Energy, exergy, economic, environmental (4E) and frequency distribution analysis of train wind gust with real-time data for energy harvesting

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Abstract
The wind gust velocity of trains are above the cut in speed of wind turbines. Multiple cases studies estimate the available wind energy and potential electrical output with numerical and computational models. These gust velocities are dynamic nature. This work collects real time data of wind gust using data acquisition, conducted 4E and Weibull frequency distribution analysis. The acquired data is further used as a velocity signal to Simulink and wind emulator wind energy harvesting systems. This distinguishes in producing benchmarking results when compared with numerical and computational models. From data interpretation and analysis, the wind gust are non-uniform and gust velocity ranges from 2.3 to 7.1 m s$^{-1}$ is recorded with a Weibull scale parameter value ($A$) of 5.54 m s$^{-1}$. The maximum power available for harvesting is after considering Betz limit is 159.6 W, whilst Simulink and emulator energy harvesting systems produces 126.4 W and 123.08 W with a maximum exergy efficiency of 49.38 and 49.14%. The estimated wind energy available for 1KM range with wind energy systems on both side of traction poles is about 3.3 KW/KM. The compared environmental and economic analysis reconfirms the feasibility of the proposed model with capacity factor 5.74%. Other findings are the corresponding variation in output with respect to dynamic-wind velocities is limited due to inertia and stored kinetic energy of system, the role of location, weather statistics and influence of tail winds in shaping wind gust velocity is also adjudged as crucial factors.

Nomenclature

| Symbol | Description                      |
|--------|----------------------------------|
| KW     | Kilowatt                         |
| K.E    | Kinetic energy (J)               |
| Kmph   | Kilometers per hour              |
| RANS   | Reynolds stress tensor           |
| SA     | Spalart–Allmaras                 |
| URANS  | Unsteady Reynolds-averaged Navier–Stokes |
| WTE    | Wind emulator                    |
| DFIG   | Double fed induction generator    |
| LCA    | Life cycle assessment            |
| WECS   | Wind energy conversion system    |
| A      | Turbine swept area (m$^2$)       |
| J      | Combined rotor and wind turbine inertia coefficient |
| V      | Wind speed (m/s)                 |
| Sec    | Second(s)                        |

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A Weibull scale parameter in m/s
k Weibull form parameter
W Work (J)
P Pressure (kPa)
R Vapor constant (kJ/kg K)
T Temperature (K, °C) at stage 1 and 2
ρ Density of wind in kg/m³ at stage 1 and 2
λ Tip speed ratio of the rotor blade tip speed to wind speed
β Blade pitch angle in °C
η Exergy efficiency
ψ/ Flow exergy of air
ΔP pressure difference at state 1 and 2 (Pa)
ω_T Rotational speed of rotor
ω_s Rotational speed of the magnetic flux in the airgap of the generator, this speed is named synchronous speed. It is proportional to the frequency of the grid voltage and to the number of generator poles.
P_m Mechanical power captured by the wind turbine and transmitted to the rotor
P_s Stator electrical power output
P_r Rotor electrical power output
T_m Mechanical torque applied to rotor
T_em Electromagnetic torque applied to the rotor by the generator
C_p Performance coefficient of the turbine
W_0 wind turbine output(W)
K_w kinetic energy of air mass
Ex Exergy (W)
E_x ph physical energy(W)
C_p coefficient of performance of wind turbine
C_p_a air specific heat of air (kJ/kg K)
C_p_v specific heat of water vapor (kJ/kg K)
T_o reference temperature (K, °C)

Introduction

Alternative sources for energy are dominating the 21st-century electricity generation. Day by day renewables are gaining more attention. Various world agencies statistics predicts the green energy superseding of brown energy by replacing thermal, gas power plants with solar, wind, Geothermal and other renewables (IEA 2021). Along with this energy recovery and nanoscale electricity generation are also blue eyed. These third potential energy sources utilize liberated waste energy for conversion. Also, nano material compounds with different charged polarities are used to generate the electricity (Anic et al. 2021). This work studies the behavior of wind gusts produced moving trains, change in gust pattern due to aerodynamic shape and speed of Trains. Also, estimate the potential of wind gusts for conversion into electricity. The moving trains produce wind gusts alongside the track due to sudden air mass movement. These gusts are able to run the wind turbines for producing electricity. The size, design shape, length and velocity of the vehicle governs wind gust’s flow structure and its time of availability. A lengthy locomotive even converts this wind gust into wind squall. Moreover, in reality railways can utilize this power for level cross posts power supply and wireless communication in remote areas. Hence, the idea of generation of electricity by this method is investigated in this work. The preliminary collected data with a maximum gust velocity of 7.1 m s⁻¹ at the traction pole is considered as strong wind breeze on Beaufort scale.

Many scholars put their effort to represent this phenomenon by using Simulink, ANSYS and experimental models for both locomotives and on road heavy vehicles. But previous analysis is based on predetermined wind velocity application to turbines, which are far away from real time behavior since wind gust patterns more dynamic. Hence, here to study the wind gust pattern to avoid the above errors a real time data collection system
with anemometer is used. Also, trains whose arrival and departure are pre scheduled, so it is quite easy to estimate the available energy for a period of time without the need of wind velocity laser scanning (Lee et al 2010). This exploration research covers a brief literature about traction wind gusts followed by wind gust real time data collection and its analysis using Weibull frequency distribution, latter is not applied for traction wind gust till now. Acquired gust velocity data is used as a signal to Simulink and wind emulator wind energy harvesters and results are compared with theoretical calculations. Since it is a new model and it is necessary to find out the constrains and abilities the exergy, economic and environmental impacts of this systems is investigated. The exergy analysis results are shown in figure 10. At last a comparative analysis is validated with similar studies.

