Optimization of the Wind Farm Layout by Repowering the old Wind Farm and integrating Solar Power Plants: A Case Study

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Abstract- Most of the wind farms established in Tamil Nadu, India, in the early 2000s have reached the end of their targeted useful life. These turbines are colonized potentially wind-rich regions and either need to be dismantled or repowered. They are embedded in a 5Dx 7D arrangement, and large areas of underutilized land lie between them. The repowering of old turbines and the development of solar power plants on underutilized land between them would help to optimize the usage of existing infrastructure and natural resources. The primary purpose of this study is to support sustainable growth in the generation of wind turbines by repowering old wind turbines. The 6 Mega Watt (MW) old wind farm in Kayathar, Tuticorin District, Tamil Nadu, was chosen as the region of interest for this study. Based on data collection from January 2016 to December 2016, an average annual wind speed of 6.92 m/s at 120 meters and an annual Global Horizontal Irradiation (GHI) of 4.92-5.21 kWh/m2 /day was observed. Energy estimates have been made using the Wind Atlas Analysis and Application Program (WAsP) and the PVSyst software. Analytical results demonstrate that when modern wind turbines were supplemented with older, larger-capacity wind turbines, overall power generation increased from 3.50 Giga Watt-hour (GWh) to 40GWh at the P90 confidence level with a ratio of 1:1.25 to 1:3-fold generation ratio and an energy yield ratio of 1:1.61 to 1:7.82-fold. The combined repowered wind turbines with the integrated solar power system have demonstrated substantial increases in annual energy production in the vicinity of 38-76 GWh / year, suggesting the use of hybrid electricity as a reliable source

Keywords - Repowering; Hybrid Energy System; Capacity Utilization Factor; Wind Turbines.

1. Introduction

The wind farms in Tamil Nadu began to develop between 1985 and 1990. The Indian government offered various incentives, such as accelerated depreciation, capital subsidies, and Tamil Nadu Electricity Board (TNEB) supported for electricity wheeling from generation point to the industry, which allowed private developers to set up wind power plants for their captive use and sell electricity to the government electricity board, thus enabling the first wind farm project to be commissioned in 1991. The wind farm project was recognized by investors as a viable way of meeting energy requirements and as an economically feasible investment option. Almost all industrial houses in Tamil Nadu and investors from other states has come forwarded to set up wind farms in the state of Tamil Nadu. The state has led the development of wind power in India from the very beginnings. Since about March 2020, the gross installed capacity of wind power in Tamil Nadu is 8969 Mega Watt (MW) [1]. The wind farms established by the government at the beginning of the 1990s had the Wind Turbine Generator (WTG) rating between 55 Kilo Watt (kW) and 500 kW with a shorter hub height and a rotor diameter of about 30 meters. The WTGs endure 20 years in existence and 25 years of service. Since the wind turbines have been operational for over 20 years, their generation and Capacity Utilization factor (CUF) have been reduced to a very low level [2]. The WTGs were installed in high potential areas of wind power with obsolete parts, resulting in a substantial increase in maintenance costs and a decrease in the total generation (1.6% annually) [3]. These WTGs often experience high failure rates and a high maintenance demand and were likely to suffer from a shortage of suitable replacement parts (generator, gearbox, blade, etc.) by the end of their life. Several methods are available to address these problems, such as dismantling the turbine, refurbishing to improve turbine life and repowering. Repowering replaces low-capacity wind turbine generators with large wind turbine generators with advanced technology.

Tamil Nadu suffered a severe power crisis recently. Tamil Nadu's power deficit grew from 6.5 percent in the fiscal year ending 2011 to 17.5 percent in the fiscal year 2013; and the reasons were delays in setting up additional generation capacity (especially thermal plants to meet base load), transmission constraints between the rest of India, and rapidly increasing demand. Although this situation has dramatically improved in recent years, Tamil Nadu needs adequate action to ensure long-term energy stability.

National Institute of Wind Energy (NIWE), Ministry of New and Renewable Energy (MNRE), Government of India, assessed the country's wind and solar power potential. The country, as per the report, has tremendous wind and solar potential to meet energy demand. Wind and solar energy are well-known and widely distributed energy resources in India. Nevertheless, since the wind speed is unpredictable and seasonal, the absence of sunlight during the night and rainy season, a single source of energy is not reliable [4].

Wind and solar energy is typically used separately for electricity generation, but these resources have some limitations. This can be attributed to climate changes, solar radiation incoherence, and frequent changes in wind speed (highly variable with time and space), which affect the systems and their efficiency [5]. Moreover, when used together, the effects of wind and solar power are complementary. The convergence of these resources will resolve the respective problems and harness the maximum potential of renewable energy resources [6].

The balancing characteristics also help to smooth the load curve and improve the operational economy [7]. Onshore wind farms are spread around vast areas, with valuable land resources underutilized between turbines. Unused land between wind turbines can be used to install a solar PV plant. But the main limitation is the shadowing of wind turbines on solar panels. It is therefore important to quantify the area available for solar PV installations. A study was performed for the Kayathar wind farm to estimate the available surface area and the maximum energy that can be harvested. As the wind farm already has an electrical infrastructure to evacuate electricity, this infrastructure can be used to evacuate solar power from the solar park if it is installed between the wind turbines.

2. Literature Review

This chapter aims to emphasize various studies in the repowering of wind turbine/wind farm and the wind-solar hybrid system performed by different professionals.

E.Martínez et al. [8] investigated the repowering technique life cycle model of low capacity wind turbines. They also examined the benefits and possible environmental effects of the wind farm repowering process. One of the important findings was that wind turbines improved both in terms of efficiency and lifetime with repowering. They also discussed that repowering wind turbines with low capacity has important environmental advantages that should be taken into account for wind turbines that hit their end of life. Abdul Haseeb Syed Adeel Javeda et al. [9] researched the partial repowering of onshore wind farms, which have degraded under the influence of wakes from upstream wind farms. He concluded that repowering significantly increased wind energy production. The possible alternatives mentioned by Laura Serri et al. [10] for the future for wind farms nearing the end of their lives were decommissioning, revamping, and repowering. Because of its numerous advantages, the author believed that repowering was the best option. The advantages included better leveraging wind energy, decreasing the number of wind turbines, and avoiding further use of land. Mohit Goyalset al. [11] evaluated numerous repowering constraints in India, such as unsatisfactory tariff, uniform State laws, the lack of evacuation facilities, etc. w. While evaluating the wind energy market, they demonstrated the Indian wind energy scenario with repowering opportunities.

