95	6.17	5.21	5.81
IRR	12.25%	9.65%	11.62%	10.32%
LCOE	₹2.86/kWh	₹2.86/kWh	₹2.86/kWh	₹2.86/kWh
Discounted payback	7.01	8.03	7.04	7.11
NPV (in Lakhs)	₹4,959.40	-₹739.97	₹3,534.56	₹684.88

TABLE 13. Sensitivity analysis on feed-in tariff in the case: repowered wind farm with solar panels.

Repowered wind farm with solar				
Parameters	**Feed-in tariff vatiation**			
	+10%	-10%	+5%	-5%
Payback	4.72	5.86	4.96	5.53
IRR	13.06%	10.37%	12.40%	11.06%
LCOE	₹2.72/kWh	₹2.72/kWh	₹2.72/kWh	₹2.72/kWh
Discounted payback	6.10	7.09	6.13	7.06
NPV (in Lakhs)	₹6,381.16	₹732.17	₹4,968.92	₹2,144.42

the O&M raises the payback and LCOE while decreasing the IRR and NPV of the project. The reduction in O&M reduces the LCOE and Payback while increasing the IRR and NPV of the project. The NPV seems to have major changes. This is because these metrics are more strongly influenced by the cash flows related to capital expenditures (CAPEX) than operating expenditures (OPEX).

When compared to capital expenses, the O&M cost normally makes up a small portion of the overall costs. It is a continuing expense that develops after the initial investment. Therefore, even if the O&M cost varies, the effect on the project's overall cost will be minimal. Because of this, variations in O&M costs do not significantly affect NPV, IRR, payback period, or LCOE.

However, it is crucial to note that the O&M cost has an impact on the overall profitability of the project and should be carefully examined when assessing the project's long-term feasibility and sustainability. A well-maintained and effectively run system can minimise operational expenses while increasing revenue over the system's lifetime.

C. SENSITIVITY ANALYSIS ON GRID FEED-IN TARIFF

The feed-in tariff (FIT) taken for the study is ₹3 /kWh. This is varied to study the impact on the economic parameters. The initial investment, O&M cost, insurance amount is kept constant.

Table 12 shows the variation in this economic parameters in the case: existing wind farm with solar panels without considering the foundation cost

The tariff hike nearly doubles the NPV. However, the fall in FIT causes the NPV to be negative, rendering the project unfeasible. The project's IRR has also been reduced to less than 10%. The project's payback time has also changed significantly.

Table 13 shows the variation in the economic parameters in the case: existing wind farm with solar panels without considering the foundation cost

The feed-in tariff (FIT) sensitivity analysis demonstrates that it produces the most significant results in terms of the economic parameters of the wind-solar project. A greater FIT results in a higher net present value (NPV) and internal rate of return (IRR), whereas a lower FIT results in a lower NPV and IRR as well as a longer payback period. However, changes in the FIT have no effect on the LCOE (levelized cost of energy).

An increase in the FIT increases the project's revenue, hence boosting the NPV and IRR. This is because of the increased cash inflows, which result in a higher discounted value of future cash flows and a shorter payback period. A drop in the FIT, on the other hand, results in lesser revenue, a lower NPV and IRR, and a longer payback period.

Importantly, regardless of changes in the FIT, the LCOE, which is determined based on the total project cost and total energy generated, remains unchanged. This is due to the fact that the FIT has no effect on the overall cost of the project.

VIII. GENERAL REMARKS

A. TECHNO-ECONOMIC REMARKS

The economic parameters of a wind-solar project are complex and interdependent. The initial investment, operation and maintenance costs, and feed-in tariff can all impact the project's profitability and sustainability. Increasing the initial investment, reducing O&M costs, and increasing the feed-in tariff generally improve the economic parameters of the project, while the opposite leads to poorer performance.

Choosing the best scenario depends on a range of factors, including project objectives, available resources, and local market conditions. However, based on the analysis presented, a lower initial investment with reduced O&M costs and an increased feed-in tariff may provide the best balance of profitability and sustainability. This scenario results in a lower LCOE, a shorter payback period, and higher IRR and NPV.