Proposed model graphical image is shown in figure 1. Some notable works are Holley’s patented mass air flow collection equipment (MACE) for harvesting wind gust energy from underground tunnels (Holley 2014). Qian jiang developed a T-Box model wind turbine to be placed in between tracks for energy harvesting. A high speed bullet train passes over for 18 hours on this T-box produces 2.6 Kilo watt hour (KWH) (Jiang et al 2010). Contributions are also made in analyzing the on-wind stream flow. Rajagopal Vinod Bethi worked on Modified Savonius wind turbine for harvesting wind energy from trains moving in tunnels derived velocity stream lines of gusts using open foam. In his investigation with a turbine diameter of 0.5 m placing at 0.10 m distance to track achieved 94.18Watt with a Cp of 0.0717. His work also studied 0.25 m–0.75 m size of turbine with 0.10 m–0.75 m distance from train (Bethi et al 2019). But in reality, especially for Indian railways turbine location at this distance is matter of safety concern. It was clear that, based on the type of wind turbine output power changes even though all other parameters are kept constant. So, it is insisted that a portable wind turbine which can be easily mounted on traction poles with optimised power extraction capability at mean gust velocity is need to be design and investigated. Emerging unconventional wind turbines are offering these features (Worldchanging. archive.). Some scholar suggested that harvesting this wind gusts when trains are moving inside the tunnel is better option rather than harvesting in open area. This is due to advantage of developing high pressure waves inside the tunnel. Unfortunately, none of the works actually studied this wave pattern with Weibull frequency distribution. This work used Weibull frequency distribution to investigate gust behavior. Zijan Guo worked on parametric analysis and optimization of a simple wind turbine in high-Speed railway tunnels. The simulated turbine response with dynamic fluid body interaction (DFBI), His work shows 157.9 W output from 350kmpf train speed inside the tunnel (Guo et al 2020). Across the world all nations have their own railway networks and some countries like European Union members have international railway lines.

According to CIA world factbook, railway tracks of world cover 1,148,186 kilometers, out of which 68525 kilometers are represented by Indian railways (CIA factbook) If we are able to use at least 1% of these tracks for wind gust-based electricity generation, this system will become an emerging source of energy. This wind gust potential is not only a possible source for electricity generation but also it can be used as compressed air storage system by using wind gust as prime mover source. Some scholars developed computation domains and boundary condition mesh generation for simulation of wind gusts effect and its ability to produce power output. Wenlong Tian worked on energy recovery from moving vehicles on highways by using a vertical axis wind turbine (Tian et al 2017). He demonstrated this effect by 3D computational fluid dynamics simulations using the Reynolds-Averaged Navier–Stokes equations for car moving on high ways. Oleg Goushcha demonstrated wind power in moving reference frames with application to vehicles. His work studied the velocity acceleration inside the moving car tunnel from 11 m s\(^{-1}\) to 18 m s\(^{-1}\) with a power output of 41 W with 0.413Cp (Goushcha et al 2019). This method has a drawback of increasing drag coefficient. Although researchers estimated and simulated the possible wind energy output, still the validation of wind gust behaviour with respect to different type of aerodynamic shape vehicles is a conflict arising concept. This is due to wind stream flow depends on vehicle length and shape. Setting of boundary conditions in simulation models to reflect the physical conditon of case is challenging. This work proposes solution for it. This is by considering wind turbine rotor swept area as the effect boundry area for capturing the wind energy. The wind potential is estimated based on it and the change in swept
area of turbine is directly proportional to power output. This idea gives a flexible way of sizing the wind turbine asper environmental aspects. Also, for this kind of instantaneous time-varying wind gust application of weibull distribution method can justify the accurate wind gust behaviour (Shirzadeh et al. 2015, Mangara 2021). This work deals with the data acquisition of wind gust produced by two different speed traction locomotives, then assessing the wind distribution behaviour using weibull distribution method. After that, assessed data is applied as a input to the wind emulator and simulation to investigate output results and energy production capability of windgusts. This systematic procedure gives the accurate energy availability at traction poles for real time atmospheric conditions compared with simulation based artificial computational models. A comparison between simulation values and real output of wind turbines are approximate when the input is same (Shirzadeh et al. 2015). Exergy analysis has performed to find the exergy efficiency and destruction rate of proposed model (Ehyaei and el Haj Assad 2021). Hence, results derived here are approximate to real time output. This work presents results of full-scale data collected in live atmospheric condition. Under these conditions all the parameters of atmosphere are mostly dynamic in nature even speed of train. Where as in CFD analysis wind flow, buoyancy, natural ventilation, thermal and humidity effects are fixed and predetermined (van Hooff and Blocken 2012). This drawback is eliminated by real time data collection and application of weibull distribution for assessing dynamic nature of wind. In this work along with wind gust parameter analysis and electricity prediction the economic and environmental impacts with this wind energy conversion system (WECS) is highlighted. The advantage of this WECS compared with regular Megawatts systems is low noise, less hazardous to wild life due to compact size etc. These are elaborated in environmental impact section. Various studies on small scale wind turbines and testing on experimental models confirms its feasibility (Tummala et al. 2016), from the most recent study by M. Palanisamy et al. a prototype model of VAWT achieved 21.508 W at a gust speed of 5.9 m s$^{-1}$ with a tip speed ratio (TSR) of 0.304 (Raja Sekhar et al. 2021). Anther study with VAWT for train energy harness shows 32.3 MWh energy could be produced in a year (Oñederra et al. 2020). Of course this theory is not only limited to trains but also applicable to fast moving vehicles on high ways (Shridhar et al. 2016). Despite of all of the above validations none of this model is implemented in large scale. In order to give reconfirmation about this case economic has been been done.

