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Design and Performance Analysis of a Grid-Connected Distributed Wind Turbine

Mahtab Murshed [1,*], Manohar Chamana [2], Konrad Erich Kork Schmitt [1], Rabindra Bhatta [1], Olatunji Adeyanju [2], and Stephen Bayne [1]

[1] Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX, USA;
[2] National Wind Institute, Texas Tech University, Lubbock, TX, USA
* Correspondence: mahtab.murshed@gmail.com; Tel.: +1 (806) 642-1719

Abstract: The utilization of wind energy has become increasingly popular in the United States and many European countries due to its abundant natural source and optimized design. While existing wind turbines are predominantly large-scale and not suitable for standalone or distributed power production, Lubbock County in West Texas offers a diverse range of renewable energy options to meet its energy needs. The region relies heavily on utility-scale wind energy sources to supply power to the Texas Grid, replacing conventional fossil fuel-based systems. Currently, standalone solar PV systems are the preferred choice for renewable energy generation. However, West Texas possesses an ample supply of wind energy that can be harnessed to establish a microgrid and provide standalone power to rural communities. By employing the latest technology and optimizing efficiency, even in low-scale generation, a 6 kW permanent magnet alternator-based distributed wind turbine has been designed. This paper focuses on analyzing the techno-economic aspects of implementing this wind turbine in a real-world scenario, taking into account wind attributes such as velocity and available power at the specific location.

Keywords: renewable energy; wind turbine; emission reduction; techno-economic; permanent magnet alternator

1. Introduction

To improve the socio-economic growth of a country, sustainable and energy-efficient delivery to end-users will play a key role. Several countries are looking into transforming their energy infostructure depending on the natural resources availability while ensuring grid stability [1,2]. At present, most of the world's energy is generated from fossil fuel-based power plants, which negatively impacts our environment [3–5]. The technique of converting fossil fuel to electric energy directly increases the ozone layer depletion rate with frequent acid rain [5,6]. Besides these impacts, several harmful chemicals now imbalance the ideal ingredients ratios of air available for fresh breathing [7]. As per the report from global energy generation, a large amount of renewable-based electricity generation can directly minimize the use of fossil fuel generators [8–15]. However, the renewable energy conversion technique has a very low impacts on the environment compared to fossil fuel-based system, its totally negligible and produce fully cleaner energy because of cleaner natural sources [16–20]. When compared to large-scale central renewable energy plants, smaller-scale renewable energy systems in microgrids and/or distributed energy systems have less or almost no negative impacts on the environment [21,22]. A common example of this is the small-sized off-grid rooftop solar system. In Texas, however, after wind, solar has good prospects to improve the overall percentage of renewable energy-based electricity generation [23]. Energy generation from wind has been a common trend. In the past, the kinetic energy from wind has been used for propelling ships, irrigational purposes, pumping water, windmills, and so on. Currently, the use of kinetic energy of wind is predominantly used for generating electricity efficiently [24–26]. To obtain higher efficiency from wind energy generation, the minimum average wind speed required is around 6.5 m/s. But in the context of West Texas, the average wind velocity is around 8.5m/s [27]. These available average

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wind speeds can be used in harnessing power from larger-scale wind energy as well as creating opportunities for distributed and/or standalone wind turbines, particularly in rural communities and ranches [28]. Although at present, standalone wind turbine technology has a lower possibility of commercialization and availability compared to solar and diesel generators [29,30]. However, several recent research indicates increased energy development trends for off-grid small-scale wind energy in the Texas coastline regions with attractive economic benefits [31]. Texas is home to several rural communities and traditional ranches which receive electricity from electric co-operatives. The electric co-operatives are looking into integrating distributed energy resources in their service territory, as well as providing incentives to their members to participate in virtual power plant programs [32–35]. High-speed distributed wind energy systems could be developed in the West Texas community with a high potential for power production. Various types of small family-owned farms and ranches are established in these areas, and most of them are currently using diesel/natural gas generators for backup [36]. Although a few wind turbines have been designed efficiently, they have not been widely installed and operated due to economic factors and poor performance during natural disasters [37]. Figure 1, Shows the current and upcoming wind farm establishments in Texas.

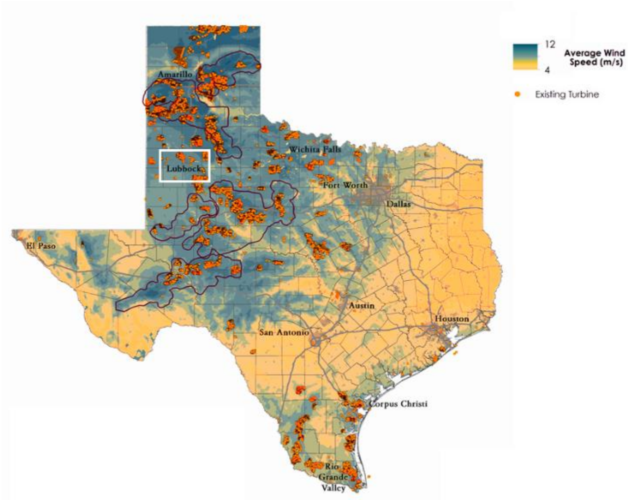

Figure 1. Wind map of Lubbock, TX.

In modern times, using the latest technology design is essential for harnessing wind energy in the high wind-speed regions to improve the overall performance and longevity of the system [38]. Two of the most common integration of wind turbines are microgrid-based and standalone wind turbines as a distributed energy resource [39]. Generally, a wind energy system has three main blocks for energy conversion: turbine blade system, coupling mechanism between blade and rotor, and rotor system [40]. However, the coupling gear system is not mandatory in the low-speed system because of its lower efficiency and higher cost with greater noise production and regular maintenance [32]. To build a high-speed standalone higher efficient wind energy system, the research focus is usually on the design of turbine blades and permanent magnet alternator (PMG). Several types of blade foils are already implemented in NACA and NREL line-ups; however, they are not suitable for every location. Considering that numerous NACA foil is used to analyze NREL because of greater availability, less maintenance, and cost-effectiveness for a small-sized wind turbine blade system [26–32]. Taking weather diversity into account, different types of foils are analyzed. Besides blade foil analysis and blade design, this research focuses on the system's cost-effectiveness and resiliency improvement. Grid resiliency refers to the ability of a power grid to withstand and quickly recover from disruptions such as power outages, natural disasters, or cyber-attacks. Figure 2 shows the statistical causes of grid outage in the US.

