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Comparison of Small-Scale Wind Energy Conversion Systems: Economic Indexes

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Abstract: Wind energy is considered as one of the most prominent sources of energy for sustainable development. This technology is of interest owing to its capability to produce clean, eco-friendly, and cost-effective energy for small-scale users and rural areas where grid power availability is insufficient. Wind power generation has developed rapidly in the past decade and is expected to play a vital role in the economic development of countries. Therefore, studying dominant economic factors is crucial to properly approach public and private financing for this emerging technology, as industrial growth and energy demands may outpace further economic studies earlier than expected. In this study, a strategy-focused method for performing economic analysis on wind energy based on financial net present value, levelized cost of energy, internal rate of return, and investment recovery period is presented. Numerical and simulation results depict the most optimal and economical system from a 3 and a 10 kW wind energy conversion system (WECS). Moreover, the aforementioned criteria are used to determine which WECS range is the most suitable investment with the shortest payback period. Finally, an economically viable and profitable wind energy system is recommended.

Keywords: renewable energy; wind energy; economic indexes; net present value; levelized cost of energy; HOMER

1. Introduction

A sizable portion of the world's population still lives in villages with limited available grid-based electrification facilities. Statistically, approximately a billion people in the world live without electricity, 80% of whom are from village areas [1,2].

Energy is an important source of social and economic development [3–5]. In China's current power industry structure, thermal power generation accounts for approximately 66%, hydroelectric power comprises approximately 24%, and other power generation methods make up 10% [6]. The huge coal consumption of thermal power generation has further expanded China's energy gap, and the burning of coal is harmful to the environment [7,8]. Carbon dioxide and smoke emitted into the atmosphere account for 70% of the total amount of pollutants in China, which is not encouraging for the country's long-term development [9]. Although China has abundant water resources, the one-time economic and human investments for hydropower station construction are higher than those for wind power station construction [10]. The construction period for a hydropower station is comparatively long, but its impact on the surrounding ecology and residents is compensable [7], and such a station can be used on a large scale. However, water resources for hydropower generation are limited. Since 2014, China's hydropower has experienced a bottleneck. In terms of nuclear energy, China's natural uranium resources are in short supply and can only support 50 standard nuclear power plants for the next 40 years [11]. In the current era, the optimal use of wind energy has been widely researched [12]. Moreover, the output characteristics of wind power and its impact on grid power flow nodes after grid connection have been analyzed [13]. Voltage oscillation, power prediction, and other wind energy conversion system (WECS) control theories caused by wind power grid connection are hot topics [14]. In [15], the authors used a standard energy cost analysis method and presented the value cost analysis method to perform technical power generation assessments on six small, medium, and large WECSs with rated powers of 20, 35, 275, 500, 1000, and 2000 kW.

To exploit the resolution of wind data, the hourly behavior given by the hybrid optimization model for electric renewables (HOMER) and scale that value until the required result is achieved [16]. In this study, we select the HOMER (HOMER Pro, National Renewable Energy Laboratory, Golden, Colorado, USA), which is a widely used software in this field [17,18]. The software requires different inputs depending on the level of detail available, that is, available resources, including the on-grid option, energy demand, and generation components, such as turbines or engines and several levels of detailing. In addition, emissions estimation is considered. Finally, a range of constraints are imposed on the model, such as production limit and scheduled generation.

The motive behind the adoption of this software is its capacity to perform preeminent possible configurations under a set of conditions and determine its financial feasibility. Different scenarios can be compared, and the incremental benefits of changing several variables can be determined. A further optimistic feature of this tool is the high resolution allowed for input data. For instance, RETScreen (Canada) uses only the monthly electricity demand, which implies prefeasibility analysis. Meanwhile, the HOMER allows the entering of an electric load in a time step equal to an hour, thereby obtaining refined results. Another important feature of the HOMER is its ability to provide a characteristic charge curve for a demand depending on the type of client being modeled [19]. Although the HOMER is a powerful tool, all the options presented have disadvantages. For example, the HOMER allows only the minimization of the net present cost (NPC) as an objective function, and multifunctional optimization cannot be carried out. Fortunately, this limitation does not diminish our study, as its aim is to analyze the financial viability of each instance project. Moreover, other limitations are related to the presence of a battery bank.