Antonio Colmenar-Santos et al. [12] stated that modern wind turbines would provide more energy, benefiting the electricity sector. An exploratory study by R.Villena-Ruiza[13] indicated that the annual output of energy for a wind farm was increased twice when new machines with equivalently capacity were used for old wind turbines. Anish, Paul, et al. [14] observed that partial repowering is more profitable than the reconstruction of the wind farm as a whole. Different technical impacts on the hub height and the wider wind turbine rotor have been quantified and measured by Roberto Local Arantegui et al. in the case of repowering [15]. The author concluded that the new turbines in repowering projects with twice the hub height, thrice the rotor diameter, and nine times the sweep area produced nine times more electricity compared to the earlier and old machines. L.Castro et al. [16] concluded that the replacement of old wind turbines was more efficacious in the production of wind energy and that the cost of investment could be recovered within five years. JH Piel et al. [17] performed a feasibility assessment of the repowering and life extension of wind turbines. The challenges for the optimal life extension have also been studied. The technical evaluation was performed by J.C.Vicente- Ramırez et al. [18] and the results demonstrated that the repowering project yielded adequate productivity, with the payback period being less than six years. Diego B.Carvalho et al. [19] examined the implementation and economic analysis of the wind farm of PV plants. The findings demonstrate that a wind farm was economically viable on its own; the incorporation of PV power to the wind farm decreased the chances of positive NPV profitability. The possibility of business improved when these two mechanisms were integrated.

Vikas Khare et al.[20] addressed the Wind – Solar Hybrid System analysis covering the facets of the pre-feasibility research, simulation, control, optimization technique, reliability and device power quality. This paper further explores the application of evolutionary technology and game theory to the development of a hybrid renewable energy system. Pragya Nema et al.[21] investigates the state-of-the-art stand-alone PV Solar – Wind Hybrid system architecture, design, operation, control and its significance in providing load power to the optimally designed controller and enhanced performance, how energy costs can be reduced along with load demand management across the year.Fatih Onur Hocaoglua et al. [22] reviewed the architecture, operation, and control characteristics of stand-alone solar hybrid energy systems and conventional sources. They found that solar and wind power systems are complementary, and the implementation of the grid network has resulted in a cheaper and efficient renewable power hybrid system. Sirengo Khisaa Ryohei et al. [23] addressed wind & solar measurements and hybrid systems grid connection.

A wind-solar thermal (heat) hybrid method has been developed to reduce wind power constraints by Zeyu Dinga et al. [24]. They Simulated optimization model focused on an optimization algorithm for particle swarm to maximize economic efficiency. The case study showed that the hybrid system achieved the highest net present value when the power ratio increased, and also decreased carbon dioxide emissions. The author concluded that the overall reliability of the device improved; the electric heater effectively minimized wind curtailment.Ghassan Halsa et al. [25] discussed power generation from a wind-solar hybrid system and correlated electricity generation costs with conventional power generation, solar power plants, and power plants, asserting that wind generation was the lower price. Authors have addressed the significance of modern power electronics, with their respective control algorithms playing a crucial role in the the reliability of the integration of renewable energy into the national grid. Hybrid power maximisation utilising MPPT control algorithms and how the p-q principle is used to control active power and reactive power, and the power factor was also discussed.. K.Boubaker et al. [26] describes the development of the Wind-Solar Hybrid system with an accurate assessment, planning and an efficient protocol to identify an optimal location on the basis of the resource capacity and the transmission network. This chapter investigates the weighted grid and the Boubaker Polynomials Expansion Scheme (BPES) protocols to evaluate the possible usage of renewable energy sources and to define the optimal location for the usage of these hybrid plants. A.B.Khamees et al. [27] reviewed wind-solar hybrid efficiency and performance and observed solar energy made a large contribution compared to wind power production. Neha Sengupta et al. [28] have developed a probabilistic approach utilising parametric and non-parametric estimation techniques to capture the variability and periodicity of renewable energy resources for the effective allocation of land to the Hybrid Power System. With the aid of Homer Software, Peter Jenkins, et al. [29] examined a hybrid power generation system performance and concluded that the hybrid system is more efficient. The new wind-solar hybrid system has been developed by Olawale Olaniyi Emmanuel AJIBOL et al. [30]. A multi-turbine wind-solar system has been tested, and the findings compared with the reference system and concluded that the multi-turbine system generated more energy.

Verma and Ahmed et al. [31] used the Wind Atlas Analysis and Application Programme (WAsP) program and concluded that the repowering of old wind turbines is a reasonable strategy. The authors also emphasized that as the construction period of wind turbines is shorter, environmentally friendly, and economical, Wind energy was found to be favorable. Romano and Mennel et al. [32] evaluated the repowering of offshore wind farms in terms of optimization parameters. The authors used the various capacities of the wind turbines for repowering. The authors concluded that repowering is better than refurbishing. Roberto Lacal-Arántegui et al. [33] explored the wind turbines repowering option (or wind farms) and a wide assortment of benefits. They concluded that the repowering of old wind turbines enhanced the performance and production of electricity and the usability of parts of the current substation.

Sawle et al.[34] addressed the architecture of hybrid systems, modelling, selection of renewable resources, criteria for hybrid system optimization, control mechanisms and descriptions of the software used for optimal sizing. This paper provided a detailed case study demonstrating that the PV-Wind – Battery – DG hybrid system offers an ideal cost and emission approach for the different Hybrid system configurations and also addresses over 25 technical methods for optimised Hybrid system sizes. Yeah, Barakat, S. et al.[35] recommended an integrated optimal solution for the Hybrid system with a multi-objective system size, considering the reduction of energy costs, the reduction of Green House gas emissions and the effective usage of renewable resources. A case study of the PV-Wind Hybrid system connected to the grid was conducted in a remote rural village in Egypt. Performance in ideal system size is obtained by applying a multi-objective particle swarm optimization algorithm (MOPSO). The developed algorithm supports load-side demand management by seamlessly transferring power from the designed Hybrid device to the grid, covering the fiscal, environmental and renewable energy usage aspects.