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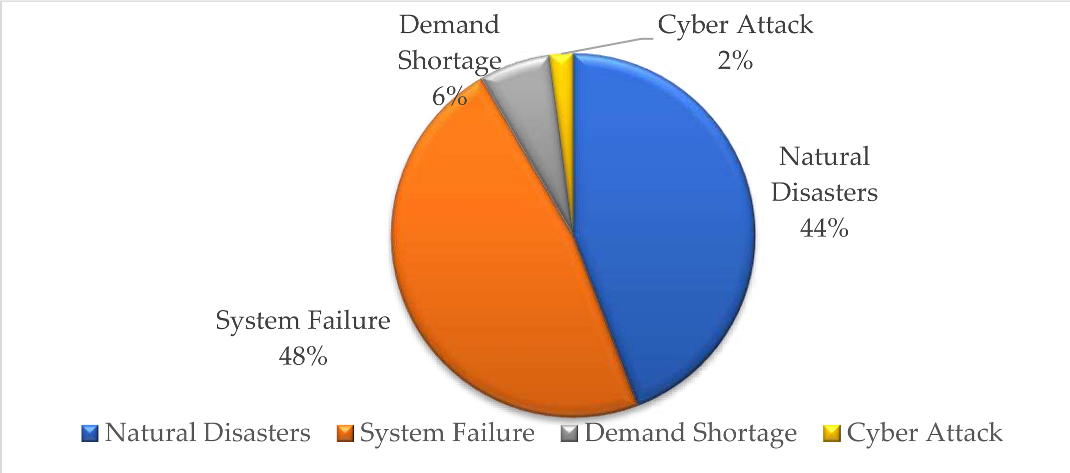

Figure 2. Statistical causes of outages.

A resilient power system is essential for ensuring the reliable and secure delivery of electricity to homes, businesses, and other customers [40,41]. There are several key factors that contribute to the resiliency of a power grid, including diversification of energy sources, such as wind, solar, hydro, and natural gas, which can help to reduce the risk of power outages by reducing dependence on any one source [42–45]. Grid modernization or upgrading the power grid with smart grid technology, such as advanced sensors and control systems, can help to detect and respond to disruptions more quickly and effectively [46]. Adding energy storage systems, ESS, such as batteries, can store excess energy during periods of low demand and release it during periods of high demand, helping to maintain stability in the grid [47]. Redundancy and backup systems, such as backup generators, in place, can help to ensure that power can be restored quickly in the event of an outage, also by protecting the power grid from cyber-attacks through the use of secure networks and other cybersecurity measures is essential for ensuring its resiliency [42–44]. Building a resilient power grid requires a combination of technical and operational measures to ensure that the grid can withstand and quickly recover from disruptions [45]. This will help to maintain the reliability and security of the power grid and ensure that electricity is delivered to customers when and where it is needed [46,47]. Microgrids and modern smart grids are often considered the best solution to improve resiliency and overall efficiency.

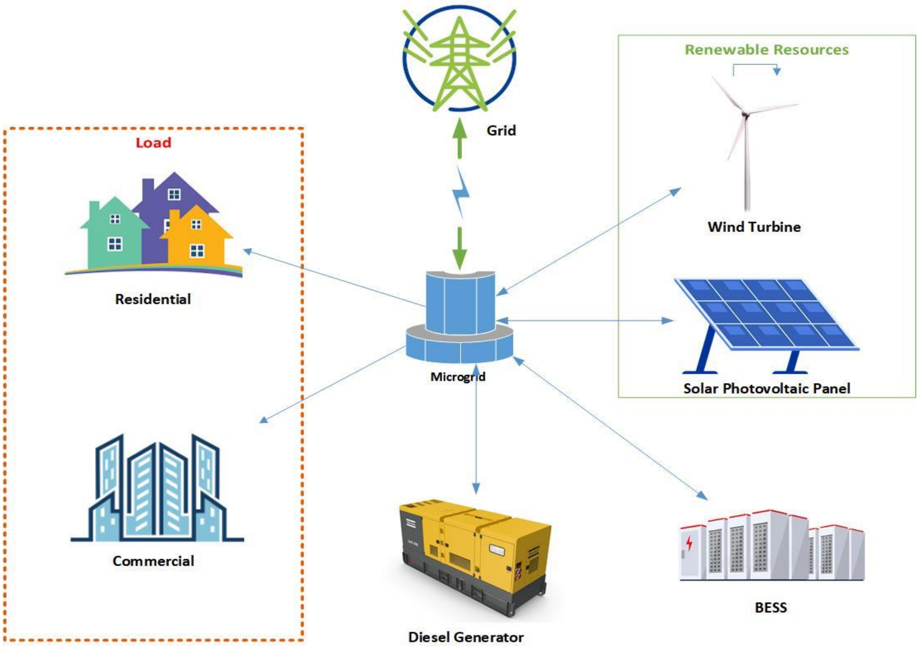

Figure 3. Schematic of a standard grid-connected microgrid.

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Microgrids are often defined as a local energy grid with distributed generation, energy storage, and possibly load management capabilities [47–50]. It operates as a separate entity from the traditional centralized power grid and can function both connected to the main grid and disconnected (island mode) [51]. Microgrids are designed to provide reliable and resilient power supply to critical loads, communities, and infrastructure [48]. They can be composed of various energy sources, such as renewable energy resources, fossil fuel-based generators, and energy storage systems [52]. A standard microgrid schematic is shown in Figure 3.

Taking these limitations into account, the targeted outcomes of this research work are to analyze the wind scenarios in Lubbock, TX, and develop the available wind power suitable for a cost-effective distributed wind system that can work effectively and efficiently work as a distributed energy source to improve resiliency.

2. Wind scenarios in Lubbock

Lubbock is one of the largest cities in West Texas. The metropolitan area of Lubbock, TX, has a population of over 330,000 [42–46]. Due to its economic, academic, and healthcare growth, Lubbock has been labeled the "Hub City." As part of the National Wind Institute (NWI) research center at Texas Tech University (TTU), the city has become a wind energy research and technology hub with multiple ongoing research projects [41]. On the other hand, Reese Technology Centre (RTC), a research facility located in a former US Air Force base by Texas Tech University (TTU), collaborating with West Texas Mesonet, is consistently collecting wind and solar data to explore the renewable potential of west Texas [54–56]. They are studying the performance of large-scale turbines under typical wind conditions and the applications of wind energy as a distributed energy resource. A historical data analysis was conducted during this study. Figure 4 shows the average monthly wind speed data of Lubbock, TX.