Ultimately, any wind-solar project must be carefully planned, designed, and operated to achieve optimal economic performance while minimizing environmental impact. By considering these economic factors, project developers and stakeholders can make informed decisions to support the growth of renewable energy and build a more sustainable future.

B. ENVIRONMENTAL REMARKS

The wind farm with solar panels has proven to be an effective way to reduce carbon emissions. The fossil fuels produce 0.92 tCO_2/MWh of electricity generated and renewable powers produce 0.065 tCO_2/MWh of electricity generated. Using this the tCO_2 saving is calculated. Around 93% reduction in carbon emission compared to fossil fuels The existing wind farm with solar panels saves between 137,895 and 158,173 tCO_2 per year. Repowering the wind farm with solar panels maintains these emission savings, with an estimated reduction of 136,676 to 156,775 tCO_2 per year.

IX. POLICY RECCOMENDATION

Several policy proposals are made to maximise the benefits of wind farm repowering and to promote sustainable practices in the wind energy sector. First and foremost, governments should enact clear and supportive legislation that enables the repowering process and stimulate the adoption of innovative technology. Second, governments should enact laws that encourage the integration of renewable energy technology, such as wind farms combined with photovoltaic (PV) installations. Third, rather than shipping old wind turbines from repowered wind farms to junk, governments should incentivize their reuse and resale. Governments can contribute to a circular economy strategy in the wind energy sector by facilitating the restoration and relocation of decommissioned turbines. Fourth, governments should fund research and development projects aimed at finding new uses for existing wind turbine components. Fifth, policies should prioritize environmental effect reduction during wind farm repowering.

Furthermore, governments should create comprehensive energy plans that include repowering existing wind farms as a crucial method for meeting renewable energy targets and lowering greenhouse gas emissions. Additionally, governments should prioritize grid infrastructure development to meet the growing capacity of repowered wind farms. Furthermore, governments should put in place systems for regular monitoring and evaluation of repowered wind farms in order to assure compliance with environmental rules and performance standards. Finally, governments should constantly examine and update wind farm repowering legislation and regulations to ensure they are in line with technology improvements, economic trends, and environmental concerns. Governments can create a supportive framework for wind farm repowering, promote sustainable practices, and maximise the benefits of renewable energy generation by implementing these policy proposals.

X. CONCLUSION

The study investigates the viability of repowering and integrating photovoltaic (PV) panels into a wind farm near Kayathar. Thirty 200 kW turbines, one 600 kW turbine, and two 2 MW turbines make up the wind farm. The study focuses on several aspects, including wind resource assessment, repowering with larger turbines, shadow analysis for PV installation, and economic analysis. Repowering the turbines with larger-capacity machines results in significant improvements in energy production, with the repowered wind farm with 2 MW turbines producing an amazing 4.2 GWh of electricity per MW of installed capacity.

A shadow analysis is performed to determine the viability of installing PV panels within the wind farm. Individual turbine shadow loss is shown to be low, with the highest area loss being less than one percent. In most cases, shadows account for less than 25% of total wind farm area.

Based on capacity and energy ratio comparisons, repowering the wind farm with larger-capacity turbines increases overall generation potential. The economic analysis emphasises the importance of initial investment, operation and maintenance (O&M) costs, and feed-in tariff (FIT) in determining project viability.

The integration of PV panels with the wind farm helps to reduce carbon emissions. Annually, the existing wind farm with PV panels saves considerable amounts of CO_2. The repowered wind farm shows similar emission savings.

The findings of this study suggest that the repowered wind farm with 2 MW turbines and integrated solar panels presents a compelling solution for the Kayathar wind farm. Notably, the sensitivity analysis reveals that this scenario's NPV does not fall into the negative range, demonstrating its financial viability and resilience to external fluctuations.