Naveen R. et. al. [36] presented an overview of the renewable energy systems integration that has been carried out in different literature studies. The optimal techniques that can be utilized to attain the energy optimization using various kinds of integration systems. This study also revealed the challenges in management and integration of renewable energy systems. PV-WIND shows as the most combinations suggested in literature works. This review article provides better insight for the understanding and feasibility of different combinations of renewable energy systems integration.

The benefits and challenges of integration of renewable energy sources in smart grid is clearly defined in [37]. It also focuses on the requirements of suitable control based strategies to be considered in grid and converter control systems.

In this work [38], two techniques Particle Swarm Optimization (PSO) and Adaptive Neuro Fuzzy Inference System (ANFIS) based on soft computing is used to improve the performance of Maximum Power Point Tracking (MPPT). The ANFIS technique has proved the best results and more robust when compared to other techniques. ANFIS method can be used to extract the optimum generated power and it's flexible in search space.

The prediction of wind energy generation using profiles of wind speed and different components simulation of the wind plants with synchronous generator. In this the wind speed is computed as fixed average wind speed around the whole rotor and considered the number of towers used and also the rotational turbulence [39].

This work [40] illustrates the study of grid connected wind power system that has parallel wind turbines, collection lines and transformers that affects the power system stability. Analysis has been carried out for 120 km and 30 km transmission lines having wind speeds of 11 m/s and 6 m/s respectively. The experimental results revealed that the power generation increases when the wind speed and also length of the transmission line increases.

The impact of wind speed and temperature on photovoltaic modules such as power, voltage, current, serial and shunt resistances as well as its performances is shown in [41]. The efficiency of solar cells has been varied not only because of temperature and solar irradiance also by the wind speed and humidity. To maintain the effective operation of the solar panels, the mutual impacts of humidity and wind should considered. It primarily helps in maximum power point tracking control for the solar panels.

This work considered the dynamic analysis of integrating the solar PV systems in to the grid system in OMAN [42]. The solar PV power consumed and generated differs throughout the year, this could benefit the load forecast and optimal use of generated power. It also helps to find out the best time to buy or sell the electricity. Analysis has been carried out using both non-cloudy and cloudy days.

The literature review was carried to distinguish the various outcomes and challenges plaguing wind power generation and wind & solar energy hybridization. It is also worth noting here that based on our knowledge, there were no studies talked about solar power plants incorporation between repowered locations. This infographic attempts to address this gap.

3. Power Scenario in Tamil Nadu

3.1. Wind Resource

At 31-03.2020, the state's installed wind power capacity is 8969MW [1], which would be about 24 % of India's total wind power capacity. The windy regions of Tamil Nadu are situated on the western side of the state.

3.1.1 Wind data Measurement

Wind resource assessment is necessary to identify potential wind sites for the large-scale deployment of WTGs. In 1985, the Government of India initiated an assessment of wind resources and has installed approximately 968 meteorological masts across India [43] to date. NIWE has installed approximately 70 numbers of wind monitoring stations in Tamil Nadu and an estimated 33.7 Giga Watt (GW) [44] of installable wind power potential at 100m Above Ground Level (AGL).

3.1.2 Wind Power Development in Tamil Nadu

The several incentives implemented by the government of India to establish wind power projects for their captive use and also to sell power to utilities. Tamil Nadu has been leading the development of wind power since the early days and continues till date. The year-wise installed wind power capacity in Tamil Nadu is shown in Table 1.

3.2. Solar Resource

NIWE has established Solar Radiation Resource Assessment (SRRA) stations at 115 locations and gathered ground-based solar measurement data since about 2011. As of 31 January 2020[1], the total installed solar power capacity in the country amounts to 3973.98 MW.

Table 1: Year Wise Wind Installed Capacity in Tamil Nadu

Year	Cumulative Installed Capacity in MW (as of March 2020)
Up to March 2007	3492.75
2007-08	3873.42
2008-09	4304.52
2009-10	4906.72
2010-11	5904.40
2011-12	6987.70
2012-13	7162.30
2013-14	7269.70
2014-15	7455.20
2015-16	7614.00
2016-17	7861.60
2017-18	8197.20
2018-19	8969.00

Source: Indian Wind Power Association (IWPA)

4. Technical Analysis: Case Studies:

4.1 Plant identification for repowering and wind-solar hybrid system Wind Resource

Tamil Nadu is among the nation's high-wind states with a wind power density of 200-600W /m^2 [45]. The Tamil Nadu State Repowering Guidelines for the Installation of Wind Turbines is released in 2019 by Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO) [46]. The research study site is situated at one of the best wind-ridden locations in Tamil Nadu and has the first generation wind turbines owned and managed by NIWE and Tamil Nadu Energy Development Agency (TEDA).

The complete data used in this research study were obtained from the NIWE and TEDA data bank (wind and solar measurement data). The database includes information about wind and solar monitoring station data, geographical co-ordinates of WTG's, modality of the turbine, capacity rating, rotor diameters, hub heights, start-up date, etc. The average yearly generation of energy for the existing wind turbines was obtained from TEDA.

4.2. Wind and Solar Regime at Kayathar Site

4.2.1 Kayathar-Site Description

The study area is situated in the Tuticorin district of Tamil Nadu, with connectivity to the road and other services. The site has an operational meteorological mast of 120 meters height (latitude: 8 ° 57'43.79 "N and longitude: 77 ° 43'12.53 "elevation: 88.08 m Above Mean Sea Level (AMSL)). The site is considered homogeneous and is primarily covered by small trees and bushes.