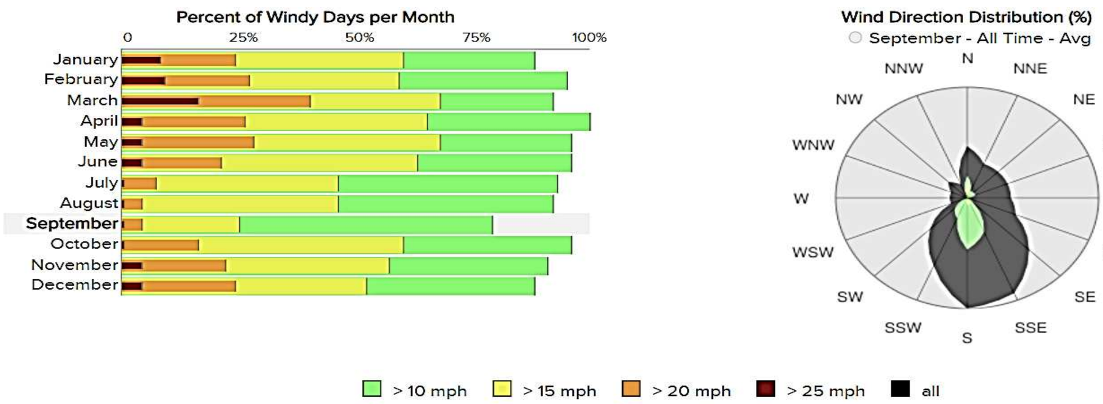

Figure 4. Annual wind speed data and wind direction of Lubbock, TX.

2.1. Data analysis

The primary objective of studying wind data in this area is to examine the average wind speeds along with maximum and minimum wind speeds in different seasons to calculate the wind energy potentials. Texas Mesonet uses an anemometer to measure the available wind velocity at 10 meters from the ground. The Weibull view of recorded data is shown in Figure 4, where the mean wind speed is around 26 mph or 11.62 m/s, and the maximum velocity is 32 mph or 14.3062 m/s, which is well over the average required for conventional distributed small-scale wind power generation.

2.2. The optimum height for maximum wind velocity

Since the research's primary goal is to improve our utility grid's overall resiliency by integrating more distributed wind turbines to households in Lubbock, TX, the height we considered is within the standard limit for a suburban area [15].

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According to a wind power law, the wind speeds can be calculated at any reference point as [19,23,24],

$$v = v_0 \left(\frac{h}{h_0}\right)^{\alpha} \quad (1)$$

Where v= wind velocity, v_0= wind velocity at height of reference, h = height (measured) and h_0= height (reference) and α = frictional coefficient. In a small town or suburban city, the frictional coefficient is α=1/3=0.33 equation (1). At the proposed 100 feet height, the wind velocity can be found as,

$$\mathrm{v} = v_0 \left(\frac{h}{h_0}\right)^{\alpha} = 11\ ms^{-1} \text{ (Yearly average)}$$

A Histogram of the MESONET site data at 10m height is shown in Figure 5.

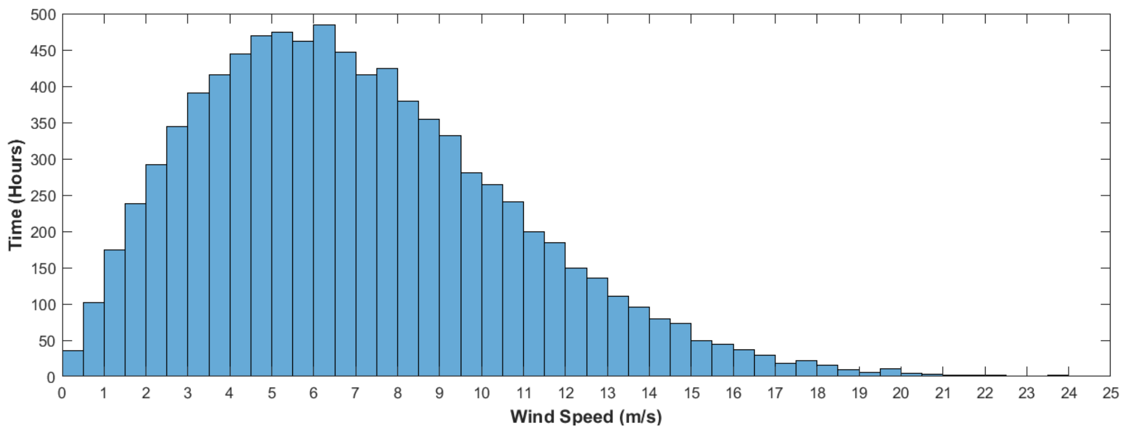
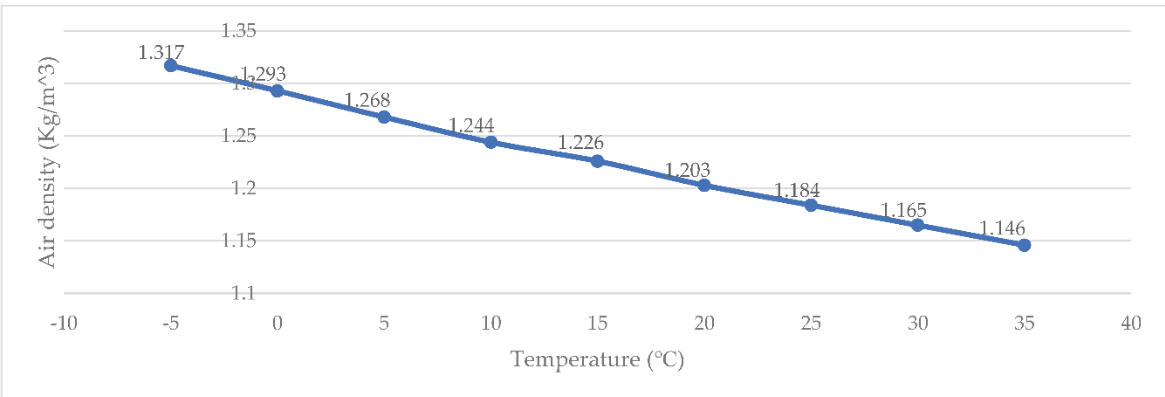


Figure 5. Collected wind speed data histogram for Lubbock, TX.

2.3. Air Density

Air density plays a significant role in wind power generation, which changes with the change in temperature [19]. The average temperature (°C) at the Lubbock region is 28°C or 82F. The air density value changing at different temperatures are listed in Figure 6 [19,25].



Relationship between air density and temperature.

2.4. Maximum Power Calculation

As Betz Law states, for wind power extraction, over 59.3% kinetic energy extraction is not possible for any wind turbine system. Maximum available power can be calculated using this law [19,22], which is given by,

$$P_{available} = \frac{1}{2}\rho A v^3 C_P \qquad (2)$$

Where swept area (rotor blade) A =πr^2 and Betz limit coefficient C_p= 0.37. Considering the maximum output power of the low-speed turbine, $P_{available}$=6 kW (Desired), height (pole) = 20 meters, blades count = 3, radius of the blade swept area, r = 2.5 meters. Hence, the blade's swept area will be $A = \pi r^2 = 19.635$ m^2. As founded the wind velocity from section III.B, v = 12 m/s or 18mph and density of the air, ϱ = 1.165 kg/m^3 for the generalized temperature of 30°C or 86F, the theoretical maximum accessible power for 6000 Watts output power (desired) will be found from eq. (2) as

$$P_{available} = \frac{1}{2}\rho A v^3 C_P = \frac{1}{2} \times 1.165 \times 19.635 \times 12^3 \times 0.40 = 6202.46\text{W} \approx 6kW$$

With available power and wind velocity, a suitable turbine blade can determine which will be quite efficient for the particularly planned case.