### Data collection

In previous works estimated the wind gust velocity based on the train speed using either computational modeling (Wang et al. 2020) or a collected signal gust velocity value. But distance between traction pole and train wind gust impact pattern and its availability. By keeping it in mind wind velocity data is collected by placing anemometers on traction poles to acquire real time data. The wind available at pole is the input to wind turbine. The frequency of different velocity ranges of wind distributions is evaluated by Weibull frequency distribution. Hence this approach is clear from approximation error when compared with computational simulation model. It is insisted that weather, direction, and swing of wind is also play a crucial role in development of aerodynamic shapes, turbulence around train. Also, there a loss of wind velocity in between train and traction poles due to tail wind influence. This phenomenon is considered for first time by this work, and it is error free due to placing anemometers on poles. This theory used in athletics, where track runners and long jumpers are gets either benefitted or adversely affected based on the wind assistance (Rule 260.14(c) of IAA ). If any athlete sets world record under wind assistance, this record is not considered if the wind assistance is beyond the standard limits. Here anemometer HemSun, HA2015 is mounted on traction poles to acquire the wind gust data. This wind gauge is used to collect local wind swing and direction. The anemometer is placed at 2-meter height on traction pole and poles are by default displaced 2.5 meter beside from the track shown in figure 2. From this data collection, it is found that the distance between traction poles and loco results in the loss of aerodynamic shape and velocity of wind. This is examined by placing anemometer near to train rather than on pole. This recorded data by digital anemometer values are collected for 10 trains including passenger trains with closed aerodynamic body and also open top type goods vehicle. While for analysis two same length and aerodynamic shape trains with accelerating, decelerating speeds are presented. Based on the collected data power potential is theoretically estimated, then gust data from data acquisition system is used as signal to experimental wind emulator and Simulink wind energy harvesting systems shown in figures 3(a) and (a). Later power, exergy efficiency and frequency distribution results are plotted at pitch angle of 0° to 6 °C. The economic analysis data is associated with (Raja Sekhar et al. 2021) and compared with similar rating and capacity factor wind harvesters. The turbine used in this work is modelled based on (Ezhilarasan et al. 2020) for 1.5 KW. Using acquired signal as input rather than directly simulating train speed and velocity by using computational boundary layer and mesh analysis results in accurate output power prediction, while latter two methods are totally hypothetical. This work also estimates the amount of energy available for 1KM range with respect to Indian railways.
Site parameters
Station: Katpadi junction railway station, India
  (Latitude 12.980000, longitude 79.129997)
  Air Density = 1.226 kg m⁻³
  Air Pressure = 1045 hPa Temperature = 40 °C Relative humidity = 45%
  Frequency of train movement = 446

Betz’s limit and Weibull distribution

The Betz’s limit law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized actuator disk that extracts energy from the wind stream (Young et al 2020). Over the decades this law is serving as a benchmarking standard for wind energy conversion. Many theories are proposed by researches to surpass this limit based on empirical relations, but yet needs to be authenticated globally (Vennell 2013). While the Newman limit (16/25) is used to govern the maximum extraction limits of tandem wind turbines (Newman 1986). Control volume based analytical methods without considering unstudy flow and non uniform pressure differences gives a way to errors in simulation findings (de Lellis et al 2018). This drawback is rectified by real time data collection and application of weibull distribution. The distribution of wind gusts of high and low speed locomotives with different velocities are shown in figures 3(a) and (b). This gives a way for feeding the right signal to Simulink and Emulator WECS.

According to Betz’s law,
The factor $16/27$ (0.593) is known as Betz’s coefficient. This also considered as maximum value of power coefficient ($C_p$). Practical utility-scale wind turbines achieve at peak 85% of the Betz limit.

The wind gust produced by train varies instantaneously, due to this turbine undergoes speed fluctuations. Hence it is difficult to predict the output power. But it is necessary to determine wind gust behavior for wind turbine output prediction. Weibull distribution is yardstick to measure the frequency of different ranges of wind gusts. This is well known by the relation.

$$f(v) = \frac{K}{A} \left( \frac{V}{A} \right)^{K-1} \exp \left[ - \left( \frac{V}{A} \right)^K \right]$$

Weibull scale parameter ($A$) in m/s. It is a measure of characteristic wind speed distribution. It’s always proportional to the mean wind speed. ‘$K$’ Weibull form parameter specifies the shape of a Weibull distribution and value in the range of 1 and 3. Low ‘$K$’ signifies very variable winds, while a larger ‘$K$’ is characterized by constant wind. The application Weibull distribution helps in representing the frequency distribution of unpredictable non uniform flow of wind gust by locomotive. This is crucial in deciding the control system for these type of wind turbines (Erdenebat et al 2020). The derived results representing the non-uniform pattern of wind gust velocities shown in figures 4(a) and (b). For both high speed and low-speed trains. The mean value of train gusts 4.99 and 4.54 suggests that it is better to design turbine with mean operating speed of 5.5 m s$^{-1}$. Since the spikes in both graphs are seen at more than 6 m s$^{-1}$.