4.2.2 Wind Characteristics of Region of Interest

The analysis was performed on the basis of the 120 m high mast time-series wind data of the Kayathar for the period January 2016-December 2016. Multi-level wind speeds were measured at 120 m (N&S), 90 m, 60 m, 30 m, and 10 m AGL, and wind direction were measured at 120 m, 90 m and 60 m AGL. After appropriate quality checks, the wind data was used for the Annual Energy Production (AEP) estimation. Figures 1 and 2 depicts the wind characteristics of the Kayathar site at 120 m, respectively. Figure 1 indicates that the prevailing wind direction at the site is from the West, with an average annual wind speed of 6.92 m/s at the height of 120 m, with the most frequent wind speed (Figure 2) being 3.5 m/s.

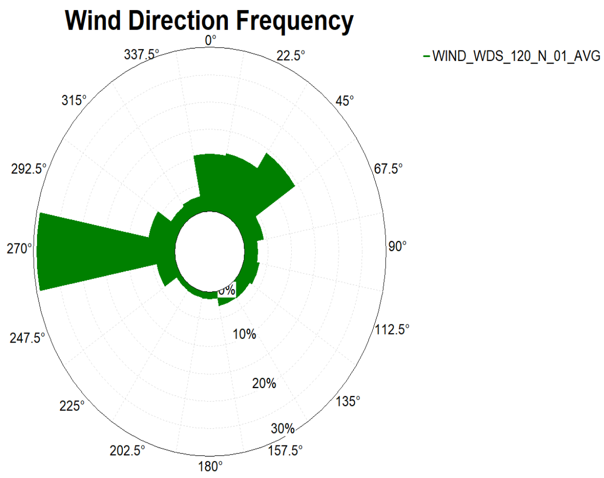

Fig.1. Wind Rose (120m)

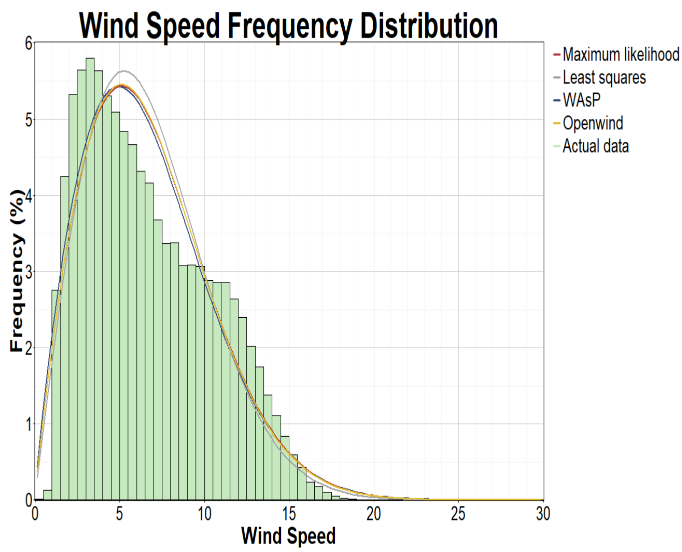

Fig.2. Wind Speed Frequency Distribution

4.2.3. Solar Characteristics of Kayathar Region

The Kayathar region has an annual Global Horizontal Irradiance (GHI) of 4.92-5.21 kWh /m^2/day according to NIWE measurement. Strong solar irradiance is present at the site from March to September, thus providing the maximum energy for the PV system. The diurnal solar characteristic is, as shown in Figure 3.

Table 2. Monthly solar irradiance data from the Kayathar site

Months	GHI (kWh/m^2)	Diffused Horizontal Irradiation (DHI) (kWh/m^2)	Direct Normal Irradiation (DNI) (kWh/m^2)	Wind Speed (m/s) @ 6 m	Temperature (°C)
Jan	167	83	143	2.97	26.51
Feb	217	76	226	3.07	27.21
Mar	202	90	164	2.38	29.26
Apr	225	124	143	3.66	32.05
May	209	118	130	4.72	31.11
Jun	224	112	163	8.1	30.32
Jul	222	116	150	8	30.49
Aug	204	120	107	6.56	29.64
Sep	208	88	162	4.42	28.76
Oct	189	96	138	4.34	29.56
Nov	152	86	104	2.54	27.04
Dec	158	83	124	2.27	26.23

Source: NIWE

The average monthly solar radiation of 3 distinct parameters, wind & temperature data was collected from NIWE's ground-based measurement repository. Table 2 presents the monthly average statistics.

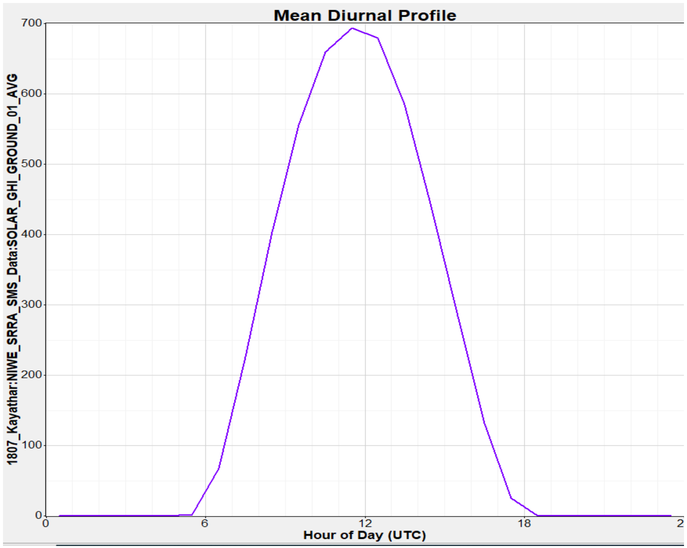

Fig.3. Diurnal GHI profile of Kayathar site

4.2.4. Schematic Layout of Wind Farm

The study wind farm operates 15 km west of Tuticorin, and the layout comprises 30 numbers of 200kW wind turbines, one number of 2000kW, and one number of 600kW WTGs. Tables 3 & 4 outlines the technical specifications and functional requirements for the old wind turbine. Figure 4 illustrates the topology of the existing wind farm.

