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Optimization of Photovoltaic Wind Energy Systems in Coastal Cities in Humid Subtropical Climate Zones

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Abstract: In the context of the global energy transition, the layout of photovoltaic and wind energy systems (centralized or distributed) directly affects their energy efficiency and economic efficiency. As a typical city in the subtropical humid climate zone, Brisbane has abundant solar and wind energy resources, and its distribution characteristics and climate conditions provide diverse choices for the layout of the energy system. This paper mainly studies the applicability of centralized and distributed photovoltaic wind energy systems based on climate and energy efficiency indicators, aiming to provide a scientific basis for energy system design under different conditions. Research methods include modeling and simulation analysis based on Brisbane meteorological data, combined with genetic algorithms to optimize PV panel inclination and wind turbine arrangement, and design key decision indicators such as climate conditions (such as solar radiation, seasonal changes in wind speed), land use and energy output efficiency. The energy efficiency performance of different layouts is evaluated to determine the optimal option for selecting a centralized or distributed system. The study shows that distributed systems have a higher cost-benefit ratio, while centralized systems excel in energy output.

Keywords: Photovoltaics, Wind Energy, Optimization, Efficiency, Cost-Benefit

1. Introduction

The rapid growth of renewable energy has made photovoltaic (PV) and wind energy systems integral to transforming the global energy structure. These systems are typically deployed in two layouts: centralized and distributed. Centralized systems rely on large-scale energy facilities for unified management and high-intensity energy demands, while distributed systems consist of smaller, localized units offering flexibility and adaptability. The choice between these layouts depends on factors like climate, land resources, energy demand, and technical-economic considerations. Despite existing research emphasizing technical feasibility and economic analysis, a decision-making framework based on climate and energy efficiency indicators is underdeveloped, especially for cities in subtropical humid climates.

Brisbane, the capital of Queensland, Australia, is a representative city in this climate zone. With its hot, rainy summers, warm, dry winters, and ample renewable resources—including 2,800 annual sunshine hours and favorable wind conditions—Brisbane presents an ideal case for studying PV and wind energy system layouts. The city's dynamic terrain and renewable energy potential enable the development of key decision indicators and optimization frameworks for energy systems.

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This study aims to identify climate and energy efficiency indicators influencing centralized versus distributed systems and analyze the optimal layout for Brisbane's conditions. Using meteorological data, energy output modeling, and genetic algorithm optimization, the study evaluates system performance through indicators such as solar radiation stability and wind speed variation. The findings provide practical guidance for energy planning in Brisbane and similar regions, contributing to sustainable urban energy systems and advancing layout optimization research.

2. Methodology

Due to the high energy consumption and demand of hotel resorts, Brisbane Holiday Village is selected as a case study. Holiday Village Brisbane covers an area of 13.4 hectares, with a relatively empty lawn and separate buildings gathered far away. This resort is suitable for centralized and distributed arrangement of photovoltaic wind energy systems. In this study, photovoltaic panels were only placed on the roof of each building. Since the orientation and size of each building in Holiday Village in Brisbane are very similar, and the distance between them is far away, there is no shade from light and wind energy, so the study needs to be done on a single building when studying the inclination Angle of photovoltaic panels.

2.1. Optimal Inclination Angle of Photovoltaic Panel

Since the inclination angle of the photovoltaic panel should be fixed at the time of the initial installation, and it is not convenient to adjust the subsequent, we must choose the best inclination angle of the photovoltaic panel based on the energy acquisition situation in different seasons.

