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A Novel 10 kW Vertical Axis Wind Tree Design: Economic Feasibility Assessment

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Abstract: A novel, small-scale vertical axis wind turbine tree was designed using turbines combining both Darrieus and Savonius blades. We tested for economic viability using wind data collected at a site in Surat Thani, Thailand. The Weibull distribution and Monte Carlo modeling with financial indices (Levelized Cost of Electricity (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and Simple Payback Period (SPP)) were used to analyze data. We found that monthly mean wind speeds varied from 2.35 m/s in October to 2.84 m/s in February, corresponding to a wind power of 28.43 W/m² and 42.68 W/m². The average annual power output was 1446.1 kWh for May 2019 to April 2021. Results show that for turbine cut-in to cut-out speeds (2 m/s to 15 m/s), the prototype has potential economic feasibility (NPV > 0 for 64.93%), although the small capacity of the wind tree, in combination with the low average wind speed at the Surat Thani test site, showed a lack of economic viability at this specific location (NPV = USD − 20,946.29). A higher-wind-speed location (Chiang Mai) showed viability, especially at a 10 m height (NPV > 0 for 84.83%). We discuss potential conditions that would make broader use of the prototype feasible.

Keywords: vertical axis wind turbine; wind energy; economic feasibility; sensitivity analysis; Monte Carlo simulation; Thailand

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1. Introduction

The global generation of wind energy in energy markets has been increasing and continues to increase (see Figure 1, data from [1]). The majority share of this has been contributed by Horizontal Axis Wind Turbines (HAWTs) rather than by Vertical Axis Wind Turbines (VAWTs) [2].

At the same time, small-scale turbines (<100 kW) have contributed less than large-scale turbines to power generation [3]. Because small-scale wind turbines are suitable for small areas and do not need transmission facilities, they are particularly appropriate for use in a 'smart grid' as a decentralized energy supply system. In addition, they produce little noise and vibration, do not require a large installation area, and are easy to maintain [4]. The technical and economic analyses of small wind turbine prototypes are important at a time when manufacturers are bringing new designs to market [5].

Figure 1. Global wind energy generation by region (note: CIS, Commonwealth of Independent States (former Soviet-era republics)).

At a time when the use of VAWTs is predicted to grow exponentially [2], small-scale VAWTs are also being developed. This paper adds to our knowledge of small-scale VAWTs, in this case with a novel 12-m-tall, 10 kW tree prototype design incorporating 33 VAWTs (Figure 2). The novel feature of this design and analysis is that it features rotors that combine two types of VAWT blades, Savonius and Darrieus (see Figure 3). This combination was prototyped with the aim to improve upon existing small-scale VAWT designs by combining the higher efficiency of Darrieus blades with the lower cut-in (starting) speed of Savonius blades. Recent research [6] has indicated gains of up to 15% in efficiency in such a design. The overarching goal of this research, then, is to provide an analysis of the economic viability of this novel small-scale multiple VAWT prototype.

Globally, the feasibility of small wind turbine installations has been extensively analyzed. Some of these investigations are summarized in Table 1.

Table 1. Summary of some selected small-scale wind feasibility studies.

Feasibility Study	Turbine Capacity	Location	Electricity Cost per kWh—LCOE ¹ (USD)
Gökçek et al. [7]	2.5 to 150 kW	Central Turkey	0.29 to 30
Mohammadi et al. [8]	20 to 150 kW	Aligoodarz in Iran	0.047 to 0.072
Mostafaeipour et al. [9]	10 kW	Shahrbabak in Iran	0.18
Saeidi et al. [10]	1.5 kW	Fadashk in Iran	0.058
Mostafaeipour et al. [11]	1 to 7.5 kW	Zahedan in Iran	0.1225 to 0.3059
Adaramola et al. [12]	20 kW to 50 kW	North-central Nigeria	0.0738 to 1.6679
Laiola et al. [13]	0.03 to 30 kW	Taranto city in Italy	0.12 to 10.6 (EUR/kWh) ²

¹ LCOE = Levelized Cost of Electricity. ² Note: This cost expressed in euro.

The results of these studies indicate mixed success; in some of these situations small-scale installations were economically viable, while others were not.

Our investigation of this new prototype turbine tree adds to the foregoing mentioned research in several areas. First, this prototype represents the first use of a domestic-scale vertical axis turbine designed for a low cut-in speed, due to its unique blade combination. Second, with respect to small-scale wind turbines in general, it has been found that many designs do not reach the threshold of economic viability given current electric grid market conditions. Karczewski et al. [14] assessed ten turbines under 10 kW in Europe, and all were found to have negative net present values. Thailand, like many other countries, is not blessed with many high wind speed areas [15], so tests of the economic feasibility of such a low cut-in speed design, which determine suitability, are important. Third, regarding Thailand specifically, there has been scant research concerning small-scale wind turbines, and hitherto no economic viability studies for this scale. Our wind tree prototype was

developed by Prince of Songkla University in Hat Yai, Songkla province, in Thailand and was tested in Surat Thani province in the southern region of Thailand. Two-year wind data for the period from May 2019 to April 2021 were collected. This wind profile was analyzed using the Weibull distribution function to assist in the interpretation of the performance of the prototype in this setting.

Figure 2. The small-scale 33 VAWT wind tree prototype used in this analysis.

Figure 3. Closeup of combined Savonius (top) and Darrieus (bottom) blades.