In conclusion, the study highlights the possibilities for repowering wind farms, incorporating PV panels, and optimizing layouts to boost energy generation, reduce emissions, and improve economic viability. The findings can help decision-makers and stakeholders involved in wind-solar hybrid projects. Reduced initial investments, cheaper O& M expenses, and higher FIT are suggested as ways to improve the project's economic performance.

REFERENCES

[1] *The Current Installed Capacity of Wind and Solar*. Accessed: May 19, 2023. [Online]. Available: https://powermin.gov.in/en/content/power-sector-glance-all-india
[2] S. Ahmed, *Wind Energy: Theory and Practice*. New Delhi, India: PHI Learning, 2016.
[3] K. Boopathi, Dr. S. Ramaswamy, Dr. V. Kirubaharan, J. Bastin, A. S. Devi, Dr. P. Kanagavel, and Dr. K. Balaraman, "Optimization of the wind farm layout by repowering the old wind farm and integrating solar power plants: A case study," *Int. J. Renew. Energy Res.*, vol. 10, no. 3, pp. 1287–1301, Sep. 2020.
[4] A. Routray, K. D. Mistry, S. R. Arya, and B. Chittibabu, "Power output evaluation of a wind–solar farm considering the influence parameters," *IET Renew. Power Gener.*, vol. 15, no. 8, pp. 1613–1623, Jun. 2021.
[5] K. Boopathi, S. Ramaswamy, V. Kirubakaran, K. Uma, G. Saravanan, S. Thyagaraj, and K. Balaraman, "Economic investigation of repowering of the existing wind farms with hybrid wind and solar power plants: A case study," *Int. J. Energy Environ. Eng.*, vol. 12, no. 4, pp. 855–871, Dec. 2021.
[6] Idaminfra. *Repowering Old Wind Turbines India*. Accessed: Nov. 29, 2022. https://www.idaminfra.com/wp-content/ uploads/2018/10/Repowering-of-Old-Wind-Turbines-in-India.pdf
[7] R. Lacal-Arántegui, A. Uihlein, and J. M. Yusta, "Technology effects in repowering wind turbines," *Wind Energy*, vol. 23, no. 3, pp. 660–675, Mar. 2020.
[8] E. Martínez, J. I. Latorre-Biel, E. Jiménez, F. Sanz, and J. Blanco, "Life cycle assessment of a wind farm repowering process," *Renew. Sustain. Energy Rev.*, vol. 93, pp. 260–271, Oct. 2018.
[9] A. Fontaine and P. Armstrong, "Uncertainty analysis in energy yield assessment," *EWEC*, 2007.
[10] A. Paul and T. Prabu, "Technical and economic feasibility study on repowering of wind farms," *Indian J. Sci. Technol.*, vol. 9, no. 38, Oct. 2016.
[11] R. Villena-Ruiz, F. J. Ramirez, A. Honrubia-Escribano, and E. Gómez-Lázaro, "A techno-economic analysis of a real wind farm repowering experience: The Malpica case," *Energy Convers. Manage.*, vol. 172, pp. 182–199, Sep. 2018.
[12] T. Prabu and K. Sasik, "Repowering a windfarm—A techno-economic approach," *Wind Eng.*, vol. 39, no. 4, pp. 385–395, 2015.

[13] M. Agrawal, B. K. Saxena, and K. V. S. Rao, "Feasibility of establishing solar photovoltaic power plants at existing wind farms," in *Proc. Int. Conf. Smart Technol. Smart Nation (SmartTechCon)*, Aug. 2017, pp. 251–256.

[14] B. N. Prashanth, R. Pramod, and G. B. V. Kumar, "Design and development of hybrid wind and solar energy system for power generation," *Mater. Today, Proc.*, vol. 5, no. 5, pp. 11415–11422, 2018.

[15] C. Suchetha and J. Ramprabhakar, "Optimal power flow controller for a hybrid renewable energy system using particle swarm optimization," in *Proc. Nat. Power Electron. Conf. (NPEC)*, Tiruchirappalli, India, 2019, pp. 1–6.