**Mathematical modeling**

The steady-state power characteristics of the turbine is used for modelling and used in Simulink and emulator based on (Ezhilarasan et al 2020). Along with that assumption regarding The drive train stiffness is infinite, friction factor and the inertia of the turbine are combined with the generator coupled to the turbine.

$$\text{Power contained in wind gust } P = 0.5 \rho A V^3$$

$$\text{Mechanical Power of turbine } P_m = C_p(\lambda, \beta) \frac{\rho A}{2} V_{wind}^3$$
Stator electric power output of generator and mechanical power output of turbine can be equated as
\[ P_m = T_m \omega_r \]

Mechanical equation for ideal generator is
\[ J \frac{d\omega_r}{dt} = T_m - T_{em} \]

Further for steady-state at fixed speed
\[ T_m = T_{em} \text{ and } P_m = P_t + P_r \]

Hence, the power available at the rotor \( P_r \) is given by
\[ P_r = P_m - P_t = T_m \omega_r - T_{em} \omega_s = -sT_m \omega_s = -sP_t \]

Overall conversion efficiency = Electrical output (\( P_e \))/Power available at turbine (\( P_t \))
\[ \eta_e = \frac{P_e}{P_t} \]

For the proposed model the cut in velocity of wind turbine is 2.3 m s\(^{-1}\) and cut-off velocity of 11 m s\(^{-1}\). But maximum velocity of wind gust produced is 7.1 m s\(^{-1}\).

Therefore, Power contained in wind gust at 2.3 m s\(^{-1}\) (\( P_{min} \)) = 9.14 Watts (W)
Maximum power contained in wind gust as produced by train at 7.1 m s\(^{-1}\) (\( P_{max} \)) = 269.14 W

The Betz’s limit validates the relation between power contained in wind to maximum power extracted from wind turbine by a fraction of 16/27 power contained in wind.

Hence, the maximum and minimum power that can be extracted is limited to
\[ P_L = P \times B_L \]

| Length (Meter) | LOCOMOTIVE 1(High speed) | LOCOMOTIVE 2(Low speed) |
|----------------|--------------------------|-------------------------|
| No. of coaches | 22                       | 22                      |
| Individual Coach length (Meter) | 23                       | 23                      |
| Gust duration (Seconds) | 31                       | 45                      |
| Estimated speed (kmph) | 59.76                     | 42.69                    |
| Gust range (meter/sec) | 2.6–7.1                   | 5.9–1.8                  |
| Shape of coach | Closed rectangle          | Closed rectangle         |
| Movement | Accelerating               | Deceleration             |
| Avg. Power in wind gust (W) | 136.5                     | 78.43                    |
| Max. Power in wind gust (W) | 269.14                    | 154.44                   |
| Min. Power in wind gust (W) | 13.21                     | 4.38                     |

**Simulink model**

Output power characteristics are obtained using simulation and wind emulator. The Real time data is fed into Simulink model of 1.5KW induction type wind turbine. For simulation and emulator experiments, one high speed train moving out of station and a low-speed train moving towards station collected data is used. Weibull frequency distribution is applied to collect wind gust data. Weibull parameters A, K is determined as shown in figures 5(b) and (c). Here we collected real time data of wind gusts produced by trains from the Katpadi Junction railway track of India. This station has a train frequency of 464 trains per day. The acquired data with respect to
time of wind gust availability is shown in Table 1 with specifications of reference locomotives 1 and 2. The acquired data from Table 1 and Figures 3(a) and (b) signals are used as input of Simulink model of phasor type wind turbine induction generator shown in Figure 3. The ratings of WECS tested with Simulink model is given in Table 2. After development of 1.5KW, 575volt, 60 Hz wind turbine simulation circuit, base speed is set to 2 m s\(^{-1}\). The acquired results from anemometer with data logger are used as input wind velocity parameter of simulation. Then the power output curves are produced and shown in Figures 5(b) and (c). While for energy exergy and economic analysis the power output the recorded gust velocities from data acquisition, that is minimum cut in velocity of 2.3 m s\(^{-1}\), mean velocity in both cases about 5.0 m s\(^{-1}\), maximum velocity in decelerating train 5.9 m s\(^{-1}\) and maximum gust velocity of 7.1 m s\(^{-1}\) instance values are used. Using these values to the Modelled harvesting system as input parameters produces exact output power values the collected results analysis gives the potential real time output when compared with remaining CFD mesh analysis based Simulink models. And helps in designing the improved WECS models with rated speed and cut in, cut off velocities. The instantaneous analysis results are shown in Figure 7(b). The wind gust velocity and train speed relation shown in Figure 7(a). In this Simulink model the exact values of input are feed to the simulated wind turbine. That is, wind turbine performance with same input in simulation and real time conditions are almost approximate. By using real time data, the error in computational modellings such as reluctant to adopting atmospheric parameters is eliminated. In computational models have fixed mesh and boundary layers while actual atmosphere is out of bound (Tabatabaei et al. 2018). This model produces a minimum output power of 4.38 W and maximum of 123.08 watts for accelerating locomotive whilst for Decelerating model the maximum power 78.5 W shown in

Table 2. Ratings of simulation model wind turbine.

| S. no | Parameter                  | Rating                      |
|-------|----------------------------|-----------------------------|
| 1     | DFIG inductionGenerator    | 1.5 Kilowatt/575 V          |
| 2     | Pitch angle                | 0-6\(^\circ\)c              |
| 3     | frequency                  | 60 Hz                       |
| 4     | Input wind velocity        | 2.3 m s\(^{-1}\) to 7.1 m s\(^{-1}\) |
figures 5(b) and (c). This operation is conducted for pitch angle of 0°, 3°, and 6° and subsequent results are shown in figure 8(b).