Our economic assessment was conducted via various economic approaches including Levelized Cost of Electricity (LCOE), Net Present Value (NPV), the Internal Rate of Return (IRR), and Simple Payback Period (SPP). Monte Carlo simulation (MCS) was used as a tool to perform the stochastic NPV, IRR, and SPP analyses.

2. Materials and Methods

2.1. Geographical Location of Surat Thani Province, Thailand

Surat Thani, where this research was carried out, is the largest province of southern Thailand, located 685 km from the Thai capital city of Bangkok, and has a coastline along the Gulf of Thailand. The province has an area of 12,891 km². The west of the province is covered by high plateaus and forested mountains. The low basins of the province are distributed in the center and along the east coast. There are numerous islands along the coast. Surat Thani is characterized by a coastal tropical climate with a dry season from January to April and a rainy season from May to December [16].

The prototype in this study was installed at GPS coordinates 8.969194, 98.797083. This location is near the center of the province, just east of the higher mountainous region. Wind speeds were measured using an anemometer set up at a height of 12 m above the ground. Hourly, daily, monthly, and yearly wind data were recorded for the analysis using an anemometer connected to a data logger.

2.2. Analysis Methodology

2.2.1. Wind Turbine Structure

The wind tree used in this study is a collection of 33 vertical axis wind turbines, 12 m in height with 4 levels. As mentioned, each rotor has a combination of Savonius and Darrieus blades, as shown in Figure 3.

Research into the relative position of each blade has been done and has investigated the relative positioning as it pertains to this specific prototype design [17]. The results of wind tunnel experiments showed that the Savonius blade should be located at the upper position while the Darrieus blade should be located at the lower position. Technical information about the wind tree is presented in Table 2.

Table 2. Technical characteristics of the wind tree prototype.

Feasibility Study	Turbine Capacity		Location
Number of blades	3		3
Blade height (H)	0.45 m		0.6 m
Blade dimension (D)	0.72 m		0.72 m
Rated power	10 kW		
Maximum power	13 kW		
Cut-in speed	2 m/s		
Rated wind speed	8 m/s		
Cut-out wind speed	15 m/s		

2.2.2. Performance Aspects Related to the Wind Tree Design

Figure 4a shows a large 1 MW HAWT wind turbine, which can transform wind power to a usable torque by blades that drive the electrical generator. Figure 4b shows our small 10 kW VAWT wind tree that combines 33 VAWTs (1 VAWT is rated at 300 W). The blades are stacked pairs of Savonius and H-Darrieus blades, which show a performance power coefficient (C_p) of around 0.2 [18].

The power that is available in the wind is dependent on several variables. The main factors of power generation are wind speed (V) and capture area (A); increases in V and A produce higher power [19]:

$$P = \frac{1}{2} A \rho V^3 \quad (1)$$

where P is the electrical power, A is the capture area, ρ is the air density (1.225 kg/m^3 at sea level), and V is the wind speed. In using Equation (1), the capture area (A) was determined, where the 33 VAWTs generated power from wind speeds within the capture area.

Figure 4. Comparison of the wind current flow to wind turbines showing (a) the power available from the wind current used by a Horizontal Axis Wind Turbine (HAWT) and (b) the power available from the wind current used by the Vertical Axis Wind Turbine (VAWT) tree, a combination of 33 wind turbines.

In the design stages of the turbine tree, one combined Savonius–Darrieus turbine was evaluated in a wind tunnel at Prince of Songkla University, and a power curve was generated for wind speeds ranging from the cut-in speed to 22 m/s.

Figure 5 shows a “top view” of Figure 4b, which illustrates wind velocity contours around the preferred “V-shape” for the relative positioning of multiple VAWTs on a mast or wind tree. Simulations by various authors have demonstrated the increased efficiency of placing VAWTs in a staggered or V-shape configuration [20], so the wind tree design used in this research incorporated this feature. Our prototype tree consists of a Y – shape with arms situated at 120 degrees of separation – or has 3 open V-shapes (see Figure 5). Within a one V, the upwind, leading turbines are beneficial in that they increase the efficiency of the downwind turbines by creating a Venturi effect in the channel between adjacent VAWTs. We note here that while benefit derives from wind entering a V-shape, turbines situated downstream may suffer substantial wake effects (when an upstream turbine has extracted power from the wind), causing potentially large power reductions [21]. This phenomenon may cause reductions in our measured power output, and is discussed further in Section 4.2.

Figure 5. Drawing of the prototype showing the three arms, 120 degrees apart, upon which the turbines are suspended.

2.2.3. Economic Assessment

We applied a three-step analysis for the economic assessment of the prototype of the wind turbine. The assessment of wind energy potential was investigated in the first step, followed by economic feasibility in the second step, and then a sensitivity analysis was carried out in the final step.

1. Wind energy potential
 - Weibull distribution function

The Weibull distribution function was used to define the wind regime and forecast the wind power potential. In this research, two-year wind speed data from May 2019 to April 2021 taken from the Surat Thani mast were used for evaluation. The probability density function of the Weibull distribution is determined as [8,22,23]:

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (2)$$

where k is the shape parameter, c (m/s) is the scale parameter, and v (m/s) is the region's wind velocity.