Table 3. Technical Specification of 200 kW WTG

Description	200 kW
Make	Micon
Rated Output(kW)	200
Hub Height(m)	29
Rotor diameter(m)	24
Type or Regulation	Stall
Generator Type	Induction

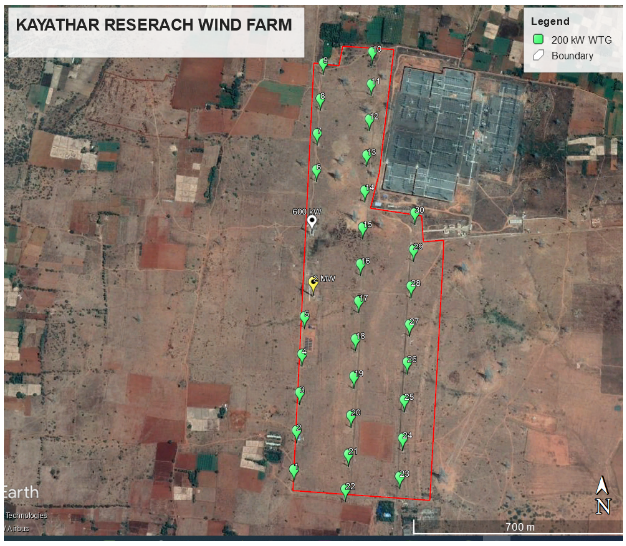

Fig. 4. The layout of Kayathar wind farm (Google map)

Table 4. Generation And Performance Details

Month	Generation kWh	Total generation kWh	CUF %
Apr-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		

Source: TEDA/TNEB

5. Methodological approach

The technique used throughout the repowering procedure is given in this section.

a) Selection of suitable site for the research work.

b) Collection of wind and solar measurement data, geographical co-ordinates of wind turbines and wind farms power generation from the National Institute of Wind Energy data banks and wind turbines power and thrust curve from public domain process wind data measurements from the Project site,

c) Process wind data measurements from the Project site, Clean and perform quality checks of data

d) Analyze the wind and solar characteristics of the site data using Excel, Windographer.

e) Preparation of contour map with Global mapper and performing wind flow modeling using WAsP software

f) Carrying out energy estimation using the existing wind turbines

g) Carrying out micro siting by replacing an existing old wind turbine with new advanced wind turbines.

h) Estimating Annual Energy production (AEP)

i) Compare existing technical information with new/advanced wind turbines

j) Configuration of solar panels between existing and new micro-site layout

k) Carrying out a shadow analysis of all the different configured layouts by using Google sketch up and Google Earth Pro

l) Estimating energy generation from PV Syst software for solar power plant

m) Analysis of all energy output and effectiveness assessment

6. Repowering Analysis and Results

6.1. Micro-siting analysis and WAsP results

6.1.1 Turbine Data

The repowering analysis was carried out on the basis of NIWE 120 m wind data. For the repowering analysis, different capacity wind turbines (as per Revised List of Models and Manufacturers (RLMM)) have been considered based on average rotor diameter and average capacity, as shown in Table 5 (The rotor diameter between 30 m and 132 m) considered in this project). The energy estimate tables discussed in this article have been added in order to obtain a basic understanding and not to recommend any particular turbines or manufacturers. Different turbines of the same rotor diameter may generate higher energy, but this study does not include a detailed energy analysis. Data for all turbines are considered with normal power and thrust curves of 1.225 kg / m3 air density.

6.1.2 Repowering Layout of the wind farm

The efficient and effective construction of wind farms depends on two key aspects: the expected energy output from turbines and the available land. The spacing of the turbines should be considered during operation; the wind turbine creates a conical wake in the downwind direction. The wind turbine installed in this wake region tends to produce less power, and the proper arrangement of wind turbines is therefore essential for the wind farm. Wind turbines on flat terrain are usually positioned somewhere between (4Dx8D) and (5Dx7D) (5 times the rotor diameter in the same row and 7 times the turbine diameter in the next row) in the direction that perpendicularly to the predominant wind direction. The existing layout and repowered layout of 200 kW of wind turbines are shown in Figures 5 to 9. The wake loss percentage was taken into consideration less than 10% in this study to obtain an optimized repowering layout. This value was considered in accordance with the onshore wind energy development guidelines. No. F.No.66/183/2016-WE Ministry of New Renewable Energy [47].

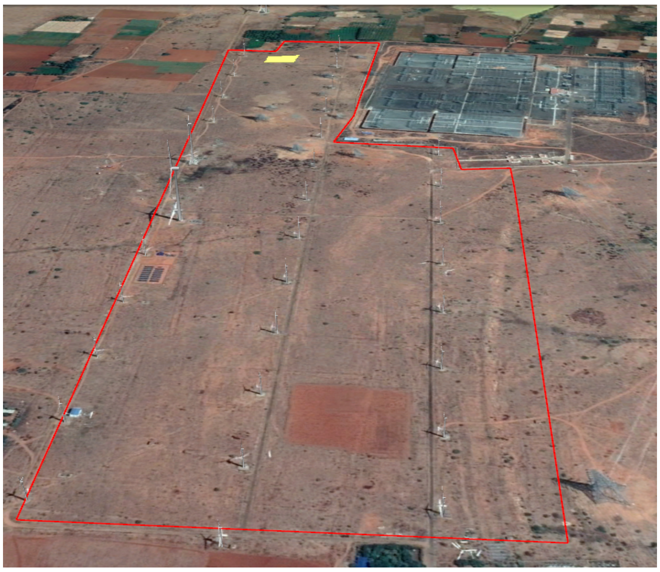

Fig. 5.a. The repowering layout of existing operational Kayathar wind farm (Google map)