A notable feature of engineering economic analysis is comparison and selection among multiple options. To obtain the net present value (NPV), the levelized cost of energy (LCOE) [20], the internal rate of return (IRR), and the payback period, the NPV and calculated NPV difference in the simulation are arranged [3,15,21]. Five comprehensive economic evaluation criteria, including NPV difference, are analyzed. Next, the results are compared with the economics of two different WECS ratings. Finally, the most economical option is chosen. In this study, the existence of objective factors, such as different WECS specifications, makes it impossible to use the five economic evaluation indicators to determine the advantages and disadvantages of the schemes directly. For an economic analysis of mutually exclusive technical solutions, selecting two options from the economic evaluation criteria of the respective programs (absolute effect test) and calculating the difference between the two solutions are necessary steps. The optimal scheme is selected according to NPV ΔNPV and IRR ΔIRR.

Shortcomings are found in certain aspects. For example, in one aspect, the load is too idealistic and does not reflect the complex diversity of the load of a real system. The WECS sample is relatively small, and economic comparisons of other WECS models are unavailable. A comparison of other models may reveal a WECS with improved economic performance.

This study was conducted in Huai'an, Jiangsu Province of China, from January to December 2018. Wind speed parameters and variation are maintained by using the cumulative Weibull equation. The mentioned assumptions are adjusted according to the site area, and the related environmental conditions of rural areas can benefit from this study. Numerous researchers have conducted economic studies on small-scale wind turbines; however, our contribution is a specific regional case study on Huai'an, China, which can be implemented in other rural/agriculture areas. The same parameters can be used for a simulation study, with minor environmental parameter changes.

2. Related Studies

2.1. Types of WECSs

The horizontal-axis WECS has rotated axis blades that are parallel to the horizontal axis of the ground and the direction of airflow. Most commercial wind turbines fall into this category. A flat-axis WECS has multiple important advantages, such as low cut-in wind speed and cutout protection when overloaded. Typically, horizontal-axis WECSs have a high power factor [22].

Most commercial wind turbines are three-bladed units, which are stable owing to their relatively aerodynamic load. Smashing the generator and gearbox of a horizontal-axis WECS on the tower side is necessary, thereby making the design complicated and expensive. However, owing to its stable power generation performance and high safety factor, current commercial wind turbines are designed as horizontal-axis wind turbines, which are depicted in Figure 1. A vertical-axis wind turbine is shown in Figure 2.

Figure 1. Horizontal-axis wind turbine. Reprinted from Li [23] with permission under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0)

Figure 2. Vertical-axis wind turbine. Reprinted from Li [23] with permission under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0)

The axis of rotation of a vertical-axis WECS is perpendicular to the ground, and the direction of intake is nearly vertical. Vertical-axis wind turbines can extract wind in every direction, and no complicated yaw devices are required. Moreover, the generators and gearboxes of such systems can be placed on the ground, thereby making the tower design simpler and more economical than that of other designs. In addition, the maintenance of a vertical-axis wind turbine can be carried out on the ground. This type of wind turbine does not require a pitch control system when using synchronous generators, as presented in Figure 2 [22]. However, vertical-axis wind turbines have disadvantages, such as self-starting difficulties, speed control problems when over speeding, and low overall power generation efficiency. To assess the exact potential of a wind project, determining the basic economic factors and configuration of an energy conversion system is important. When small wind turbines are installed, the generated and transmitted power are set to a direct current by a rectifier [24,25]. A simplified structure of a WECS is shown in Figure 3 [26].