According to Just et al. [24,25], k and c are determined as follows:

$$k = 0.83 v^{0.5} \quad (3)$$

$$c = \frac{\bar{v}}{\Gamma(1 + k^{-1})} \quad (4)$$

where Γ is the gamma function and $\bar{v}$ is the average wind velocity and is defined as follows:

$$\bar{v} = \frac{1}{n} \sum_{i=1}^n v_i \quad (5)$$

$\Gamma(x)$ is evaluated as:

$$\Gamma(x) = \int_0^{\infty} \exp(-u) u^{x-1} du \quad (6)$$

The standard deviation of the wind velocity illustrates how much variation exists in the average value of the wind velocity. It is evaluated as follows:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (v_i - \bar{v})^2} \quad (7)$$

The indicators of $\bar{v}$ and σ are evaluated similarly based on the Weibull distribution function [26].

- Wind power density

The wind power density and wind energy density per unit area are defined by Keyhani et al. [27] as:

$$p(v) = \frac{p(v)}{A} = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (8)$$

$$\frac{p(v)}{A} = \frac{1}{2} \rho c^3 \left(1 + \frac{3}{k}\right) T \quad (9)$$

where $p(v)$ is the wind power (W), $\frac{p(v)}{A}$ is the wind power density (W/m²), ρ is the air density, A is the rotor blade swept area (m²), and T is time.

- Evaluation of energy produced by the wind turbine

The capacity factor (C_F) of the wind turbine represents the ratio of the output energy generated by the wind turbine to the rated power. The capacity factor can be evaluated as [12,28]:

$$C_F = \frac{P_{Out}}{P_{Rp}} = \frac{e^{-\left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_i}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k} \quad (10)$$

where P_{Out} , P_{Rp} are the output power and the rated power, respectively, and v_i , v_r , and v_f are the cut-in speed, rated speed, and cut-out speed, respectively. The output energy of the wind turbine for a given time (T) is given by:

$$P_{Out} = C_F P_{Rp} T \quad (11)$$

In addition, when calculating the energy generation for a year, the annual energy is expressed as:

$$P_{Out} = 8760 C_F P_{Rp} \quad (12)$$

2. Economic feasibility

Four economic indicators that are used to assess economic feasibility, the Levelized Cost of Electricity (LCOE), the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Simple Payback Period (SPP) [29–33], were assessed as follows:

- Levelized Cost of Electricity (LCOE)

The cost of electricity generated by a wind turbine affects the decisions of an investor in a wind energy project. The viability of wind energy development is determined by its ability to produce electricity at a low generating cost per kW, so a correct evaluation of all electricity-producing costs for the entire life span of the wind turbine system is necessary [12].

Although there are different methods to assess the energy costs of wind turbines, the Levelized Cost of Electricity has frequently been used in previous research [7]. The process to assess the economic aspects of the wind turbine is as follows [9]:

We call I_0 the initial cost of the wind turbine and C_{OM} the operational and maintenance costs including land rent, insurance, tax, salary, and other costs. The yearly expenses of

operation and maintenance, C_{OM} , throughout the operating lifespan of the wind turbine of n years can be evaluated depending upon its initial invested capital as:

$$C_{OM} = mI_0 \quad (13)$$

where m is a fraction that evaluates C_{OM} depending on I_0 .

The cost of electricity generated by the wind turbine per kWh can be evaluated as per the following equation:

$$LCOE = \frac{I_0}{8760C_F P_{Rp} n} \left\{ 1 + m \left[\frac{(1+r)^n - 1}{r(1+r)^n} \right] \right\} \quad (14)$$

where n is the number of years in the lifespan of the wind turbine, and r is the rate of discount.

- Net Present Value (NPV)

The NPV method is generally used to assess the financial feasibility of renewable energy projects. Net present value operates on the theory of present value and evaluates the difference between the present values of cash inflows and the present value of cash outflows at a given target rate of return or cost of capital [34]. A project is economically viable if the NPV is positive, while a negative value denotes an investment that is not feasible [35]. The formula is as follows:

$$NPV = -I_0 + \sum_{t=1}^n \frac{CF_t}{(1+r)^n} \quad (15)$$

where I_0 is the initial cost, CF_t is the net cash flow in year t , r is the discount rate, and n is the number of years for the lifespan of the wind turbine.

According to Ertürk [36], the discount rate is the weighted average cost of capital (WACC). It is defined using the following equation:

$$WACC = w_d r_d (1-t) + w_e r_e \quad (16)$$

where w_d is the weight of the debt, r_d is the cost of the debt, t is the tax rate, w_e is the weight of the equity, and r_e is the cost of equity.

Cost of debt: the cost of the debt is evaluated using the following equation.

$$r_d = r_f + DRP + CRP \quad (17)$$

where r_d describes the cost of the debt, r_f describes the risk-free rate, DRP describes the debt risk premium, and CRP indicates the country risk premium [36].

Cost of equity: the cost of equity is defined based on the CAPM model by calculating the country risk premium [36].

$$r_e = r_f + \beta_1 (r_m - r_f) + CRP \quad (18)$$

where r_e describes the cost of equity, r_f describes the risk-free rate, β_1 describes leveraged beta, which defines the risk of the leveraged company on the market, and r_m describes the market premium.

- Internal Rate of Return (IRR)

The internal rate of return is the discount rate at which the net present value of the total cash flow of a project is equal to zero. The attractiveness of a project is defined on the basis of the internal rate of return. The internal rate of return is used to compare against the enterprise's required rate of return. The larger the IRR obtained, the more desirable the project [37].

$$-I_0 + \sum_{t=1}^n \frac{CF_t}{(1+IRR)^n} = 0 \quad (19)$$

where IRR is the internal return rate.