[16] B. Tejesh, B. S. G. Charan, and C. M. Krishna, "Development of hybrid PV wind system for EVs with battery management system," in *Proc. 2nd Int. Conf. Adv. Electr., Comput., Commun. Sustain. Technol. (ICAECT)*, Bhilai, India, Apr. 2022, pp. 1–4.

[17] V. Vanitha, N. Ramesh, and R. Resmi, "Hybrid wind and solar based battery charging controller," in *Proc. Innov. Power Adv. Comput. Technol. (i-PACT)*, Vellore, India, Mar. 2019, pp. 1–5.

[18] R. S. Yendaluru, G. Karthikeyan, A. Jaishankar, and S. Babu, "Techno-economic feasibility analysis of integrating grid-tied solar PV plant in a wind farm at Harapanahalli, India," *Environ. Prog. Sustain. Energy*, vol. 39, no. 3, May 2020.

[19] S. R. Ara, S. Paul, and Z. H. Rather, "Two-level planning approach to analyze techno-economic feasibility of hybrid offshore wind-solar PV power plants," *Sustain. Energy Technol. Assessments*, vol. 47, Oct. 2021, Art. no. 101509.

[20] I. Mamia and J. Appelbaum, "Shadow analysis of wind turbines for dual use of land for combined wind and solar photovoltaic power generation," *Renew. Sustain. Energy Rev.*, vol. 55, pp. 713–718, Mar. 2016, doi: 10.1016/j.rser.2015.11.009.

[21] S. Shanghavi, W. M. Grady, and B. Schwarz, "Evaluating the impact of wind turbine shadows on an integrated wind and solar farm," in *Proc. 3rd IEEE PES Innov. Smart Grid Technol. Eur. (ISGT Europe)*, Oct. 2012, pp. 1–6.

[22] V. Hamsadhwani and S. R. Mohanrajan, "Optimal photovoltaic capacity planning for windfarm expansion," *Int. J. Eng. Adv. Technol. (IJEAT)*, vol. 8, no. 5, pp. 2126–2131, Jun. 2019.

[23] *Renewable Energy Cost Analysis: Wind Power. (N.D.)*. Accessed: Mar. 7, 2023. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/RE_Technologies_Cost_Analysis-WIND_POWER.ashx

[24] M. M. Riaz and B. H. Khan, "Techno-economic analysis and planning for the development of large scale offshore wind farm in India," *Int. J. Renew. Energy Develop.*, vol. 10, no. 2, pp. 257–268, May 2021.

[25] (2022). *Draft—National Repowering Policy for Wind Power Projects*. Accessed: Mar. 7, 2023. [Online]. Available: https://mnre.gov.in/img/documents/uploads/file_f-1666005996212.pdf

[26] *Consultative Paper for Issue of Tariff Order for Wind Energy and Related Issues*. Accessed: Mar. 7, 2023. [Online]. Available: https://www.tnerc.gov.in/PressRelease/files/PR-120320211500Eng.pdf

[27] S. N. Bureau. (Apr. 20, 2021). *Solar O&M Gets Set for the Big League in India*. Saur Energy International. Accessed: Mar. 7, 2023. [Online]. Available: https://www.saurenergy.com/solar-energy-news/solar-om-gets-set-for-the-big-league-in-india

[28] D. B. Carvalho, E. C. Guardia, and J. W. M. Lima, "Technical-economic analysis of the insertion of PV power into a wind-solar hybrid system," *Sol. Energy*, vol. 191, pp. 530–539, Oct. 2019.

[29] E. M. Barhoumi, S. Farhani, P. C. Okonkwo, M. Zghaibeh, and F. Bacha, "Techno-economic sizing of renewable energy power system case study Dhofar region-Oman," *Int. J. Green Energy*, vol. 18, no. 8, pp. 856–865, Jun. 2021.

[30] H. R. Rajaram, B. Krishnan, and B. Guru, "Leveraging on repowering of wind sites for potential wind-solar hybrid capacities: A case study," *Int. Energy J.*, vol. 21, no. 1, pp. 183–192, Mar. 2021.

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