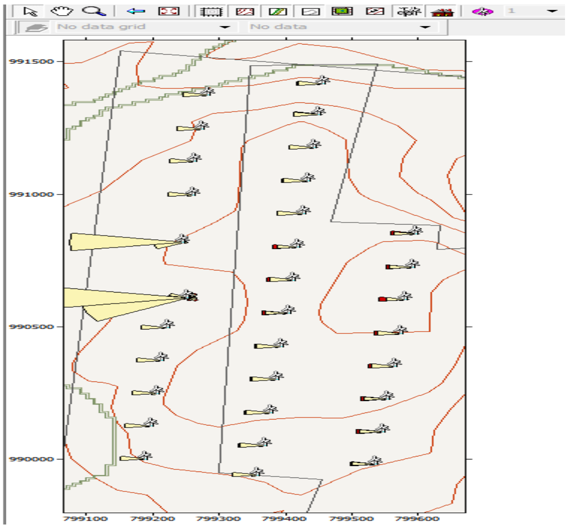

Fig. 5.b. The repowering layout with wake loss roses (Using WAsP tool)

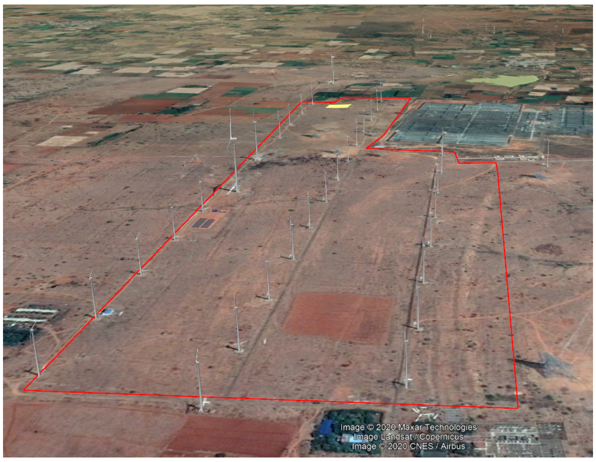

Fig. 6. Layout of one-on-one wind turbine substitution for 200 kW with 250 kW capacity at exactly the same co-ordinates (Google map)

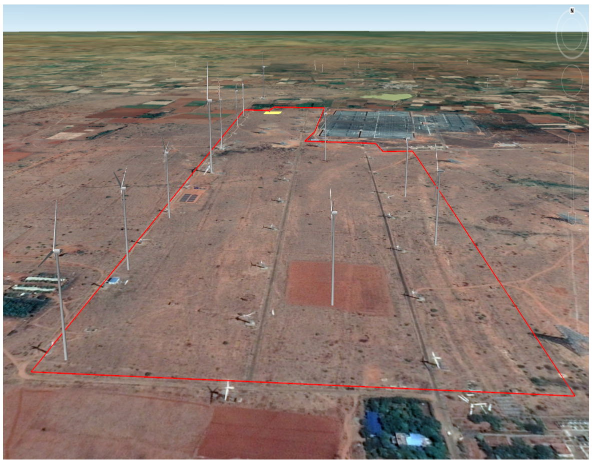

Fig. 7. Layout of substitution of old 200 kW wind turbines with a capacity of 850 kW wind turbine (Google map)

Fig. 8. Layout of substitution of old 200 kW wind turbines with higher capacity wind turbine 2700 kW (higher hub height and longer blades) - (Google map)

Fig. 9. Layout of substitution of old 200 kW wind turbines with higher capacity wind turbine 3000 kW (higher hub height and longer blades) (Google map)

6.1.3. Micrositing Analysis

For micro-siting analysis, an industry-standard software, the WAsP model (version 12.4), was used, and the Wind Atlas technique was used to generate the spatial wind environment in that region. The most significant inputs for this computer software were the location-specific wind resource details, topography details, and the wind farm layout (WTG co-ordinates). In order to optimize the old wind farm layout, to minimize wake losses, to guarantee safety for the neighbouring construction, and to optimize the use of the existing grid and logistic infrastructures, WTG positions were evaluated. Using the WAsP model, it would be possible to accurately create energy generation from different configurations (Figures 5-9), turbine sizes, and hub heights once the models have been set up. After considering standard corrections and uncertainty factors, the final results have arrived. The findings revealed that the region suggested had large wind power densities at higher height.

6.1.4. Annual Energy Estimation (AEP)

Table 5 summarizes the energy estimate from seven different capacities of wind turbines at different levels of confidence (probability of exceedance) at the research site.

Table 5. Annual Energy Estimation of the various capacities of wind turbines at a different confidence level

S.NO	Name of the WTG (As per RLMM list)	Rotor Diameter (m)	Hub height (m)	Capacity (kW)	wake losses %	P50 [GWh]	CUF %	P75 [GWh]	CUF %	P90 [GWh]	CUF %
1	WTG 1	30	50	250	8.47	0.362	16.55	0.338	15.44	0.316	14.45
2	WTG 2	58	65	850	5.63	1.73	23.23	1.62	21.74	1.52	20.4
3	WTG 3	87	85	1500	5.37	4.47	34.04	4.18	31.88	3.93	29.94
4	WTG 4	111	120	2100	5.85	6.71	36.48	6.29	34.21	5.91	32.1
5	WTG 5	122	127	2200	5.86	6.95	36.02	6.52	33.83	6.13	31.81
6	WTG 6	132	130	2700	6.32	8.46	35.79	7.93	33.55	7.46	31.54
7	WTG 7	125	120	3000	6.36	8.71	33.16	8.17	31.09	7.68	29.23

Table 6. Repowering Capacity & Repowering Capacity Ratio

S.NO	Name of the WTG (As per RLMM list)	Rotor Diameter (m)	Hub height (m)	Capacity of WTG (kW)	Repowering capacity	Repowering Capacity ratio	Repowering energy ratio
1	WTG 1	30	50	250	7.50	1.25	1.61
2	WTG 2	58	65	850	7.65	1.28	2.32
3	WTG 3	87	85	1500	10.50	1.75	4.67
4	WTG 4	111	120	2100	12.60	2.10	6.02
5	WTG 5	122	127	2200	13.20	2.20	6.24
6	WTG 6	132	130	2700	16.20	2.70	7.60
7	WTG 7	125	120	3000	18.00	3.00	7.82

The mean annual level of power generation varies from 3.16 -76.8 lakhs kWh/per WTG at P 90 level, with CUF 14.45-29.23 percent estimated from the 250 kW-3000 kW rating machine in this region. This factor should really be changed according to the actual grid availability, availability of Machines, etc. In addition, the Row x Column spacing is used only for the predominant wind direction in order to bring for an optimized repowered layout. Table 6 presents the repowering ratio for different configurations and different turbine capacity. The repowering ratio was based on the existing capacity installed. On the basis of the study of various capacities between 250 kW and 3000 kW, the capacity increased from 1.25 – 3.0 times. Accordingly, the energy yield ratio has increased from 1.61 to 7.82 times.