- Simple Payback Period (SPP)

The payback period indicates the length of time requested for a project's accumulated revenue to return its initial cost through the yearly cash flow. A short payback period is better than a long one for a particular project. In this study, the simple payback period is applied to assess the time of recovery of investment of the project. Generally, the *SPP* can be calculated from the following formula [34].

$$SPP = \frac{I_0}{AAR} \quad (20)$$

In (20), $AAR = AEP \times P$, I_0 is the initial cost, AAR is the average annual revenue based on hourly production, AEP is the yearly energy production, and P is the price of energy accepted by the electricity company.

3. Variances for Monte Carlo and sensitivity NPV analysis

The power function provides the base equations from which to calculate Monte Carlo variances of expected annual energy output (kWh/year) for a prototype with a certain wind speed. Considering the information stated, some parameters in Monte Carlo analyses were assumed as fixed, some to be probabilistic, and some were calculated using other parameters. The distribution of each parameter referred to was given by M. Ertürk et al. and Rocha et al. [36,38]. The suppositions about the parameters are summarized in Table 3.

Table 3. Probability distribution and definition of parameters for input variables.

Parameter	Distribution	Minimum	Maximum	More Probable
Initial cost (USD)	Uniform	14,102	17,628	
O&M Cost (%)	Uniform	1	3	
Lifetime (years)	Triangular	20	30	25
Salvage value ratio (%)	Triangular	5	20	20
Energy Price (USD/kWh)	Triangular	0.18	0.22	0.2
Capacity factor (%)	Uniform	0.10	34.81	
Inflation (%)	Uniform	1	3	2
Payment deadline (years)	Uniform	5	25	
Interest rate	Triangular	2	6	4
Cost of debt (%)	Calculated			
Cost of equity (%)	Calculated			
Weight of debt (%)	Uniform	0	100	
Weight of equity (%)	Calculated			
WACC (%)	Calculated			
Annual energy production (kWh)	Calculated			

The Monte Carlo analysis included the uncertainty involved in the existing project variables, and was run using 10,000 simulations for the NPV, SPP, and IRR. We found 10,000 trials to be a sufficient number of iterations, because with this number, the standard deviation at a 95% confidence level converged considerably.

For the simulation in this study, the capital structure was assumed to vary from 0% to 100% of the weight of debt, with a uniform distribution of a minimum of 5 years and a maximum of 25 years being considered for the payment deadline. In relation to the lifetime of the prototype, a triangular distribution was defined based on the lifetime of the material used to make the prototype, with 20 years being the shortest and most probable lifetime and the maximum lifetime being 25 or 30 years. A uniform distribution was adopted with a maximum value of 17,628 USD, then one minimum value, assuming the initial cost subsequently reduces by 20%, to 14,102 USD. A triangular distribution was assumed for the electricity price, in which the price varied from -20% to $+20\%$.

In terms of capacity factor, our scenario modeled from the cut-in speed up to the cut-out speed. Wind speed was regressed with the capacity factor and these cut-in and cut-out speeds were calculated to correspond to capacity factors of 0.10 and 34.81, respectively.

Following this, we ran simulations for the actual wind and capacity factor data as recorded at our Surat Thani location.

We used the Crystal Ball [39] add-in for Microsoft Excel in order to run the Monte Carlo simulations. Table 3 presents the assumed input distributions and values input into Crystal Ball.

Finally, for insight into not only the economic viability of the prototype in Thailand in general, but as tested at the Surat Thani location, for comparison we assessed the results of sensitivity analyses in two other situations of a higher capacity factor. Using our regression analysis, we input capacity factors for wind speeds at heights of 2.5 m and 10 m recorded at Chiang Mai [40]. Our VAWT tree has maximum height of 12 m, with all turbines above 2.5 m, so assessing sensitivity at 2.5 m will produce a conservative estimate of the VAWT tree's performance.

3. Results

3.1. Wind Energy Potential

3.1.1. Wind Characteristics

The monthly variation in wind speeds from May 2019 to April 2021 is plotted in Figure 6 and data provided in Table 4, below. The annual average speed over the two years was 2.58 m/s. The highest monthly average was in February (2.84 m/s), while the lowest was in October (2.35 m/s).

Figure 6. Monthly variation of wind speed at 12 m.

Table 4. Monthly mean wind speeds and standard deviations.

Months	V	σ	Months	V	σ	V Average	σ Average
May 2019	2.48	1.80	May 2020	2.54	2.00	2.51	1.90
June 2019	2.57	1.95	June 2020	2.52	2.01	2.55	1.98
July 2019	2.45	1.90	July 2020	2.50	1.86	2.48	1.88
August 2019	2.43	1.98	August 2020	2.51	1.87	2.47	1.93
September 2019	2.58	1.96	September 2020	2.62	1.90	2.60	1.93
October 2019	2.36	1.89	October 2020	2.35	1.95	2.36	1.92
November 2019	2.40	1.87	November 2020	2.47	1.84	2.44	1.85
December 2019	2.69	1.94	December 2020	2.65	1.85	2.67	1.90
January 2020	2.80	1.97	January 2021	2.76	1.88	2.78	1.92
February 2020	2.74	1.99	February 2021	2.84	2.05	2.79	2.02
March 2020	2.72	1.93	March 2021	2.70	1.91	2.71	1.92
April 2020	2.65	2.00	April 2021	2.60	1.89	2.63	1.94
Yearly	2.57	1.93	Yearly	2.59	1.92	2.58	1.92

Table 5 provides data for the monthly mean shape parameter, scale parameter, and power density. The results reveal that the shape and scale parameters are in the range of 1.27–1.40 and 3.22–4.13 m/s, respectively, in different months from May 2019 to April

2021. The highest and the lowest values of wind power were equal to 42.68 W/m² and 28.43 W/m² and happened in February 2021 and May 2019, respectively.