**Emulator model**

As already known, the static and dynamic behavior of wind turbine is emulated using Wind Turbine Emulator. This emulator is a complete stand-alone Wind Energy System shown in figure 4. This wind turbine simulator consists of a DC motor coupled with generator (DFIG) for the management of static and dynamic behavior of actual wind turbine (Zouheyr et al. 2021). Most of the wind emulators (WTE) use fuzzy logic based closed-loop operations including this experimental setup (Benzaouia et al. 2021). Here the behavior of wind distribution is analyzed by Weibull distribution and train wind gust irregularities are recorded. This accurate data is fed into wind emulator as a signal similar to Simulink model for output power generation. For this LabView is used as condition monitoring software. The signal received as machine language used to run the motor, of which DFIG is connected. Here motor is the prime mover as link wind turbine in real time. Both are run as per the input signal which is identical not a computational estimation. Hence the motor coupled DFIG output is same as turbine coupled DFIG. Hence there is no matter of concern about output deviation in real-time. The emulator actually duplicates all hardware required to run WECS. Hence it is a benchmarking setup in trusting output characteristics. The maximum extractable power according to theoretical calculation including Betz limit is 159.6. 126 W power is produced by the turbine in Simulink. The wind emulator achieves the maximum power of 123 W. Wind emulator is a hardware level simulation with an ability to track torque-speed and power-speed characteristics of a wind turbine at different wind speeds and pitch angle. The output exergy flow with respect to this change in pitch angle is shown in figures 9(c) and (d). The emulator power output with respect to wind gust is shown in figures 6(b)–(d). Here it is observed that the sudden change in wind swing doesn’t adversely affect the output power as like in Simulink model. This reconfirms the effect of inertia and kinetic energy of machine in encountering the sudden changes in gusts and maintaining the output power variation in limited proportional for a short time span system. This is the first time identified in these kinds of works. Further analysis is needed to be done by considering this factor along with drag and power coefficient for development of wind turbines for harvesting train wind gust.
Results and discussion

It is clear from the theoretical, Simulink and emulator statistics that, the wind energy produced by train gust with variable velocity distributions can generate power. The power output is never more than 60% in almost all the cases due to energy conversion loss in wind turbine while converting air mass of kinetic energy into mechanical energy and converting this mechanical energy into electrical energy. The Betz’s coefficient ratifies it (de Lellis et al. 2018) as no turbine can extract 59.3 percent of total input energy. Although tamer wind turbines are beyond this law but are not authenticated. This work results also signifies it. It is evident from the output of simulink figures 5(b), (c) and emulator 6a, 6b and 6c, that the turbine self regulates with change in sudden wind velocities, due to its inertia and kinetic energy of turbine. While in Weibull frequency distribution the spikes of wind gusts are developed as shown in figures 4(a) and (b). Both of the Simulink obtained results specify that the increase in gust factor causes to reduce the time of gust available as shown in figure 7(a). It means speed of train directly proportional to wind gust and inversely to time of gusts available. When speed of the train is high, time of wind gust produced is low and vice versa. This can also be influenced by length of train. For a normal locomotive of length in between 200 to 600 meters the wind gust available is varies from 20 to 50 s. During gust generation wind velocity is fluctuating between peak to peak. This dynamic nature of wind gust not projected properly in any computational simulation analysis. Its due to fixed boundary and mesh condition of computational analysis (Solazzo et al. 2008). Another finding from real time data analyzing is the dynamic nature of wind gust of 2 m s$^{-1}$ to 5 m s$^{-1}$ variations. The reason for this may be coasting and accelerating of locomotive. Meanwhile the corresponding output fluctuations are limited and does not follow pattern as like wind gusts but adjusted based on inertia of model. The individual test case run of both Simulink and emulator at specific velocities 2.3, 5, 5.9 and 7.1 m s$^{-1}$ gives 4.38, 46.20, 71.04 and 123.08 W for wind emulator and 4.2, 46.43, 72.42 and 126.12 W for Simulink respectively by without change in pitch angle is shown in figure 7(b). Change in wind gust with constant train speed needs to be specifically investigated in order to find the aerodynamic turbulence of wind, wind assistance of atmosphere due to distance between train and poles. These are not examined here to maintain the current course focus on 4E analysis. This may come to limelight after this work extended to design suitable small turbine for traction wind gust. From figure 7(b), the output power is directly proportional to the wind gust velocity. One more
observation is trains with poor aerodynamic shapes namely open top goods trains are delivering more fluctuating wind gust, all these are analysis are for specific models are currently conducting as a separate case study. Meanwhile regular passenger trains with closed deliver wind gusts with comparatively in consistent. The reason behind this is due to creation more turbulence winds around open top trains as mentioned above (Solazzo et al. 2008). This turbulence distorts the wind gust stream flow which results in circulating winds around loco and poor gust production at the traction poles. To harvest maximum amount of wind energy these systems need an unconventional wind turbine with high power coefficient (Carpintero-Renteria et al. 2020). But here the investigation conducted with regular horizontal axis wind turbine to get standardized view about the system. From figures 8(a) and (b) it is confirmed that simulation, emulator and theoretical calculations validation with table 3 demonstrates the higher output which is an average of 78.5 W for decelerating loco and 138.6 W for accelerating loco. While coming to the role of generated power, it can satisfy lighting load demand of railway cross over signal huts. But it needs additional electrical distribution support with voltage step up and step down applications. The table 3 shows the comparison of proposed model with similar experiments, which used computational methods namely Reynolds stress tensor navier-stokes (RANS), dynamic fluid body interaction(DFBI), 3D CFD, Spalart-allmaras (SA) and Unsteady Reynolds-averaged Navier–Stokes (URANS). Pitch angle control is one of the method to regulate output power of wind turbine especially wind velocity is beyond cut-off speed. Pitch angle adjust the angle of turbine blade thus results in calming angle of attack to control turbine output. The proposed is examined at three different pitch angles 0°, 3° and 6° and its corresponding power output in terms of exergy efficiency and destruction is shown figures 9(a)–(d) is shown for both simulink and emulator model. This gives a maximum exergy destruction of 54.27% with pitch angle of 6°. Also output power flow is more dynamic with respect to same input signals at pitch angle 6 shown in figures 9(b) and (d). Further economic analysis gives a capacity factor of 5.74 as compare with remaining models is shown in table 5 is reiterating its practical feasibility.
### Table 3. Comparison of different WECS operated with vehicle wind gust.