6.1.6. Power Evacuation System

The new wind-solar hybrid system is proposed to be connected to the 110/33-11 kV Ayyanarathu Substation.

7. Solar Photovoltaic panel (SPV integration) with WTG

The solar plant was integrated into the wind farm, repowered location of the wind farm to optimize the layout and enhance energy harvest. However, the incorporation imposes a constraint that the shadow of the wind turbines falls on the solar panels during the daytime. When the turbine rotor rotates, it sheds shadows, and frequent changes in the Solar Photo Voltaic (SPV) production were initiated. This could result in the loss of energy generation. Shadow analysis was performed for the sun's annual and daily movement. The availability of shadow-free areas to place solar panels is thus essential to be estimated. The Kayathar wind farm was considered in repowering locations with 50 m, 65 m, 85 m and 120, 127 and 130 m of hub height—the area of the study comprised flat and open topography. The areas excluded in the locations addressed were highways, HT towers, and structures. The other significant exclusions in the area were located in each wind turbine. The exclusion of this field gives the SPV installation reasonable space in that area. The shading effect outside this area was expected to be too diffusive. The proposed solar technology was monocrystalline (Silicon (Si)) because its efficiency and lifespan (foreseen at least 25 years) were reasonable in comparison with other technologies. In estimating the energy yield from the solar plant, PV Syst software was adapted. In this study, in four cases, Shadow Analysis was carried out. The first was the energy generation calculation with the wind turbine; the second was to substitute wind turbines one by one with a higher hub height. The other two cases involved the removal and replacement of the existing wind turbines by new greater power machines and the installation of high hub wind turbines and the deployment of solar plants between the wind turbines. These scenarios are discussed and then swap-off among dependent variables such as annual energy production, CUF, and energy generation per square meter area.

7.1. Estimation of Power Output from the Solar Plant

After a shadow analysis, the total area available for the solar panel systems and solar power capacity was evaluated in four scenarios. It was presumed that a $10m^2$ area was required to build 1kW of the solar panel. In Figures 10-13, the red colour line shows the boundary line of the wind farm, while the yellow colour shows the shadow region of the wind turbines.

Case 1: Estimation of solar power capacity and energy generation where Wind Turbines are already existing.

After performing a shadow analysis of the existing old wind turbines (Figure. 10), this scenario showed that the total shadow-free surface available was 385108 m^2. The shadow region of the wind turbines was estimated to be 181730 m^2. From this shadow-free zone, 38 MW of solar power plants can be installed and operated.

Fig. 10. Shadow Area of 200 kW Wind Turbines

The net energy production is estimated using PV Syst software after taking account of the various losses dependent on the determined data of solar radiation. The total power output from the 38 MW solar power plants is 62625.52 Mega Watt-hour (MWh) /year. Table 7 displays the monthly electricity production.

Table 7. Month Wise Energy Generation for Case 1.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Year**
Energy Generation (MWh)	5059	5177	5955	5388	5700	5338	5296	5647	5655	4978	4085	4344	**62625**

Case 2: Wind turbine repowering one to one scenario by incorporating solar plants

Old wind turbines are substituted in this scenario by modern wind turbines of 250 kW (Figure 11) at the same location. The totally free of shadows available in this scenario is 214840 m^2. Solar plants may be installed in the shadow-free region of 21.4 MW. Solar plants may be installed in the shadow-free region of 21.4 MW. The net energy generation from the 21.4 MW of solar power plants will be 35268 MWh / year.

Case 3: Re-powering wind turbines with higher capacity machines (2700 kW) with solar plant integration

Under this scenario, aging wind turbines are supplemented by modern wind turbines with taller hub height and larger blades of 2700 kW capacity. In the same location (Figure 12), a minimum of 228125 m^2 shadow-free region is possible, and a maximum solar power capacity of 22.81 MW could be installed. After consideration of different losses from the 22.81 MW solar plant, the net energy would be 37595 MWh / year.

Case 4: Re-powering wind turbines with higher capacity machines 3000 kW with solar plant integration

Old wind turbines are bolstered in this case by modern 3000 kW wind turbines. (Figure.13) at the same location. The estimated usable shadow-free region is 219213 m^2 and the estimated solar power that can be installed is 21.92 MW at the same site. Total electricity generation from the 21.92 MW of solar plants is 36,127 MWh per year.