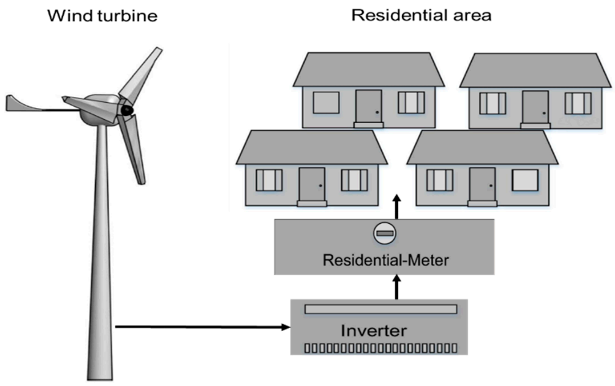

Figure 3. Simplified scheme of a wind energy conversion system. Reproduced from Becerra et al. [26], with permission from Elsevier. Copyright (2017) Elsevier Ltd.

2.2. Wind Speed

Wind has intermittent speed by nature and is extractable. Average wind speed can be described using the Weibull distribution function. The cumulative Weibull distribution function is expressed in Equation (1), as follows:

$$F(\mu) = 1 - e^{[-(\frac{\mu}{c})k]} \tag{1}$$

where c and k are the scale and shape parameters of the cumulative Weibull function, respectively.

Wind speed is generally decomposed into four components, namely, normal wind speed, gust, ramp gradient wind, and background noise wind [2].

1. Normal wind speed.

Time affects wind speed, which means that a number greater than zero can be used.

$$V_{wa} = K_b, \tag{2}$$

where V_{wa} is the basic wind speed, and K_b is a constant greater than zero.

2. Wind gust.

The instantaneous changing of wind can be described as gusts. Wind speed can be seen as a cosine piecewise function when it changes.

$$V_{WG} = \begin{cases} 0, & t < T_{1G} \\ \frac{G_{\max}}{2}\left[1 - \cos 2\omega\left(\frac{t - T_{1G}}{T_G}\right)\right], & T_{1G} \le t < T_{1G} + T_G \\ 0, & t \ge T_{1G} + T_G \end{cases} \tag{3}$$

where V_{WG} represents gust wind speed (m/s), $G_{\max}$ is the maximum wind speed (m/s) for gusts, T_{1G} is the start time for gusts (s), and T_G represents the gust cycle (s) [14,27].

3. Ramp wave gradient.

The ramp component is used to reflect the gradual nature of wind speed, and its variation is linear [11,20].

$$V_{WR} = \begin{cases} 0, & t < T_{1R} \\ R_{\max}\frac{t-T_{1R}}{T_{2R}-T_{1R}}, & T_{1R} \le t < T_{2R} \\ R_{\max}, & T_{2R} \le t < T_{2R} + T_R \\ 0, & t \ge T_{2R} + T_R \end{cases} \tag{4}$$

where V_{WR} is the ramp wind speed (m/s), $R_{\max}$ is the maximum ramp wind velocity (m/s), T_{1R} is the start time (s), T_{2R} is the end time (s), and T_R is the maintaining time (s) [3,28].

4. Background noise.

$$V_{WN} = 2\sum_{i=1}^{N} \sqrt{S_v(\omega_i)\Delta\omega}\cos(\omega_i t + \varphi_i) \tag{5}$$

where V_{WN} is the background noise wind speed (m/s). The actual wind speed of a wind turbine can be expressed as follows:

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \tag{6}$$

To capture the wind energy resource status of an area, the Weibull distribution in the HOMER software is used to calculate the average wind speed.

2.3. Economic Evaluation Criteria

The NPC is the sum of the present value of outflows generated by a capital asset, and its calculation formula is as follows:

$$NPC = \sum_{k=0}^{n} \frac{CO_k}{(1+i)^k} \tag{7}$$

where n is the investment period, CO_k is the cash outflow for kth year, and i is the predetermined discount rate. Levelized Cost of energy (LCOE) consumes energy in the cost of input, such as consumer electricity, coal, diesel, and so on. LCOE consumption refers to the various energy costs of companies' actual production expenses during a statistical period. In terms of the sum of costs, calculating the cost of each energy source and sum of energies is necessary when calculating energy consumption cost. In contrast to the procurement of other materials, energy price is determined by the overall scarcity of resources. Enterprises have no bargaining power in energy procurement, owing to the macro-customization of the state. Therefore, the energy cost data in this study are used only for comparison and have no practical significance.