In consideration of the swift area of 19.635 m, efficiency can be obtained as,

$$Efficiency, \eta = \frac{\textbf{Total extracted power}}{\textbf{Available energy}} \times 100 = 77\%$$

3. Design of 6 kW Wind Turbine

Before building a wind turbine system, whether it is a small or large size, there are some major factors that decide the design procedure of the system.

3.1. Blade design

A standalone wind turbine with a maximum capacity of 6 kW has been simulated using NACA 2101 airfoil. Figure 7. shows the pressure distribution on the selected airfoil. After choosing the airfoil, an analysis of airfoil pressure distribution and polar extrapolation was conducted. Airfoil pressure distribution refers to the distribution of pressure around the surface of an airfoil as it moves through the air. The pressure distribution is a crucial factor in determining the lift and drag forces acting on the airfoil, which in turn determines its performance.

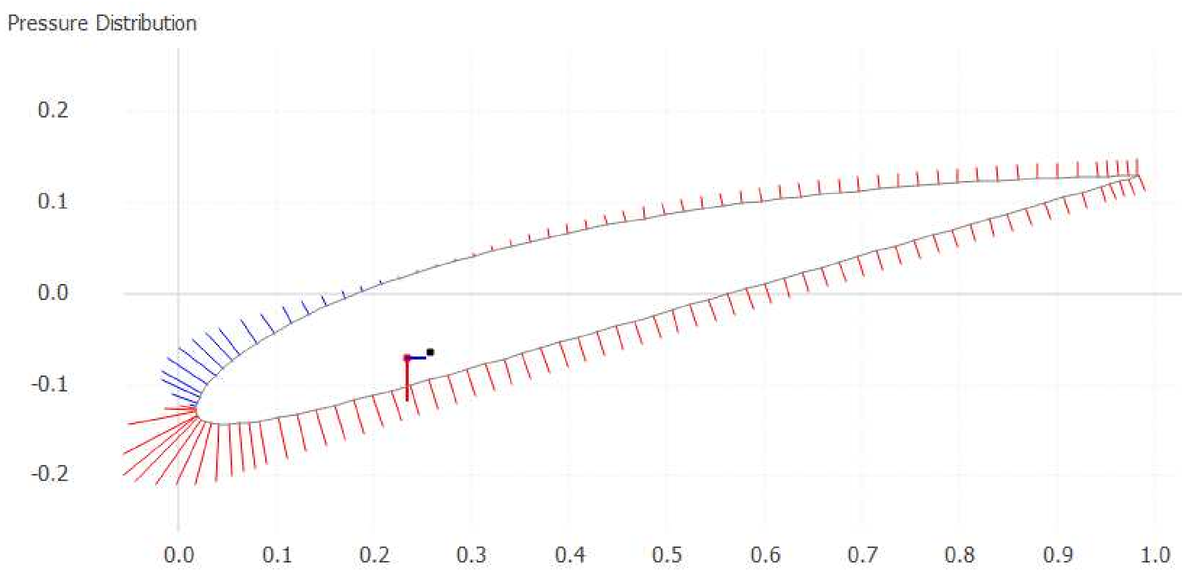


Figure 7. Airfoil pressure distribution.

Airfoil polar extrapolation is a method used to predict the performance of an airfoil at different flight conditions based on its lift and drag characteristics. An airfoil polar is a graph that shows the lift coefficient (Cl) on the vertical axis and the drag coefficient (Cd) on the horizontal axis for a given

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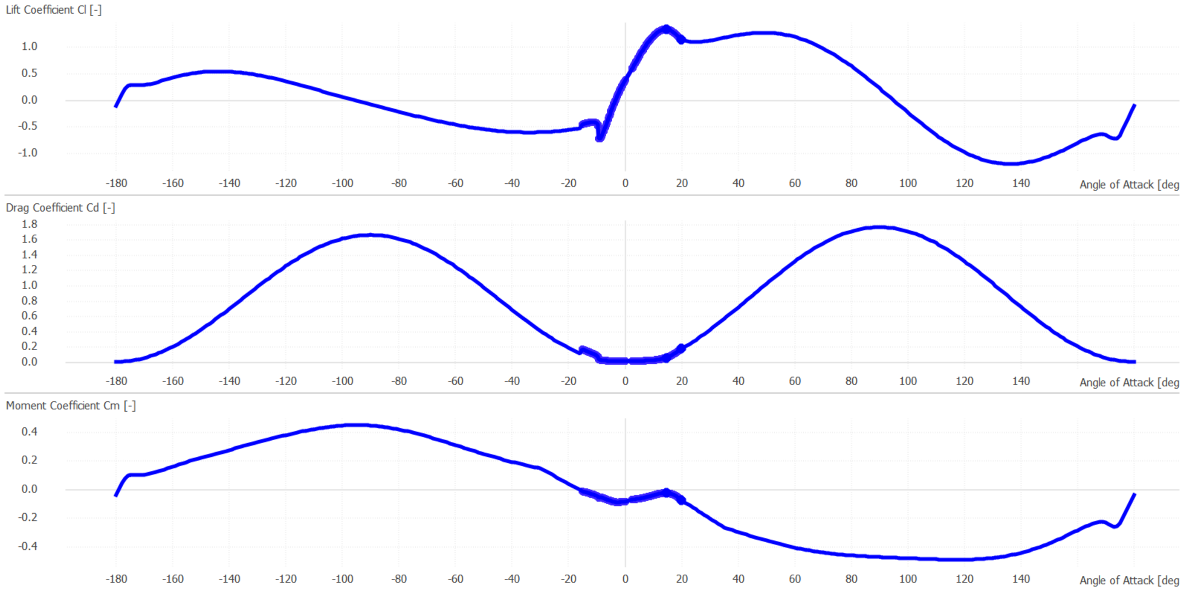
airspeed and angle of attack (AoA). The polar is generated by testing the airfoil in a wind tunnel using the computational fluid dynamics (CFD) simulations performed on Qblade software.



Extrapolated Lift (Cl), Drag (Cd), and Moment (Cm) coefficient

Figure 8. shows the extrapolated scinarios for lift coefficient Cl, drag coefficient Cd, and moment coefficient Cm of a 360 degree angle of attacks with chosen airfoil.