|                        | Savonius WT in railway tunnel (Bethi et al 2019) | WT in railway tunnel (Guo et al 2020) | WT beside highway (Tian et al 2017) | WT in car frame (Goushcha et al 2019) | Proposed (On traction pole) |
|------------------------|-----------------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|----------------------------|
| Power (W)              | 464                                           | 157.9                               | 139                                 | 41                                   | 159.6                      |
| Wind gust (m/s)        | 18                                            | 100                                 | 15                                  | 18                                   | 7.1                        |
| Method study           | RANS equations with turbulence                | DFBI technology, and URANS turbulence | 3D transient CFD                    | (URANS), SA                          | Recorded step signal to emulator turbine |
| Limitations            | Distance b/w train and WT = 0.5               | Specifically for bullet trains      | Steady boundary conditions          | Drag effect on car                   | Need of aerodynamic shape investigation |
Model validation

This work has been compared with similar model wind gust operated WECS shown table 3. Site atmospheric data such as air density, mean wind speed is acquired and analyzed using Weibull distribution for the scalability and flexibility of system (Asmine et al 2011). Using Weibull distribution wind gust parameters namely A, K is derived. Those are vital in determining suitability of WECS for particular location. Then theoretical output is estimated. The actual acquired signal operated simulation and wind emulator model systems characterized the effect of gust behavior. The efficiency findings for both models at different pitch angles are shown in figures 8(a) and (b). This approach assures the lack of fallacy. While the comparative analysis with similar model’s results differed with proposed due to key concern of wind turbine inertia. This inertia does not adjust with the sudden rise or fall in input velocity in reaming models. But our tested turbine of 1.5KW has an inertia as low as 0.015 kg·m² (Morren et al 2006). Hence the flywheel energy store for regulated output may be necessary when this type wind system roll out. The errors and uncertainty analysis of the proposed can be further validated based on (Lackner et al 2008). Despite of all above compared models also demonstrated the possibility of real time execution of this systems. The following 3E analysis thoroughly examine the systems real time implementation capability.

Exergy analysis

The exergy efficiency and destruction rate with respect to different pitch angles are represented graphically and also in table 4. The conversion of low-grade energy into high grade energy is impossible by virtue of second law of thermodynamics. Even though wind energy is considered as a high-grade energy source as compared with thermal and heat energy obtained from fossil fuels. Here it is essential to find out the maximum available energy (exergy) of the system, since the source of wind is a train gust. And also, this analysis helps in better understanding of this exploratory source behaviour. Wind exergy analysis are conducted for various types of turbines by various authors using boundary element methods (BEM), real time analyses (Ozgener and Ozgener 2007, Lackner et al 2008, Ahmadi 2009, Ajam et al 2021). The exergy destruction, kinetic, physical, chemical and potential exergies are the key factors in reflecting about internal energy distribution with in system. Here the chemical and potential exergies are neglected and analysis has been conducted for kinetic and physical
The results show a maximum 49.38 exergy efficiency and 54.27 exergy destruction of system at pitch angles 0 to 6°. The exergy efficiency is derived based on (Ozgener and Ozgener 2007).

Exergy efficiency ($\eta_{ex}$)

$$\eta_{ex} = \frac{W_0}{K_w}$$

Flow exergy of air ($\psi$)

$$\psi = \frac{W_0}{K_w}$$

By the energy balance equation.