The method uses the total present value of the net cash benefit amount and the net cash investment amount to calculate the NPV. Next, in terms of the size of the NPV, if the NPV of the investment is greater than zero, then a project can create value for an investor. However, if the NPV is less than zero, then the project causes the investor to lose money.

According to the aforementioned definition,

NPV = total present value of future returns—total initial investment.

$$NPV = \sum_{k=0}^{n} \frac{CI_k - CO_k}{(1+i)^k} - C_0 \tag{8}$$

where $CI_k - CO_k$ is the k-year cash flow, and C_0 is the starting investment amount. The IRR, which is also known as the intrinsic rate of return, is the actual rate of return on an investment and the discounted rate that makes the NPV zero. The IRR is not affected by the interest rate but rather is an efficiency indicator that reflects the profitability of funds accumulated by the project. Moreover, the IRR is an important indicator for examining the efficiency of project funds. In general, a project is feasible when the IRR is greater than the benchmark rate of return.

According to the above definition,

$$C_0 \times (1 + IRR)^{-0} + C_1 \times (1 + IRR)^{-1} + C_2 \times (1 + IRR)^{-2} + \cdots + C_n \times (1 + IRR)^{-n} = 0 \quad (9)$$

where C_k is the cash flow of the k-th year, and $x = (1 + IRR)^{-1}$.

Next, Equation (9) can be converted to

$$C_0 + C_1 x + C_2 x^2 + \cdots + C_n x^n = 0 \quad (10)$$

Interpolation x can be used as the IRR calculation in the HOMER based on this calculation method.

The payback period refers to the amount of money in the savings, which is equal to the amount of time that the initial investment amount needs to reach. That is, the payback period refers to the time needed to recover an investment based on cash backflow [6,21].

3. Research Method

In this section, we propose WECS models and compare two low-rating WECSs based on cost evaluations.

- In wind energy, the most common problem involves wind speed and direction.
- To synthesize the load data, the collected load profile is imported, and average household power consumption, with a monthly average power consumption of 900 kWh, is synthesized.
- The economic analysis results of this study are analyzed, the shortcomings of this field are identified, and reasonable recommendations for improving economic performance are proposed.

To complete the economic analysis of the WECSs, data on wind speed and combined load should be collected. Average wind speed per hour can be calculated using the Weibull distribution random generator of the HOMER. The load selected for this study is the electricity consumption of three households with normal electricity consumption rates. Each household is calculated with a monthly average of 300 kWh. Load data of 8760 h of synthesis are obtained using the synthesis function of the HOMER. In the HOMER software, the 3 and 10 kW WECS microgrid models are designed separately, and the capacity and cost of each component are determined.

The expression of the NPV difference is

$$\Delta NPV = \sum_{k=0}^{N} (PV_A - PV_B)(1 + i)^{-k} \quad (11)$$

where PV_A and $PV_{B,}$ are cash flows for options A and B, respectively, such as $PV_A = CI - CO$. The cash flow of a scheme with a large initial investment amount is often subtracted from the cash flow of a scheme with a small initial investment amount.

The actual calculation formula is as follows:

$$\Delta NPV = (PV_A - PV_B)(P/A, i, n) - (C_{0A} - C_{0B}) \quad (12)$$

where (P/A, i, n) is the present value of the annuity, and the coefficient can be obtained from the aforementioned equation.

The criteria for determining the NPV difference are presented below.

- When $\Delta NPV \geq 0$ at the time, the scheme with a large initial investment amount is better than the scheme with a small initial investment amount.
- When $\Delta NPV < 0$ at the time, the scheme with a small initial investment amount is superior to the scheme with a large initial investment amount.

The IRR difference refers to the corresponding discounted rate when the NPV difference is zero. The expression of the IRR difference is

$$\Delta IRR = i_1 + (i_2 - i_1) \times \frac{\Delta NPV_1}{\Delta NPV_1 + |\Delta NPV|} \tag{13}$$

where $i \leq \Delta IRR$, and Time $NPV_A > NPV_B$ when time is considered as an evaluation plan and the judgment scheme used is consistent.