Table 5. Monthly Weibull parameters (k , c) and power density.

May 2019– April 2020	k	c	P (W/m ²)	May 2020– April 2021	k	c	P (W/m ²)
May 2019	1.31	3.63	28.43	May 2020	1.32	3.53	34.63
June 2019	1.33	3.71	33.88	June 2020	1.32	3.48	34.89
July 2019	1.30	3.54	30.41	July 2020	1.31	3.65	30.15
August 2019	1.29	3.29	32.70	August 2020	1.31	3.63	31.36
September 2019	1.33	3.73	33.81	September 2020	1.34	3.86	32.82
October 2019	1.28	3.22	29.74	October 2020	1.27	3.26	29.97
November 2019	1.29	3.41	29.14	November 2020	1.30	3.71	29.35
December 2019	1.36	3.90	34.94	December 2020	1.35	3.94	32.35
January 2020	1.39	4.06	38.09	January 2021	1.38	4.06	36.98
February 2020	1.37	4.11	37.07	February 2021	1.40	4.13	42.68
March 2020	1.37	3.98	36.65	March 2021	1.36	4.04	36.11
April 2020	1.35	3.82	35.91	April 2021	1.34	3.81	33.50

3.1.2. Design Evaluation

Figure 7 shows the power curve generated from wind tunnel testing of the turbine for various wind speeds for the 33 VAWT tree. At wind speeds of 2–8 m/s while operating the generator, all of the VAWTs in the wind tree could not operate within the V shape, while at wind speeds of 8–12 m/s they were fully operational and generated increasing peak power to a maximum of 5.5 kW. After that, the power decreased slightly between 12 and 14 m/s, whereafter it remained stable above 14 m/s, perhaps influenced by the vortices effect [41]. Each VAWT in the wind tree may experience a slight reduction in power at wind speeds over about 13 m/s. Although the maximum rated power of the prototype is 10 kW, the normal operation of VAWTs will produce power that is affected by many variables that may reduce the power generation, such as the wind profile at a specific location, the configuration of the V shape, and the vortices effect.

Figure 7. The power curve resulting from the prototype using 33 VAWTs.

3.1.3. Wind Energy Production

The amount of power generated monthly and the yearly capacity factor of the prototype are illustrated in Figure 8. The results obtained show that the highest monthly energy output was 168 kWh in February 2021, while the lowest monthly energy output was 72.5 kWh in October 2020. The total annual power output from this prototype from May 2019 to April 2020 was 1386.1 kWh, with the capacity factor being 1.58%, and then 1506.1 kWh and 1.72% for the period May 2020 to April 2021. The average power output for the entire period of May 2019 to April 2021 was 1446.1 kWh.

Figure 8. The monthly energy output of the prototype in Surat Thani.

3.1.4. Wind Turbine Cost

The total cost of the prototype wind turbine is USD 17,628. The following Figure 9 presents the distribution of component costs for the wind tree installed in Surat Thani. The tower cost represents the largest investment factor, followed by the generator cost, the foundation cost, the blades cost, the system control cost, the control system house, and other costs.

Figure 9. The component costs of the wind tree prototype.

3.2. Economic Feasibility Analysis

The economic analysis of the prototype wind turbine was carried out to evaluate the cost of one kWh of power generated by the wind tree operated at the research site with assumptions as follows:

The lifetime of the wind tree (n) was assumed to be 25 years (as estimated in [42]).

The inflation rate was assumed to be 2.41% [38].

The operation and maintenance costs (C_{OM}) were about 1%.

The wind tree was assumed to generate an identical amount of energy output each year throughout its lifespan [7].

The salvage value was assumed to be 20% of the initial cost based on the assumption of the IEA (2010) [43].

The U.S. dollar (USD) to Thai Baht (THB) exchange rate was taken to be 1 USD = 29.7 THB [44].

The regulated price for wind power was fixed at USD 0.204 per one kWh [45].

According to the report of the Electricity Generating Authority of Thailand (EGAT), the electrical energy from fossil fuel consumption released 0.483 kg of carbon dioxide into the atmosphere for one kWh in 2019 (carbon coefficient) [46].

The sale rate of carbon credits was USD 11.14 ton [15].