Input wind Kinetic energy

$$k_w = \omega_0 + k_{\omega_2}$$

$$K.E = \frac{1}{2} m v^2$$

Here mass flow rate is

$$m = \rho \pi r^2 v$$

From exergy balance equation

$$E_{x,\beta} = E_{x,ph} + k_c$$

$$E_{x,ph} = (C_p + \omega C_p, v) T_0 \left[ \frac{T_2}{T_0} - 1 - \ln \left( \frac{T_2}{T_0} \right) \right] + (1 + 1.6078 \omega) R T_0 \ln \frac{P}{P_0}$$

Inlet and outlet physical exergies

$$E_{in} = (C_p + \omega C_p, v) T_0 \left[ \frac{T_2}{T_0} - 1 - \ln \left( \frac{T_2}{T_0} \right) \right] + (1 + 1.6078 \omega) R T_0 \ln \frac{P_2}{P_0}$$

Table 4. Theoretical and experimental results with real time wind gust data at instant.

| S. No | Wind gust (m/s) | Power contained in wind (Watts) | Wind emulator (Watts) | Simulink (Watts) | Exergy destruction (Ex_{des}) Joule | Exergy Efficiency($\eta$) |
|-------|----------------|-------------------------------|---------------------|-----------------|-------------------------------------|--------------------------|
| 1     | 2.3            | 9.14                          | 4.38                | 4.2             | 4.76                                | 4.94                     | 47.92 | 45.95 |
| 2     | 5.0            | 94.01                         | 46.20               | 46.43           | 47.81                                | 47.58                    | 49.14 | 49.38 |
| 3     | 5.9            | 154.44                        | 71.94               | 72.42           | 83.4                                 | 82.02                    | 46.01 | 46.89 |
| 4     | 7.1            | 269.14                        | 123.08              | 126.12          | 141.06                               | 143.02                   | 45.73 | 46.86 |

Table 5. Comparison of proposed model cost analysis with existing model (Karczewski et al. 2017).

| Nominal power | Turby   | Energy Ball | Aerocopter 450 | Proposed |
|---------------|---------|-------------|----------------|----------|
| Country       | Holl and | Holland     | Poland         | India    |
| Installation (€) | 14441   | 3654        | 8063           | 2500     |
| O&M (€)       | 300     | 60          | 150            | 500      |
| IC (€)        | 14741   | 3714        | 8213           | 3000     |
| IC per kW (€/kW) | 7758    | 7428        | 3422           | 2000     |
| Capacity factor | 2.0%    | 1.7%        | 2.6%           | 5.74%    |
Inlet and outlet K.E of wind turbine, from ref [34].

\[ \text{K.E}_{\text{in}} = \frac{1}{2} u_1^2 \]  
\[ \text{K.E}_{\text{out}} = \frac{1}{18} \rho u_1^2 \]  

The exergy destruction rate is given by

\[ Ex_{\text{des}} = T_0 \left[ c_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{\rho_2}{\rho_1} \right) - \frac{C_p(T_0 - T_{\text{avg}})}{T_0} \right] \]  

Economic analysis

These analysis gives a detail view about the proposed projects ability to operate commercially. Since our work is very new to current world, the economic analysis by comparing with previous models of same rating has been done to present the scenario of low rating wind turbines (Karczewski et al 2017). The capacity factor is estimated for proposed model and cost details as given asper indian market trend. Here, capacity factor which is defined as ratio of the amount of electricity produced (AEP) by a turbine to total output if it operated at the full nominal capacity for the entire period. The important parameters for economic anlysis are derived for detailed insite about the economic feasibility.
LevIALIZED COST OF ELECTRICITY (LCOE)

Here it is the ratio of total life time cost of wind energy system to the sum of total electricity produced from the system in its life time (Ngoc et al 2021).

\[
\text{LCOE} = \frac{\text{Life time cost}}{\text{Life time output}}
\]

That is,

\[
\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1 + r)^t} = \sum_{t=1}^{n} \frac{E_t}{(1 + r)^t}
\]

\( I_t \) investment expenditures in the year \( t \), \( M_t \) operations and maintenance expenditures in the year \( t \), \( F_t \) fuel expenditures in the year \( t \), \( E_t \) electrical energy generated in the year \( t \), \( r \) discount rate, \( n \) expected lifetime of system or power station.

Net present value (NPV)

It is actually the difference between inflow and outflow of cash over a time. It measures the value of investment or project can add to firm.

\[
\text{NPV} = \text{LS} \times \text{NES} \times \text{PVAF} - \text{IC}
\]

\( \text{LS} \) - lifespan, \( \text{NES} \) - Net annual energy savings, \( \text{PVAF} \) - Present value annuity factor, \( \text{IC} \) - Investment cost

Internal rate of return (IRR)

It calculates the return rate of investment without considering risk free rate, inflation, and financial risk. It estimates the future annual returns from project.

\[
\text{IRR} = \frac{(\text{Project cash flows})}{(1 + r)^i} - \text{initial investment}
\]

\( R \) = discount rate, \( i \) = time period

Simple pay back period (SPP)

It is the time required to return the initial investment through yearly cash inflow. A short pay back period denotes a high value profits for renewable sources.

Figure 11. Economic analysis comparison.
The comparison of different cost parameters from the figure 11 demonstrates its feasibility. While the current model compares with systems installed a decade ago, hence, almost all costs are brought down this confirms the cost reduction of wind turbines with technological advancements, and our own estimated capacity factor leads the remaining models. The economic model estimation of proposed system derives its root from (Rajasekar et al. 2021).