4. Results and Discussion

In a complete WECS, the power generation unit can be deployed in the HOMER to use the wind turbine, battery bank, inverters, and diesel generators as backup power sources.

A micro home is built with a grid, as shown in Figure 4. Simulation is performed after all the parameters are set.

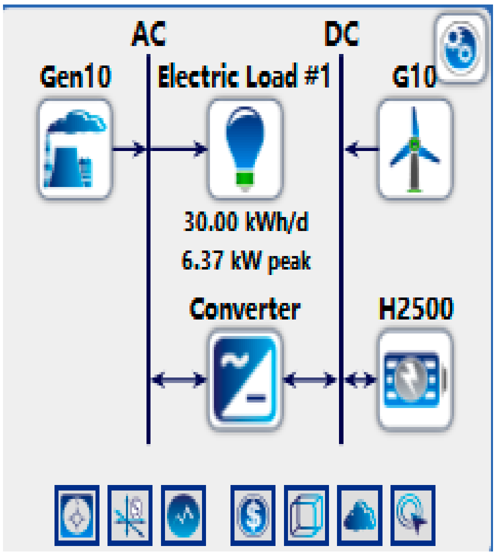

Figure 4. Physical configuration of a microgrid system in HOMER.

4.1. Data Collection

According to the inverse transformation definition, if X_i has 1 in [0, 1], then the probability variable function of the random variable obeying the b distribution on the interval is $F_1(x)$ can be set to Y_i density function $F_2(y)$ by making $x = F_2(y)$. Next, $y = F_2^{-1}(x)$, and

$$x = F(\mu) = 1 - e^{[-(\frac{\mu}{c})^k]} \tag{14}$$

Then,

$$\mu = c[-1n(1-x)]^{\frac{1}{k}} \tag{15}$$

As x to $1 - x$ are subject to the random variables of the b distribution, they can replace each other.

$$V_i = c(-\ln X_i)^{\frac{1}{k}} \tag{16}$$

Based on the probability density function of wind speed, average wind velocity can be generated using the Weibull density function. Monthly average wind speed is shown in Figure 5.

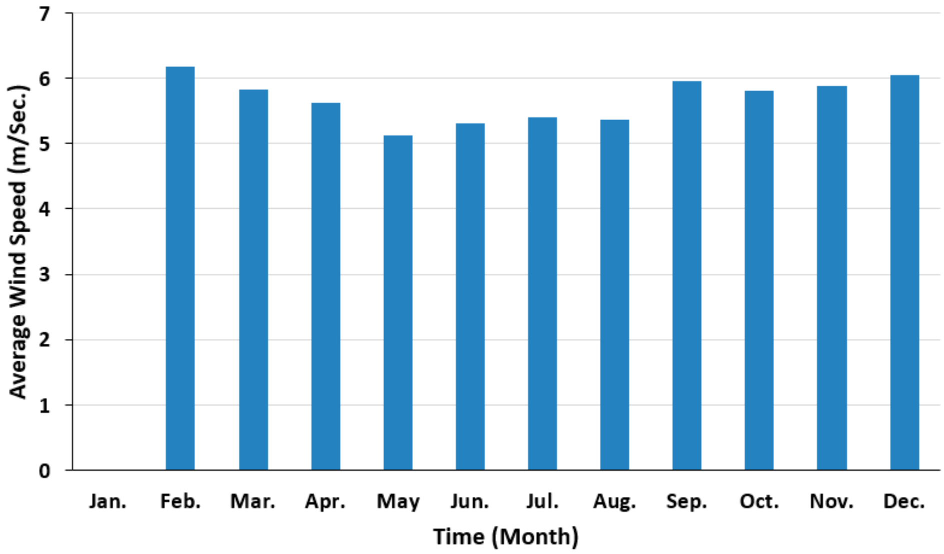

Figure 5. Monthly wind speed data.