The chord of a wind turbine blade is the distance from the leading edge (the front of the blade) to the trailing edge (the back of the blade) [12]. The chord length is one of the most important geometric parameters in blade design, as it affects the blade's aerodynamic performance and structural efficiency [19]. Longer chords generally result in greater lift and lower drag but also require more material, making the blade heavier and more expensive. The thickness of a wind turbine blade is the distance between the upper and lower surfaces of the blade. Blade thickness affects the blade's stiffness and strength, as well as its aerodynamic performance [12]. Thicker blades are generally stronger but also have a greater drag due to the increased thickness of the boundary layer of air around the blade [12]. The twist of a wind turbine blade refers to the change in the angle of attack along the length of the blade. Blade twist is an important design parameter that affects the blade's performance and load distribution. The twist is typically designed to be greater near the root of the blade and to decrease towards the tip so that the blade can maintain a relatively constant angle of attack along its length, even as the speed of the airflow changes with blade radius. Figure 10 shows the blade chord, thickness, and twist properties.

Considering the parameter from Figure 9, the final blade design shown in Figure 10 is achieved by considering the wind turbine blade chord, thickness, and twist as important design parameters that affect the blade's aerodynamic performance, structural efficiency, and load distribution. Optimal values for these parameters are determined through a combination of computational simulations using Qblade, with the goal of achieving maximum energy capture with minimal loads and structural stresses.

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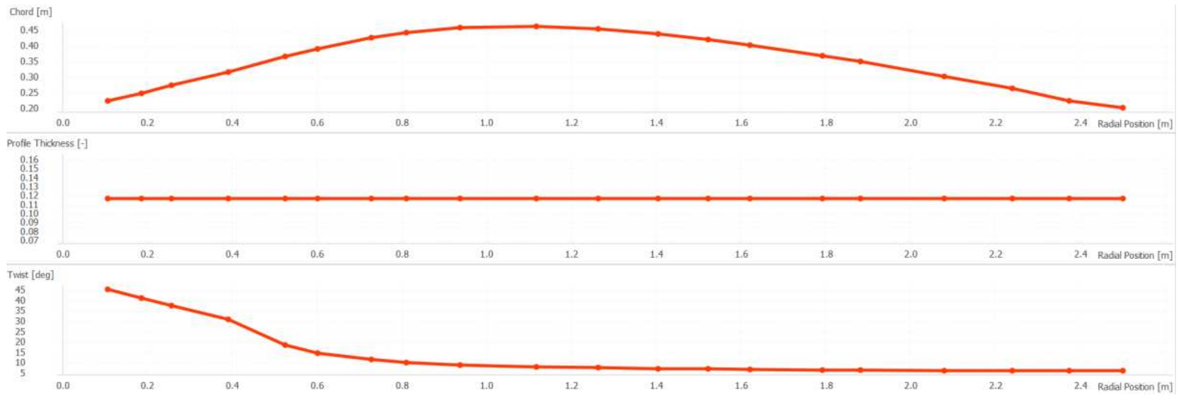

Figure 9. Blade chord, thickness, and twist properties.

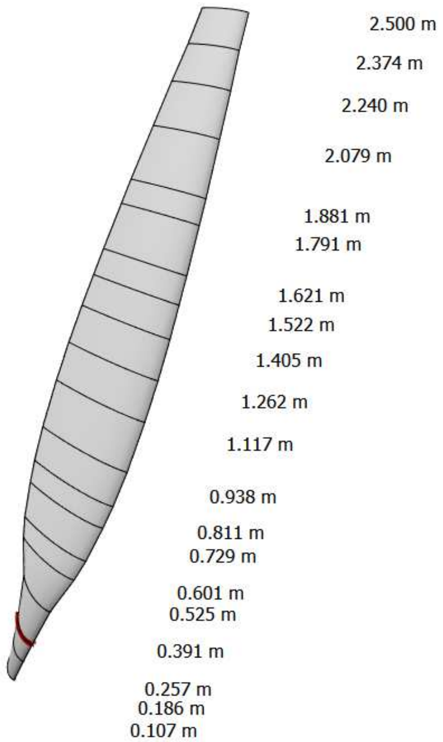

Figure 10. Design of turbine blades.

3.2. Permanent magnet alternator

THHN and TFFN are two types of electrical wiring that are commonly used in PMA construction. THHN stands for Thermoplastic High Heat-Resistant Nylon-Coated and is a type of single conductor electrical wire [57,58]. It is rated for 600 volts and 90°C and is designed to withstand high temperatures. TFFN, on the other hand, stands for Tinned Copper Stranded Flexible Fixture Wire. TFFN wire is similar to THHN wire but is designed to be more flexible and is commonly used in applications where the wire needs to bend or be manipulated easily. TFFN wire is also rated for 600 volts and 90°C and is made from tinned copper [59]. When it comes to winding, THHN and TFFN can both be used for winding applications, depending on the specific requirements of the application. THHN wire is generally used in applications that require a more rigid wire, while TFFN wire is used in applications that require a more flexible wire [58,60]. Since durability and lower maintenance are one of the design goals, THHN winding wire was selected for the design. In order to calculate the number of poles the rotating machine equation has been used.

$$S_{Rated} = \frac{120\times f}{N} \quad (3)$$

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Where S_{Rated}, f, and N are rated , frequency, and number of poles, respectively.

Apart from that, to generate maximum energy, a bigger magnetic field is required to make the generator more compact. Which has been derived from,

$$\phi_g = B_{av} \times \left(\frac{\pi \times D \times L}{P}\right) \quad (4)$$

Where ϕ_g= magnetic flux, B_{av}= flux density (average), D= stator diameter (inner), L= stator length.

Figure 11 shows the 3D design of the permanent magnet alternator, where the detailed designed parameters are given in Table 1 for the desired output.

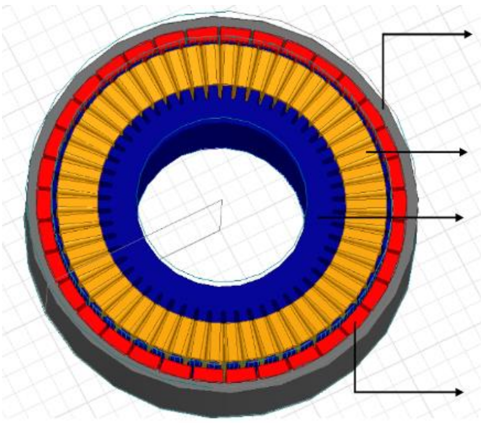

Figure 11. 3D presentation of designed permanent magnet alternator.

Table 1. Major parameters for the designed PMA.