Environmental impacts and role of proposed system

Eventhough conventional wind turbines emits low carbon footprint, long blades of turbine creates noise pollution and also animal hazardous (Saidur et al. 2011). This issue always prevails in high MW turbines, since power output is proportional to swept area. While the proposed system uses a rotor radius of less than or equal to 0.6 meter can be able overcome these constrains. The reduced size aids in reduced noise level and better pitch control. Also death or harming the birds is negligible due compact turbines. And also many case studies revealed that environmental impacts are different at different stages such as installation, operation and maintenance to decommissioning of systems (Arvesen and Hertwich 2011). Wind energy directly does not contribute to carbon emissions like thermal plants and vehicles. But, the carbon footprint and Chlorofluorocarbon emissions of WECS is due to system components transportaion and energy utilization during its assembly (C et al. 2021).

Unlike rest of renewables and energy recovery systems presented model output can be predictable since gust behaviour is analysed and also train movement with the concerned line is also known. Hence the exploration gives a systematic advantage in providing electricity of operation, maintenance of trains especially in remote areas. While comparing with solar energy systems the proposed model generates output as long as train moves on the particular track. The impact and environmental issues of proposed system with conventional wind turbines is shown in table 6.

Table 6. Comparison of Environmental aspects of proposed Gust based WECS at various stages (Saidur et al. 2011).

| Impact type                                          | Relevant receptors                                      | Related stage | Conventional WECS | Loco WECS |
|-----------------------------------------------------|--------------------------------------------------------|---------------|-------------------|-----------|
| Ecosystem degradation                               | Ecosystem: functions and services                      | Not specific  | Relatively high    | Negligible|
| Habitat loss                                        | Biodiversity: animals and birds                        | Installation  | Possible           | Rare      |
| Mortality of individuals or Population change       | Biodiversity: Birds                                    | Installation  | Low               | Rare      |
| Physical damage                                     | Biodiversity: Birds                                    | Operation     | Possible           | Rare      |
|                                                     | Location                                               | Installation  | Needed             | Not required|
|                                                     | Birds                                                  | Operation     | Possible           | Rare      |
| Habitat disturbance                                 | Biodiversity: birds and animals                        | Operation     | Yes                | May be    |
| Enhancement of environmental/social parameters      | Biodiversity: animals and birds                        | Decommissioning | Yes              | Low impact|
| Noise                                               | Wild life and locations                                | Operation     | More               | Negligible|
| Carbon emissions                                    | Environment                                            | All stages    | Relatively high    | Low       |

\[
SPP = \frac{\text{Initial investment} (I_c)}{\text{Units generated} (U) \times \text{Unit price} (P)}
\] (26)

The comparison of different cost parameters from the figure 11 demonstrates its feasibility. While the current model compares with systems installed a decade ago. Hence, almost all costs are brought down this confirms the cost reduction of wind turbines with technological advancements. And our own estimated capacity factor leads the remaining models. The economic model estimation of proposed system derives its root from (Rajasekar et al. 2021).

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Conclusion and future scope

This work proposed anemometer recorded real time data collection for measuring wind gust velocity of trains along the traction poles. The Weibull frequency distribution is applied to 2 recorded train wind gusts and its A of 5.54, k of 3.00 values demonstrates the consistent reliable wind availability for energy harvesting. The Simulink and emulator experiments with real time data developed a output of 126 W, 123 W with a exergy flow of 267 Joules. The power available in kilometer range is calculated as 3.3 KW. The economic possibility of this proposed model is compared with three similar rating small wind turbines and this models shows capacity factor of 5.74. Also, environmental impacts of the proposed system is highlighted. Model is validated with similar studies. The relation between gust velocity, time of gust and speed of the train is discussed. While this work further analysis includes developing the hardware prototype based on Weibull frequency estimation, size and optimizing of wind turbine for specific gust velocities. Later this would be compared with Simulink and emulator results. It is evident from initial studies that the aerodynamic shape of train can change the gust velocity and frequency of gusts, but to determine the turbulence pattern of wind a detailed investigation is needed. Model
predictive controller’s applications may be the good choice for this kind of wind turbine performance optimization. Harvesting this kind of fluctuating wind energy is still under laboratory stage. And yet an attempt has been made. A case study with real turbine on traction poles may gives a much clear idea. The following are notable findings in this work.

The key findings of this work include

(a) Finding the frequency distribution of wind gust produced by traction locomotives with $A$ of $5.54 \text{ m s}^{-1}$ to $5.77 \text{ m s}^{-1}$ and $K$ of 3.00.

(b) Estimation of wind power potential for a kilometer range to be 3.3KW with reference to Indian railways.

(c) Change in wind gust behavior with respect to different types of vehicles, speed and aero dynamic shape.

(d) The power potential in wind at maximum wind gust speed of 267 W while available power for conversion is 159.6 W at 7.1 m s$^{-1}$ gust velocity. Also, for proposed locos with accelerating and decelerating train average power available in a single gust time is 78.5 W and 138 W respectively.

(e) Environmental issues for this proposed model are quite decent while compared with regular model. And it offers predictable output unlike other renewables.

(f) Estimating the economic feasibility of train gust operated WECS. The exergy analysis gives idea on the potential of wind energy for real time application.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Statements and declaration

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Both authors contributed equally to the study conception and design. Material preparation, data collection and analysis were performed by Alajingi Ram kumar. The first draft of the manuscript was written by Alajingi Ram kumar and supervised by Marimuthu R. Both authors read and approved the final manuscript.

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