The import load element has an internal automatic simulation and a load profile that is collected by itself. Next, household electric load, with a monthly average power consumption of 900 kWh, is simulated directly. Figure 6 shows the data input of the load, which considerably simulates the power consumption of an actual household.

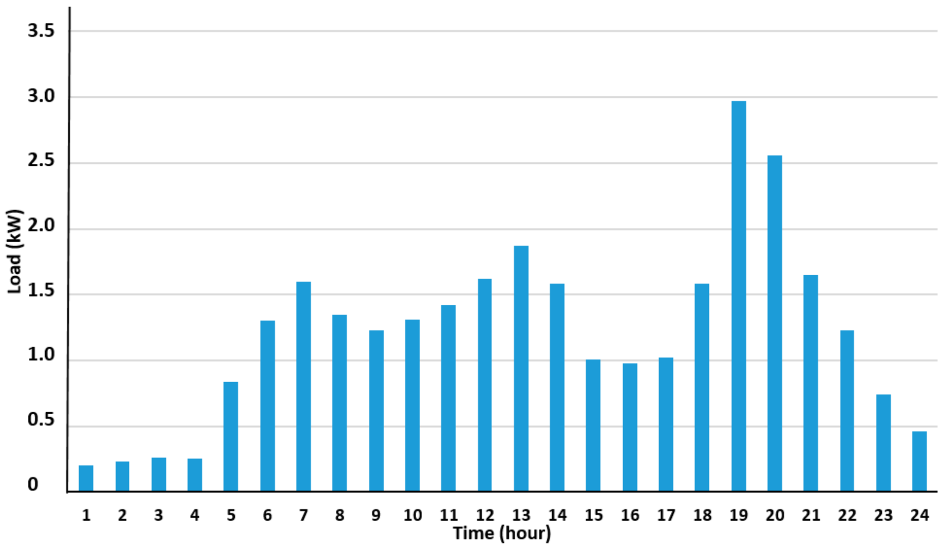

Figure 6. Daily load profile.

4.2. WECS (Cost Optimization)

The obtained data and employed discounted and inflation rates are summarized in Table 1.

Table 1. WECS data.

Unit Size	10 kW	3 kW
Initial investment (¥)	139,017.60	159,073.00
Total NPC (¥)	498,984.90	551,435.60
LCOE (¥)	2.77	3.06
IRR	39.1%	33.1%
Nominal discount rate	6.00%	6.00%
Expected inflation rate	2.40%	2.40%
Actual discounted rate	3.52%	3.52%
Diesel cost (¥)	6.69	6.69
Annual power generation (kWh/year)	8705.00	7171.00
Present value (¥)	43,304.00	40,116.00

According to Equation (8), the NPVs of the 10 and 3 kW WECSs calculated from the data in Table 2 are ¥475,324.62 and ¥410,071.37, respectively.

Table 2. Calculation of NPV of WECS.

Time (Year)	10 kW Present Value (¥)	3 kW Present Value (¥)
0	−139,017.00	−159,043.00
1	43,304.00	40,116.00
2	43,304.00	40,116.00
3	43,304.00	40,116.00
……	……	……
20	43,304.00	40,116.00

Figure 7 shows that the investment recovery periods of the 10 and 3 kW WECSs are 3.21 and 3.96 years, respectively.