The discount rate (r) is the weighted average cost of capital (WACC), which was defined as follows: the weight of debt (w_d) was 50%, and the levered β_1 was evaluated from the unlevered β_1 for the renewable energy sector, which is given by Damodaran [47]; the unlevered beta value was 0.77. The levered β_1 is shown in Equation (21) [38].

$$\beta_{levered} = \beta_{unlevered} \left(1 + \frac{D}{E}\right) (1 - t) \quad (21)$$

The risk-free rate, $r_f = 2.14\%$, was obtained by the average of the daily indicator of the 10-year U.S. Treasury bond for the period between 2 January 2019 and 31 December 2019 [48]. DRP and CRP were assumed to be 2% [36]. Hence, the cost of debt was evaluated at a rate of 6.14%. The value r_m was determined through the total of the market risk premium (7.93%) as in Damodaran [49], and the r_f (2.14%), resulting in $r_m = 10.73\%$. In addition, Thailand's corporate tax rate at the time was 20%. As a result, the cost of equity was calculated to be 15.16%. Assuming a North American inflation rate of 2.41% [38], the deflated costs of the debt and equity were 3.64% and 12.45%, respectively. Thus, the WACC would be 7.68%.

One half of the total initial cost of the project (50%) was assumed to be funded by a loan with a yearly interest rate of 4% [50] for a repayment period of 25 years. The annual financial costs (AFC) are evaluated as follows [37]:

$$AFC = TFC \times CRF \quad (22)$$

In (22), TFC is the total financing capital and CRF is the capital recovery factor. The CRF is calculated by the following formula:

$$CRF = \frac{i(1+i)^m}{(1+i)^m - 1} \quad (23)$$

where i represents the interest rate of the loan, and m is the payment period (Table 6).

Table 6. Financial costs.

Total Financing Capital (TFC)	8814 USD
Interest rate (i)	4%
Payment period (m)	25 years
Capital recovery factor (CRF)	0.064
Annual financial costs (AFC)	564.201 USD/year

As shown in Table 7, the Levelized Cost of Electricity was found to be USD 0.54 kWh, the NPV is USD −20,946.29, the IRR is −14%, and the payback period is 60 years (the SSP of 60 years was obtained with the assumption that the wind tree's lifespan could be extended to 60 years).

Table 7. Economic results.

Parameter	Value	Unit
Levelized cost of electricity (LCOE)	0.54	USD/kWh
Cost of capital (WACC)	7.68	%
Net present value (NPV)	−20,946.29	USD
Internal rate of return (IRR)	−14	%
Payback period (SPP)	60	Years

3.3. Sensitivity (Uncertainty) Analysis

We constructed a linear regression model between capacity factor and wind speed. The trend line of 24 data points (capacity factor versus wind speed) represented the energy generation from the wind prototype as influenced at all recorded wind speeds at Surat Thani. The whole sample set used in the regression model is given in Table 8.

Table 8. The sample for the regression model.

Wind Speed (m/s)	Capacity Factor (%)	Wind Speed (m/s)	Capacity Factor (%)
2.48	1.15	2.54	1.61
2.57	1.76	2.52	1.76
2.45	1.16	2.50	1.59
2.43	1.21	2.51	1.30
2.58	1.67	2.62	1.86
2.36	1.01	2.35	0.97
2.40	1.21	2.47	1.67
2.69	1.81	2.65	1.55
2.80	2.15	2.76	2.03
2.74	2.16	2.84	2.50
2.72	1.95	2.70	2.15
2.65	1.74	2.60	1.72

For the estimation of the parameters of the regression model, the regression tool in Excel was used. The results are given in Table 9.

Table 9. The results of the regression model estimation for capacity factor.

Statistics	Values
Sample size	24
Coefficient of wind speed	0.0267
F value	128.91
R square	85.42%
Intercept	−0.052
t-Stat of intercept	−8.62
t-Stat of Coefficient	11.35

The goodness of fit of the sample can be seen from the graph given in Figure 10, which describes the sample data and the best fit line generated by the regression model.

Lastly, the electricity generation for different wind speeds that was used to analyze the potential of the prototype was estimated using the regression model. The estimated power generation values are given in Table 10.

In addition to the prior base case analysis, the economic feasibility of the prototype was analyzed by conducting Monte Carlo analyses for NPV, IRR, and SPP. We performed 10,000 simulations, with the probability distributions for the variables as given in Table 3.

Figure 10. Scatter diagram and linear regression line.

Table 10. Power generation for different wind speeds.

Wind Speed (m/s)	Capacity Factor
2	0.10%
3	2.77%
4	5.44%
5	8.11%
6	10.78%
7	13.45%
8	16.12%
9	18.79%
10	21.46%
11	24.13%
12	26.80%
13	29.47%
14	32.14%
15	34.81%

Figure 11 shows that the feasibility probability for the prototype through its possible range of speeds from cut-in to cut-out speed (2–15 m/s) was 64.93% (the proportion of the distribution in blue, where NPV > 0). Put another way, in this proportion of instances, with the specified distributions and wind speeds, the prototype was economically viable. Considering NPV values, the lowest NPV value was −27,857.39 USD, and the highest NPV value was about 52,182.74 USD. An average of 10,297.83 USD was obtained. The standard deviation of these 10,000 values was 19,921.78 USD.

Figure 12 shows that the distribution of the IRR is skewed to the left and the average IRR value is 13%. The lowest IRR value is −37%, the highest IRR value is 41%, and the standard deviation of these 10,000 values is 15%. Around 66.45% of the IRR values are higher than 7.68%.

Figure 13 shows that the distribution of the SPP is skewed to the right with a skewness of 9.27. The average SPP value is 15.45 years, the lowest SPP value is 2.22 years, the highest SPP value is 882.07 years, and the standard deviation of these 10,000 values is 45.73 years. Around 89.72% of the SPP values are lower than 25 years.

Figure 11. Probability distribution for the NPV.

Figure 12. Probability distribution for the IRR.