Parameters	Value
Rated power (Pout)	6500 W
Reference speed (N)	100 rpm
Voltage (V)	24 V
Permanent magnet depth (LPM)	10.0 mm
Stator slots amount (Q)	54
Poles (P)	34
Air-gap (g)	1.0 mm
Stator diameter (outer) (S_{out})	208 mm
Stator diameter (inner) (S_{in})	92 mm
Stator length (L)	61 mm
Rotor diameter (outer) (R_{out})	292 mm
Rotor diameter (inner) (R_{in})	270 mm

4. Result analysis

Distributed wind turbines, also known as small wind turbines, can bring several economic and resiliency benefits to communities [51]. Some of the key advantages are cost savings by generating their own electricity; communities can reduce their dependence on the grid and lower their energy bills. This can be particularly beneficial for remote or rural communities, where energy costs are often higher; distributed wind turbines can provide communities with a source of renewable energy that is not dependent on the larger grid. This can help to increase energy security and reduce the risk of power outages [51,61].

4.1. Power Generation

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To calculate the economic and resiliency benefits, two cases were compared. In both cases, a small community load profile is considered with an average daily load demand of 100 kWh and the highest peak demand of 10.62 kW, as shown in Figure 12.

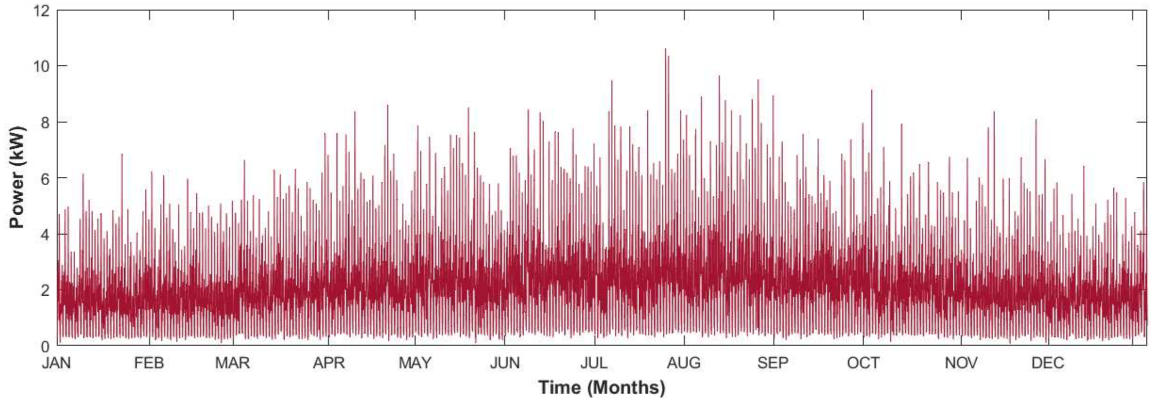

Figure 12. Considered load profile for economic and resiliency benefit analysis.

A comprehensive demand analysis was conducted for commercially available battery and system converter size consideration, the peak monthly load demands are shown in Figure 13.

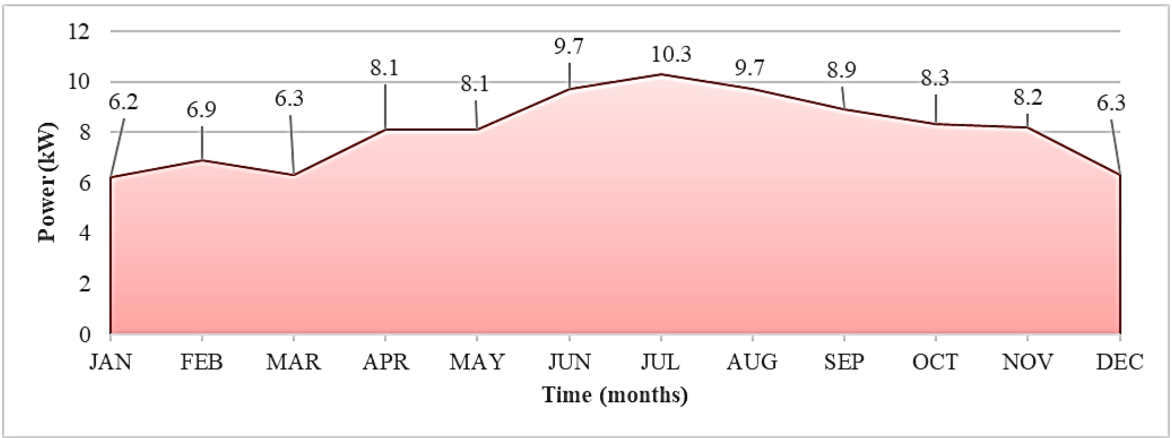

Figure 13. Monthly peak demand curve.

Both base case and proposed case system architectures are shown in Figure 14. Where case 1: grid-only mode, considering only utility as the sole supply source to the load. However, case 2 consists of a 6 kW grid-connected distributed wind turbine with a 47.1% capacity factor, 20 kWh Li-ion batteries as a storage system, and an 8 kW system converter. The Li-ion battery has an expected lifetime of 17 years by the manufacturer, where the overall analysis period is 25 years. Therefore, a replacement battery has been considered for the 17th year. The detailed information on the proposed system is tabulated in Table 2.

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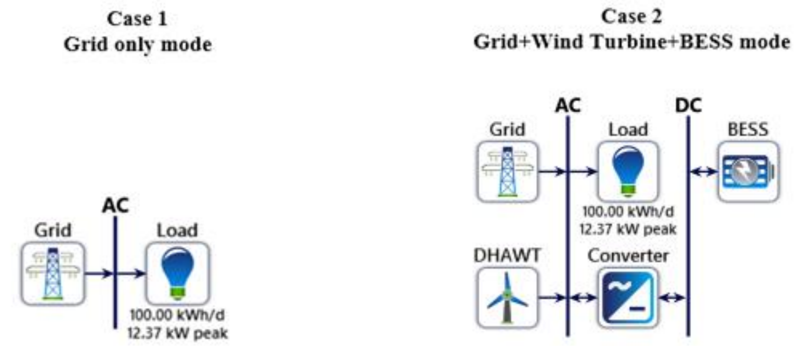

Figure 14. System architectures to determine the economic benefits and resiliency period.

Table 2. Distributed energy resource summary.