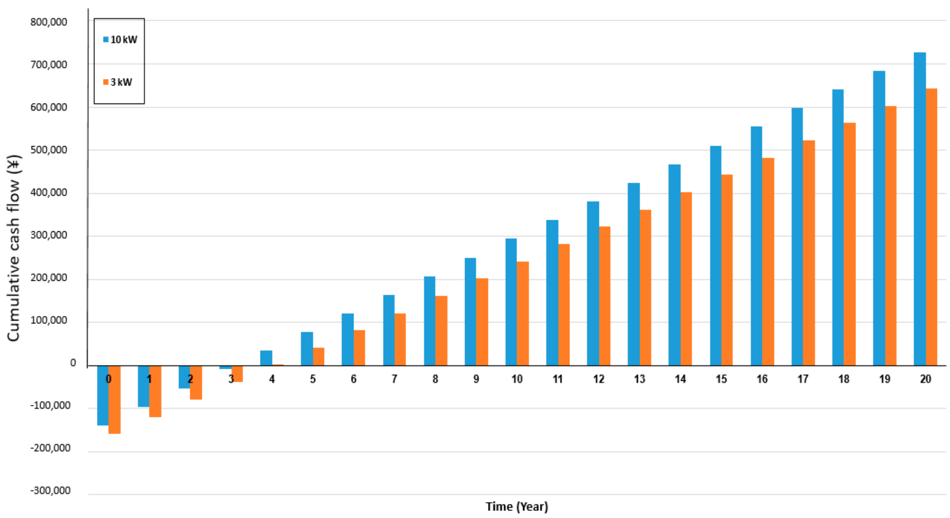

Figure 7. Calculation of investment payback period.

Table 3 demonstrates that the 10 and 3 kW WECSs meet their absolute economic effects; that is, the NPV is greater than zero. In addition, the IRR is greater than zero and the benchmark rate of return. The 3 kW WECS has a lower NPV than the 10 kW WECS, which has lower energy costs, a shorter payback period, a higher IRR, and a higher NPV.

Table 3. Comparison of evaluation criteria.

Economic Evaluation Indexes	3 kW System	10 kW System
NPC	¥551,435.6	¥498,984.9
COE	¥3.06/kWh	¥2.77/kWh
NPV	¥410,071.37	¥475,324.62
IRR	33.1%	39.1%
Payback period	3.96 years	3.21 years

The advantages and disadvantages of the schemes can be seen by calculating the NPV difference between the two investment schemes. A 10 kW WECS with a small investment amount can be obtained by using a 3 kW WECS with a large investment amount.

$$\Delta NPV = (40116 - 43304)(P/A, 3.52\%, 20) - (159073 - 139017) = -65614.4 \quad (17)$$

Equation (17) clearly depicts the NPV difference between the two schemes, that is, $\Delta NPV < 0$. Therefore, the 10 kW WECS with a small investment is better than the 3 kW WECS.

After the two designed systems are compared based on numerical and simulation results, the 3 kW WECS demonstrates a lower NPV than the 10 kW WECS, which has a lower COE, a shorter payback period, and a higher NPV and IRR. However, this result does not conclude that investing in a 3 kW WECS will give a financial loss but rather that it is a comparatively unfavorable choice. The numerical calculation and simulation results show that investing in a 10 kW WECS would be economical. Investors and domestic and agriculture consumers must choose the most suitable solution according to their capital situation, region, and load and demand requirements. The recommended system is expected to be an optimum beneficial option for not only rural-area electrification but also small commercial and industrial utilization, agricultural purposes, street lighting, and communication booster and transmitting stations.

5. Conclusions

In this study, we propose a wind-based grid-independent economic comparison. The proposed economic index comparative study determines the most viable and profitable investment to satisfy residential, small commercial, and agricultural electricity demands and for energy-poor rural communities.

We present the following conclusions of the study.

- Low energy cost, short payback period, high NPV, and high IRR are observed in the 10 kW WECS.
- The 3 kW WECS has a lower NPV than the 10 kW WECS.
- The NPC rate is suitable for adopting a 10 kW system.
- The COE is 2.77 ¥/kWh in the 10 kW system, which is favorable.
- IRR values are calculated as 33.1% and 39.1% for the 3 and 10 kW systems, respectively, which is in favor of the latter system.
- Payback period is longer for the 3 kW system than the 10 kW system, which is 3.96 and 3.21 years, respectively. Thus, the most profitable investment, with a shorter payback period, is the 10 kW system.

Furthermore, we determine that the major economic obstacle in a standalone wind energy system involves the installation of extra storage devices, such as batteries, a flywheel, a capacitor bank or a fossil fuel-based generator, and the extraction of specific wind speeds in undesirable weather conditions. Future research directions which may improve the economic performance of clean technologies, such as wind energy, include wind–solar hybrid systems, solar PV, and other related devices.

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