Figure 13. Probability distribution for the SPP.

Results for percentage certainties for the above sensitivity analysis and subsequent analyses using Surat Thani, Chiang Mai 2.5 m, and Chiang Mai 10 m data are given in Table 11 below. Although when considered through its entire range of supported wind speeds, the tree produces possible certainties (NPV = 64.9%; IRR = 66.5%; SSP = 89.7%), when situated specifically at the Surat Thani site, negative values were obtained for all measures. At Chiang Mai, situated near ground level, the tree has NPV and IRR certainties of approximately 60%, with SPP = 100%, and even more promisingly, the VAWT has NPV and IRR certainties of near 85% and a SPP certainty of 100% at a height of 10 m.

Table 11. Summary of percent certainties for NPV, IRR, and SPP for: (a) the full range of wind speeds for VAWT from the cut-in to the cut-out speed of the turbine; (b) VAWT as situated at the Surat Thani site; (c) VAWT if situated at Chiang Mai (2.5 m high); (d) VAWT if situated at Chiang Mai (10.0 m high).

Situation	NPV	IRR	SPP	Interpretation
(a) Cut in–Cut out of VAWT (2–15 m/s)	64.93%	66.45%	89.72%	Possibly feasible
(b) Surat Thani (2.35–2.84 m/s)	0	0	0	Not feasible
(c) Chiang Mai 2.5 m (4.8–9 m/s)	59.93	59.96	100	Marginally feasible
(d) Chiang Mai 10 m (5.8–10.3 m/s)	84.83	84.86	100	Probably feasible

4. Discussion

The analysis of the prototype used in this paper generated useful insights when considering the characteristics of the site and the prototype, the initial cost, and the estimated lifetime. While varying LCOE, SPP, and IRR, we showed that under these conditions, economic viability was suboptimal. This finding was arrived at in this specific circumstance, in which the average annual windspeed was near or only slightly greater than the cut-in wind speed required for the prototype (see Figure 6). After a two-year experiment, the data provide useful information that could be used to improve the financial feasibility of the prototype or recommend suitability for use in other locations. We therefore have the following suggestions based on our consideration of the physical attributes of the site and the prototype and the economic sensitivity analysis.

- Regarding the site selection and prototype characteristics.

4.1. Site Characteristics

At our experimental site, we found a low average annual wind speed value, less than v_r , the rated wind speed. Clearly, while the prototype, when used as extant, may not be economically viable at this general site, there may be many other general locations for which it is suitable, where the wind speed is higher.

In terms of our specific site, the location was occluded by trees on three sides and by a large building on the fourth side. This may have contributed to our lower recorded wind speeds, and our inability to attain the optimal capacity. This is particularly relevant with respect to the contribution of the VAWTs on the tree levels closer to the ground. The tower of our prototype is 12 m high with four levels, so the first level with the largest number of wind turbines (12) is only 4 m above the ground. This design might generate more energy if it is installed in more open areas, at the top of hills, or on building rooftops, for example. Careful prior consideration needs to be paid to the specific characteristics of the site when selecting a location for a wind tree of this particular design.

4.2. Prototype Characteristics

As mentioned above, the prototype looks like a triangle with the widest section nearest the ground. Nearly two thirds of the VAWTs are on the two lowest levels, meaning the largest potential contribution to energy production comes from the level that probably experiences the lowest wind speed (wind speed generally increases with height [51]). Energy production may therefore be substantially enhanced by using a modification to the

prototype that has a greater proportion of VAWTs on higher levels. Such a design may be more like an inverted triangle or rectangle.

The V-shape benefit accrues from the wind striking the V-shape at an optimal angle, parallel to axis of symmetry, toward the open V. However, when the wind strikes at the optimal direction for one V in the design, this means that one third of the VAWTs on the prototype (i.e., those on the arm that lie behind the V) will be operating sub-optimally due to the wake effect and shielding by other VAWTs. When there is at least some degree of alignment with the incident wind direction among adjacent turbines, wake losses will be incurred [52]. In low wind conditions, this may greatly reduce the power (by up to 33%). Put another way: when the wind angle is optimized for one V in the design, the efficiency of the remaining arm is probably minimized. Therefore, with respect to wind direction, the energy production of the prototype as a whole should be researched from various input angles, because the maximum contribution to energy generation may lie at an intermediate angle where all or a substantial proportion of the VAWTs can move at some speed. Rather than emphasizing maximizing the energy output of individual VAWTs or those only in one V, the energy potential of the whole prototype, 33 VAWTs, should be assessed through all incident angles and maximized.

When the incident angle at which the energy production of the whole tree is maximized is known, it is recommended that the annual directional characteristics of the wind be then carefully considered before affixing the tree in its position to the ground. Since our prototype as tested in this study was attached to the ground in a fixed orientation, this may have been a contributing factor in producing less than optimal results. In seasonal monsoon climates, this probably means affixing the device to the ground with an orientation so that the energy production is maximized twice a year (typically winds peak at a maximum at some point in the dry and wet monsoons, often approximately 180 degrees apart). At Surat Thani where this research was done, the predominant wind directions are opposite, being Northeast and Southwest [53].

With the results of studies into maximization with respect to angle, and wind directional characteristics in mind, consideration might be given to using a prototype that has only two arms (one V). In areas with one predominant wind direction over the course of a year, the V could be fixed to the ground with the V's axis of symmetry parallel to the prevailing wind (for example, in Nakhon Phanom the wind is predominately from the East–Southeast [54]).