Distributed Wind turbine			Battery			System Converter		
Quantity	**Value**	**Units**	**Quantity**	**Value**	**Units**	**Quantity**	**Value**	**Units**
Total Rated Capacity	6	kW	**Energy In**	2,965	kWh/yr	**Hours of Operation**	8,374	hrs/yr
Mean Output	2.83	kW	**Energy Out**	2,865	kWh/yr	**Energy Out**	23,848	kWh/yr
Capacity Factor	47.1	%	**Storage Depletion**	18.8	kWh/yr	**Energy In**	24,586	kWh/yr
Total Production	24,757	kWh/yr	**Losses**	119	kWh/yr	**Losses**	738	kWh/yr
Wind Penetration	67.8	%	**Annual Throughput**	2,924	kWh/yr	**Capacity**	8	kW
Hours of Operation	8,253	hrs/yr	**Autonomy**	4.63	hr	**Mean Output**	2.72	kW
Levelized Cost	0.035	$/kWh	**Expected Life**	17	yr	**Maximum Output**	8	kW

4.2. Resiliency analysis

To evaluate the resilience of a power grid, time series analysis can be a useful tool. Time series analysis involves the statistical modeling and Analysis of data that is collected over time, with the goal of identifying patterns, trends, and anomalies [62]. A time series analysis has been conducted to determine the resiliency period for the proposed system shown in Figure 15. The maximum resiliency time for the proposed system is 16 hrs, as calculated.

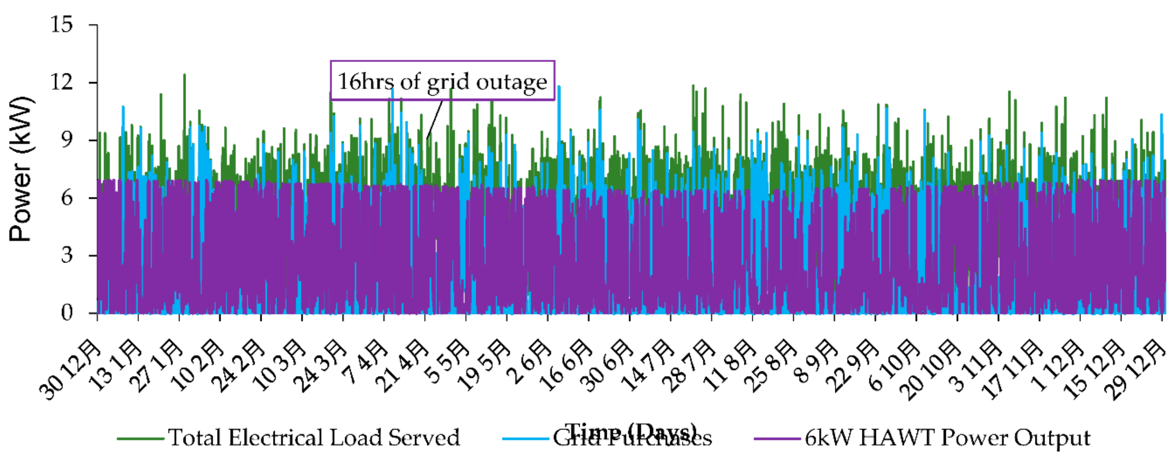

Figure 15. Time series data of DER connected proposed system.

Figure 16 issulstrates the battery state of charge during the 16 hours of outage where no load priority has been considered. In the beginning of the outage the battery state of charge was 83% where towards the end of the outage it went to 5% as the battery minimum charge state was declared 5% on HOMER Pro.

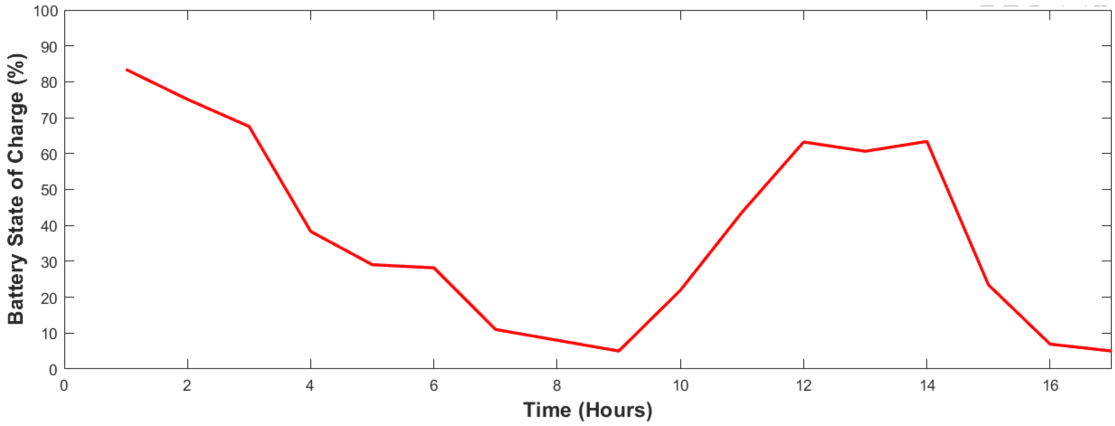

Figure 16. Battery SoC during outage.

Although during outage the distributed wind turbine was mostly generating maximum power, in two occasions it was unable to generate power due to the lack of sufficient wind speed. The renewable penetarted power from the distributed horizontal axis wind turbine is shown in Figure 17.

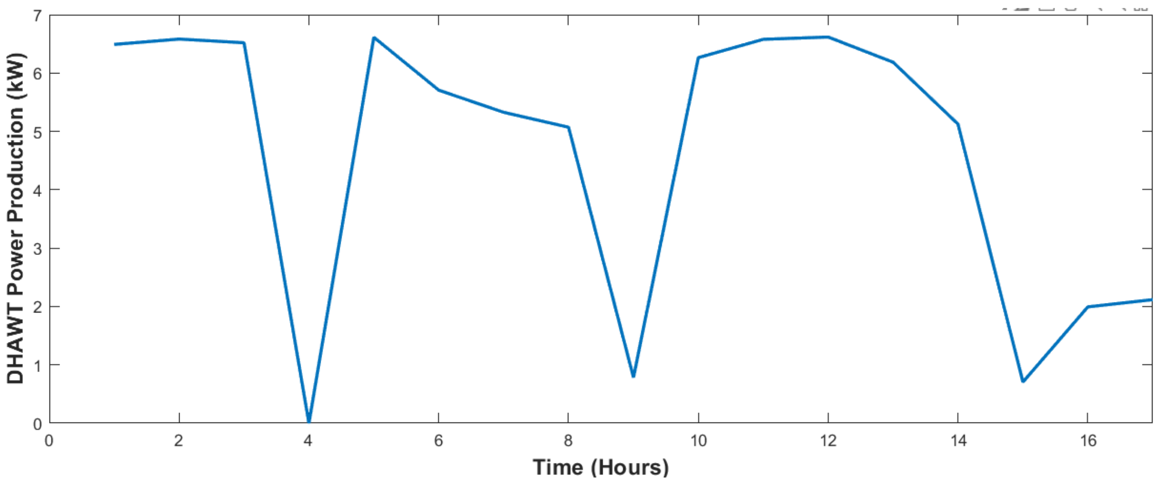

Figure 17. Power generated by distributed wind turbine during outage.