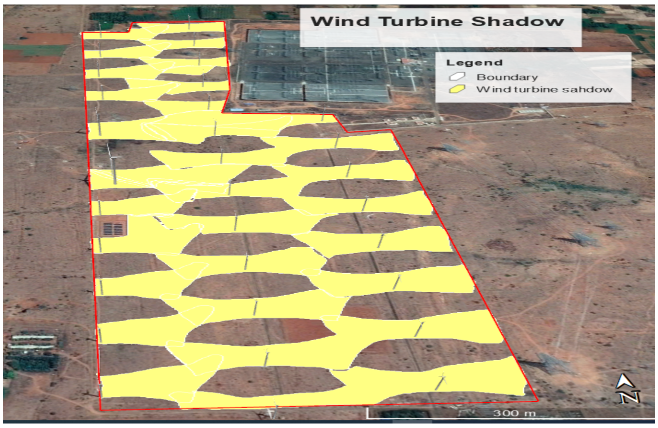

Fig. 11. Shadow Area with the Proposed 250 kW Wind Turbines

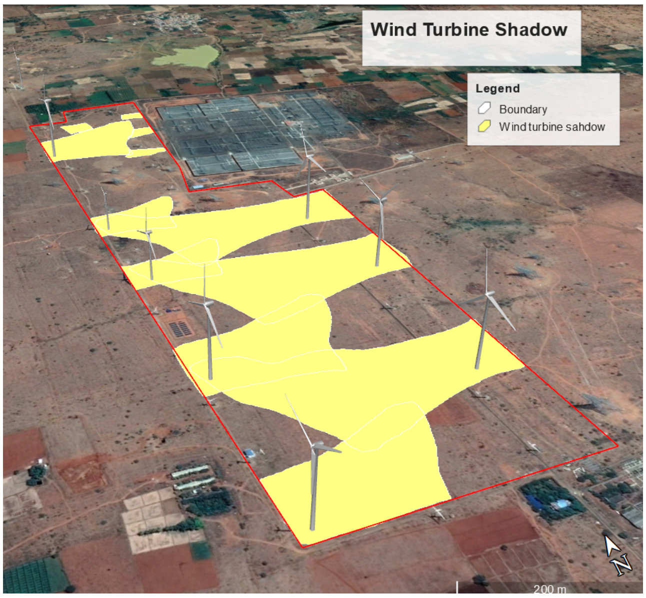

Fig. 12. Shadow Area with Proposed 2700 kW Wind Turbines

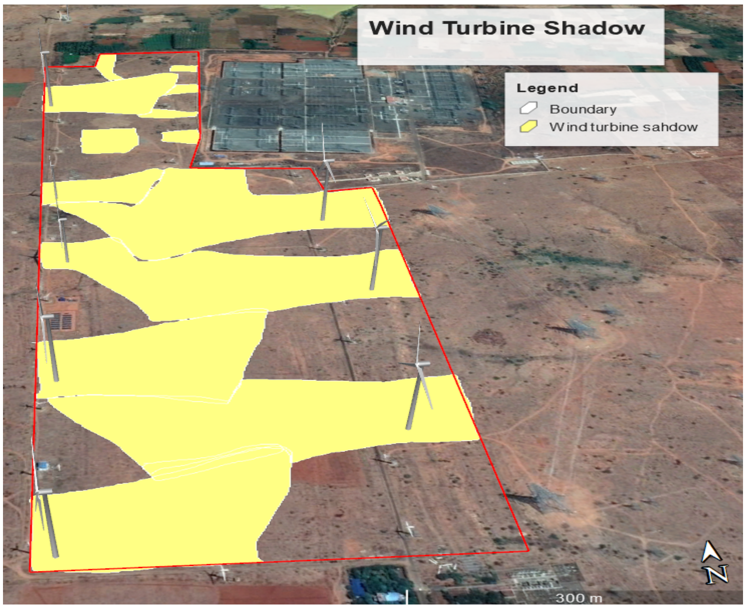

Fig.13. Shadow Area with the Proposed 3000 kW Wind Turbines

7.2. Analysis and discussion

The study found that the installation of solar power plants between the wind turbine and inside the existing old operating wind farm boundary increased the plant capacity from 21 to 38 MW and thus enhanced the energy ratio from 1:4.75 to 1:7.33. The outcomes are shown in Table 8.

Table 8. Hybrid Power Generation

Scenario	WTG	Hub height (m)	Shadow free area (m^2)	Installable Solar Power MW	Energy Generation form Solar GWh	Total capacity MW (W+S)	Total Capacity Ratio	Energy Generation from wind GWh	Total Energy Generation (W+S)@ GWh	The ratio of energy generation increment
1	WTG 0	27	385108	38	62.63	44.0	7.33	5.89	68.52	11.63
2	WTG 1	50	214840	21	35.41	28.5	4.75	9.48	44.89	7.62
3	WTG 6	130	228125	23	37.60	39.2	6.53	44.76	82.36	13.98
4	WTG 7	120	219213	22	36.13	40.0	6.67	46.08	82.21	13.96

@ W – Wind @ S – Solar

The study reveals that the current operating/old wind turbines develop less shadow areas but would support a more potential of solar power plants. For one to one wind turbine substitution, sheds lesser shadow area, and the power ratio increased to 1:4.75 times. While substituting the existing layout machines with higher capacity wind turbines (2700kW and 3000 kW), the larger turbine sheds a wide shadow region (Figure 11 and Figure 12), but increasing the total capacity ratio by 1:6.5 times. The hybrid wind-solar power plant can generate electricity in the 44.89-82 GWh range and the generation ratio is rising by 14 fold.

8. Conclusion

This study examined the location of repowering wind turbines integrated with a solar power plant and how they influenced the production of energy, infrastructure, and land-use optimization. A 6 MW wind farm situated at Kayathar was chosen as the investigation region. The statistical analysis shows that when the old wind turbines are completely dismantled from the site and substituted by new /advanced technology and higher hub height turbines, the overall electricity production increased from 3.59 GWh to 40.19 GWh at confidence level P90 with an increase of repowering capacity ratio by 1.1.25 to 1:3 times with an energy yield ratio by 1:1.61 to 1:7.82 times.

This study also looked at the integration of solar plants between wind turbines within the existing operating/repowered wind farm. In the case of one to one wind turbine substitution, the overall hybrid power ratio is enhanced by 1:4.75 times, when the increase in the capacity of the wind turbines (2700 kW and 3000 kW) with larger rotor diameter, the average hybrid power ratio increased by 1: 6.5 times, indicating the effective resource use of hybrid energy.

The findings also reveal that since wind power generation in this study area is from May to September, and since all old wind turbines generate an 8 percent Capacity Utilization Factor, by utilizing the proposed wind-solar integrated method, the underutilized resources can be exploited to the maximum. However, a thorough study of the load flow needs to be carried out.

Further research:

An additional area of investigation is going to be the evaluation examination of the load flow study for other generations from the repowered wind farms and solar power plants, and its financial aspects, necessary to know if market-driven repowering / hybrid projects are able to achieve socio-economic benefits to society.

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Data Availability

The authors confirm that the data supporting the findings of this study are available within the article. However, the raw data that underpin the results of this study are available at the National Institute of Wind Energy https://niwe.res.in/department_r&d,rdaf_time_series_data.php. "As per the policy & guidelines, data provided to parties would be for their exclusive use only, and under no circumstances, these data reproduced/transferred to other agencies either electronically or in physical form."

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