A better option with a single V in a situation with a varying or bimodal wind direction would be to make the V containing the VAWTs movable, so that the wind always faces the open V-shape. This could be done by physical (i.e., using a wind vane) or electronic means. This would always maximize the energy output and could substantially increase the potential of this kind of prototype in low-wind, variable-direction situations.

- Regarding economics (sensitivity analysis).

The analysis showed that the LCOE of the wind turbine in this location is neither cost-competitive nor financially feasible considering the electricity price offered by the Electricity Generating Authority of Thailand (EGAT). The prototype has a negative NPV, the payback period is longer than the lifetime of the system, and the IRR is less than the cost of capital. Hence, this wind turbine prototype for energy generation is not economically feasible given the wind profile at this location.

More optimistically, our sensitivity results show the prototype, for the assumed values of variables, could have values of economic feasibility of 64.93% with average wind speeds that vary from 2 to 15 m/s. When we investigated situating the wind tree prototype at Chiang Mai, we produced much more promising results than at Surat Thani. This was especially so when situating the tree at a height of 10 m. At this height, the NPV and IRR certainties become very probable at nearly 85%, alongside a SSP of 100%. As mentioned, higher wind speed values may be achieved by maximizing efficiency via optimizing site selection and orientation decisions. In the context of Thailand, for example, this VAWT

would be well suited to a location such as Chiang Mai, with an average annual wind speed of 7.7 m/s [40].

Our analysis also investigated the effect of lowering the initial costs. When we assumed a reduction in initial costs of 20% in the sensitivity analysis, the results were more favorable. There may be several ways to reduce initial costs and increase the viability of this prototype.

For example, it can be seen from Figure 9 that about 75% of the initial prototype component costs are from tower, generator, and blade costs. We suggest that if a two-arm fixed or moveable design is constructed, these initial costs would be significantly reduced, and simultaneously higher power generation may be achieved so that a positive NPV may be attained.

In addition, we note that this prototype was designed and produced in Thailand for the first time, so it is likely that the initial cost of the wind turbine was not optimal. As more economical materials are sourced and the final production costs become optimized, costs would probably be less.

As well, because of its compact and lightweight design, this prototype may be suitable for installation on the rooftop of a building. Some costs with respect to the foundation may be reduced by using this approach, if the roof used is built in a reinforced manner.

5. Conclusions

In this paper, the major aim was to evaluate the possibility of using a novel, small-scale vertical axis wind turbine tree in the south of Thailand at a low-wind site. For this objective, we measured the wind speed at a 12 m height for a period of two years from May 2019 to April 2021. These data were then utilized, and the Weibull distribution function was employed for wind data analysis. The wind energy potential and wind characteristics were investigated. Furthermore, the performance and economic viability of the novel wind turbine were evaluated using a feasibility analysis and a sensitivity analysis.

The monthly average wind speeds were between 2 and 3 m/s. The average annual wind speed and standard deviation were equal to 2.58 and 1.92, respectively. The maximum wind power occurred in February 2021 with a value of 42.68 W/m², whereas the minimum value happened in May 2019 and was equal to 28.43 W/m². Furthermore, Weibull's *k* values, which measure the wind potential of the site, were higher during the winter–spring dry season months and lower during the summer–autumn rainy period; the lowest *k* value was recorded in October 2020 (1.27) and the highest was in February 2021 (1.40).

We have discussed some design modifications that can enhance the potential of this VAWT tree, particularly in low wind speed conditions. These include design changes that: (a) maximize the number of turbines that receive the greatest wind velocity; (b) take into account orientation and wind direction; and (c) a reduce wind shadow areas.

In terms of economic analysis at a low-wind site such as this, we conclude that the characteristics of this design did not produce economic viability at the Surat Thani site, after considering the Weibull distribution and modeling with LCOE, IRR, SPP, and NPV. However, our sensitivity analysis showed that the feasibility probability (NPV) of the prototype would be 64.93% for a wind speed from 2 to 15 m/s. Thus, if situated at a site such as Chiang Mai, especially when at a height of 10 m, we conclude that this prototype would be economically viable. When exploring the future expanded use of a wind tree of these characteristics in a country such as Thailand, some things need to be borne in mind. As aforementioned, Thailand is a country that does not have a large number of areas that have high wind speed [15], so the potential situations for installation of this turbine have to be considered carefully. Areas in Thailand that have higher wind speeds are nearly always those places at higher elevation, so it will be in these regions that the installation of a VAWT such as this will become economically viable. In addition, since our VAWT is domestic in scale, with a low energy output, to ensure positive SPPs (i.e., a positive return on investment in less time than the life of the turbine), careful site selection is essential.

Because of their lower capacity, smaller-scale renewable energy systems often require subsidies to encourage use in marginally suitable conditions, especially those areas with less sunlight or wind. Unfortunately, in Thailand where this study was conducted, government subsidy schemes for wind power have recently been allowed to expire. On a more optimistic note, the Thai government announced in March 2020 Thailand's Power Development Plan, which promises to have increases in wind power of 90 MW per year in 2023–2025 [55]. With this new scheme, the potential situations for smaller-scale wind turbines will be enhanced.

Site selection, possible prototype design alterations, and economic subsidies should be taken into account so that then a prototype of this size and characteristics will produce satisfactory results.

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