The relationship between battery SoC and renewable penetration can be obtained by comparing Figure 16 and Figure 17. At the beginning of the outage wind turbine's power generation and battery-stored energy were at max. Battery discharge was expedited when there was no power generation from the wind turbine. The resiliency

4.3. Economic Benefits

For the purpose of computing the techno-economic Analysis of the proposed DER-based system, some economic data are required [53]. The project lifetime, nominal discount rate, inflation rate, and emission penalty for the project location can be found below [53,54]. Considering the economic data required for this analysis, a number of economic formulas are considered as shown in eq 5-8 where *C* refers to cost.

Total annualized cost,

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$$C_{annual,i} = \sum(C_{capital} + C_{operation\ and\ maintance} + C_{replacement} + C_{fuel})_i \quad (5)$$

Cost of energy,

$$Cost\ of\ energy = \frac{C_{annual,i}}{E_{total\ load\ served}} \quad (6)$$

Capital recovery factor,

$$CRF\ (i,N) = \frac{i\ (1+i)^N}{(1+i)^N - 1} \quad (7)$$

Where, disount rate is i, and N represents number of years.

Total net present value,

$$C_{NPV} = \frac{C_{annual,total}}{C_{capital\ recovery\ factor}} \quad (8)$$

a detailed techno-economic comparison between the two cases is tabulated in Table 3.

Table 3. Detailed techno-economic comparisons of systems.

Economics	Units	Grid only	Grid and DER
Discount Rate	%	3%	3%
Annual Inflation	%	3%	3%
Project Life Time	Years	25	25
Total Net Present Value	$	$83,795.64	$64,985.94
Levelized Cost of Energy	$/kWh	$0.09	$0.0667
Cost of Energy reduction	%	0	23.00%
Capital Investment	$	0	$30,300
Replacement	$	0	$7,100
Salvage	$	0	$7,092
Operation and Maintenance	$	$83,795.64	$34,678
Emission Penalty Rate	$/ton	$12/ ton	$12/ton
Emission Penalty	$	$276	$114
Capital return rate, CRR	%	0	3.82%
Simple Payback Period	Years	0	15.4 years

The proposed system adding a 6.0 kW of wind generation capacity and 20 kWh of battery capacity will reduce the operating costs to $1,387/yr with a simple payback period of 15.4 years and an IRR of 3.82%. The cumulative cash flow of both grid only and DER connected to the grid is shown in Figure 16.

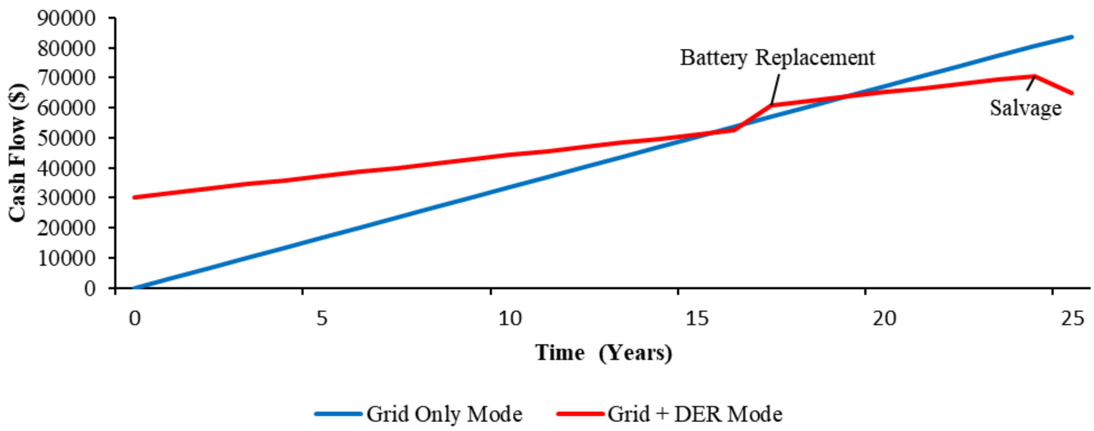

Figure 18. Cumulative cash flow over the project lifetime.

4.4. Environmental Benefits

Small wind turbines are a clean, renewable energy source that does not produce greenhouse gas emissions or other pollutants [2,61]. A comprehensive emission analysis was conducted for both grid-only and grid-tied 6kW distributed horizontal axis wind turbines with a 100kWh per day community load to evaluate the benefits. Detail comparisons by GHG elements are shown in Table 4.

Table 4. Emission analysis comparison.

Elements	Value (Grid only)	Value (Grid+6kW DHAWT)	Units
Carbon Dioxide	23,068	9,543	kg/yr
Sulfur Dioxide	100	41.4	kg/yr
Nitrogen Oxides	48.9	20.2	kg/yr

Nitrogen Oxides 48.9 20.2 kg/yr.

As shown in table 4, the overall emission reduction by the proposed grid-connected distributed turbine is over 50%.

5. Conclusions

This research work examines the potential of distributed wind energy in Lubbock, located in West Texas, where an average wind speed of 11.6 m/s provides a reliable source for electricity generation through appropriate turbine utilization. The design and analysis of a distributed wind turbine were conducted to assess its ability to harness the energy from this high wind flow, as conventional wind farm setups are typically lengthy and commercially oriented. The research focused on wind data analysis, determining the optimal turbine blade foil combination, and designing a robust and compact rotor for the distributed turbine system. The dimensions of the blade were carefully calculated to maximize wind coverage within the available high wind speeds. The economic and resiliency potentials of distributed wind turbines were evaluated, revealing multiple benefits for communities, including cost savings, enhanced energy independence, local job creation, community ownership, and environmental advantages. In conclusion, the study demonstrates that distributed wind turbine systems in Lubbock, TX, have significant potential to play a crucial role in national energy economics and improve resilience during grid outages.

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Nomenclature

NACA National Advisory Committee for Aeronautics
NREL National Renewable Energy Laboratory
BESS Battery energy storage system
DHAWT Distributed hotizontal axis wind turbine
SoC State of Charge
Cl Lift coefficient
Cd Drag coefficient

Cm Moment coefficient
AoA Angle of attack
PMA permanent magnet alternator
A Swift area
h Height
m Mass of air, kg
v Wind velocity, m/s
ρ Air density, kg/m3
C_P Betz limit coefficient
α Frictional coefficient
p Static pressure, kPa
V Volume of air, m3
η efficiency, %
N rated speed
,f frequency
P pole quantity
ϕ_g magnetic flux
B_av flux density
D= stator diameter
L= stator length.
T Temperature, °C
IRR Investment return rate

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