2.1.1. Establishment of Photovoltaic Radiation Model

In order to determine the optimal inclination of photovoltaic panels, the total radiation formula HT is used in this study to calculate the amount of solar radiation on the surface of photovoltaic panels. The formula is as follows[1]:

$$H_T = H_B + H_D + H_R = (H_g - H_d)R_b + R_d H_d + H_g \rho \frac{1-\cos\beta}{2} \tag{1}$$

H_B: Direct Radiation
H_D: Diffuse Radiation
H_R: Reflected Radiation
H_g: Total Radiation on a Horizontal Surface
ρ: Ground Reflectance
R_b: Radiation Ratio between Tilted Surface and Horizontal Surface
β: Tilt Angle of Photovoltaic Panel

2.1.2. Radiation Ratio R_b

According to the inclination formula, Karami showed that the radiation ratio R_b can be calculated as follows[2-3]:

$$R_b = \frac{\cos(\varphi \pm \beta)\sin\omega_s + \omega_s \sin(\varphi \pm \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + \omega_s \sin\varphi\sin\delta} \tag{2}$$

φ: Latitude
ω_s: Solar Hour Angle

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δ: Solar Declination
β: Tilt Angle of Photovoltaic Panel

2.1.3. Solar Declination δ and Solar Angle ω_s

Solar declination is the angular distance of the Sun with respect to the Earth's equator, and is the Angle between the sun's rays and the Earth's equatorial plane. The formula for calculating solar declination is:

$$\delta = 23.45\sin(360\frac{284+n}{365}) \tag{3}$$

n: Day number, indicating the day of the year.

The solar Angle is the hour Angle of the sun with respect to the local meridian, indicating the sun's position during the day. Used to describe the angular distance of the sun in an east-west direction from its local noon position (meridian). The calculation formula of the day Angle is:

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \tag{4}$$

φ: Latitude
δ: Solar Declination

2.1.4. Diffuse Radiation Ratio R_d and Reflected Radiation Ratio H_R

Diffused radiation ratio calculation formula:

$$R_d = \frac{1+\cos\beta}{2} \tag{5}$$

Reflected radiation ratio calculation formula:

$$H_R = H_g\rho\frac{1-\cos\beta}{2} \tag{6}$$

2.1.5. Inclination Optimization Method of Photovoltaic Panel

Combined with the above formula (1)-(6), the influence of different inclination β on the total radiation HT is calculated, and the inclination corresponding to the maximum value is found, which is the optimal inclination. The specific steps are as follows: determine the latitude φ and the ground albedo ρ of the study area. The horizontal radiation amount Hg is obtained according to the given meteorological data. The above formula is used to calculate HT at different inclination angles. Use numerical methods (such as MATLAB programming or Excel simulation) to find the inclination corresponding to the maximum value.

2.2. Centralized Arrangement of Turbine Fans

2.2.1. Arranging the Spacing

The Park wake model proposed by N. O. Jensen and modified by Katic et al. can be used to design the arrangement spacing of fans[4]. The model assumes that the wind speed in the wake zone is uniformly distributed, the loss of the wake zone speed is related to the thrust coefficient of the fan, and the width of the wake zone is linearly expanded. The minimum spacing between fans can be obtained by this calculation method.

In order to make each fan can receive the maximum wind of the main wind direction, the appropriate fan spacing can be calculated through calculation, so that the wind energy can be used to the maximum extent.

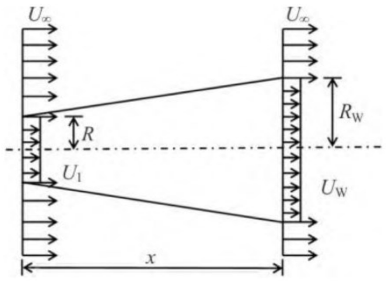

Figure 1: Wake Effect Cross-Section in Wind Turbine Arrangement[5]

As shown in Figure 1, for the wake cross section at the distance x between the wind wheel disk and the downstream, the law of conservation of mass can be used to obtain[5]:

$$\rho\pi R^2 U_1 + \rho\pi(R_W^2 - R^2)U_\infty = \rho\pi R^2 U_2 \tag{7}$$

R: Wind Turbine Radius
R_W: Wake Radius at Downstream Distance x
U_∞: Atmospheric Inflow Velocity
U_2: Wake Velocity at Downstream Distance x
Due to the linear expansion of the wake, the wake radius at the downstream distance x of the wind turbine is:

$$R_W = R + kx \tag{8}$$

k: Wake expansion coefficient: Determined by ground roughness and wind turbine hub height. In practical engineering, the wake expansion coefficient k is generally taken as 0.075 for onshore conditions
x: Horizontal distance along the wind flow direction starting from the rotor position (i.e., the plane where the wind turbine center is located).
According to the one-dimensional momentum theorem, the relation between wake velocity and inflow velocity when the pressure in the wake region recovers to atmospheric pressure is as follows:

$$U_2 = (1 - \alpha)U_\infty \tag{9}$$

α: Wind wheel axial induction factor
α is the wind wheel axial induction factor, which is determined by the wind wheel thrust coefficient C_r. The calculation formula of the wind wheel axial induction factor can be expressed as:

$$\alpha = \frac{1-\sqrt{1-C_r}}{2} \tag{10}$$

Cr: Turbine thrust coefficient
By linking formula (7) to formula (11), the wake velocity distribution at the position x of the wake region can be obtained as

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$$U = U_{\infty}[1 - (1 - \sqrt{1 - C_r})(\frac{R}{R+kx})^2] \tag{11}$$

Through the formula, it is found that the wind speed of the wake is much smaller than the initial wind speed, so the exhaust distance of the fan should avoid the rear fan being located in the wake area of the front fan[6].

2.2.2. Distributed Arrangement of Turbine Fans

Distributed wind turbines are typically small in scale and can be flexibly installed on top of buildings, in small open Spaces, or combined with other facilities. A priority should be given to reducing wake effects during installation to optimize energy capture and reduce interference. Compared to centralized systems, it requires less land and is more suitable for decentralized application scenarios close to the point of electricity consumption. For the distributed turbine fans in this study, each turbine fan is placed on the roof of the building due to the large spacing between each building, high building carrying capacity, abundant wind energy resources at the roof and low turbulence.

2.3. Solar Energy Conversion

The power generation of solar panels is calculated based on factors such as the output power of the panels, sunshine intensity and efficiency. The calculation formula of solar power generation is simple and clear, but its accuracy depends on the accuracy of input parameters and reasonable estimation of comprehensive efficiency.

Photovoltaic panel power generation calculation formula[7]:

$$E = AG\eta \tag{12}$$

E: Power Generation of the Solar Panel
A: Effective Area of the Solar Panel
G: Irradiance per Unit Area
η: Overall Efficiency of the Solar Power Generation System
Overall system efficiency:

$$\eta = \eta_{panel}\eta_{inverter}\eta_{other} \tag{13}$$

η_{panel}: Panel conversion efficiency
$\eta_{inverter}$: Inverter efficiency
η_{other}: Other losses

2.4. Conversion of Wind Energy

After the arrangement of the fan is determined, the production capacity of the fan is simulated and analyzed. Using RETScreen's software function, it provides scientific basis for the design and evaluation of wind power generation projects through multi-dimensional analysis of technology, economy and environment.

In the data collection phase, wind resource data is first obtained, including long-term wind speed data at the project site, which can be obtained through weather stations, satellite monitoring, or field measurements. At the same time, RETScreen's built-in climate database can be used to quickly extract key parameters such as local wind speed, temperature, and air density by entering the latitude and longitude of the project site[8]. If the data are not uniform, the wind speed frequency

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distribution curve needs to be fitted using Weibull distribution as input for subsequent energy calculation. In addition, it is also necessary to collect the technical parameters of the fan, such as hub height, rotor diameter, rated power and power curve, and input site characteristics data (such as terrain, elevation and surface roughness) to fully consider the impact of the actual environment.

In RETScreen, the performance of a wind turbine is simulated by an energy model. The wind speed frequency distribution is combined with the fan power curve to calculate the energy output under different wind speed conditions. In addition, the power generation calculation process of RETScreen will take into account various actual loss factors, including fan operation efficiency, wake effect, downtime and power transmission loss, etc., to ensure the accuracy and reliability of the predicted results.

2.5. Economic Calculation

The cost-benefit ratio (CBR) is an important indicator to evaluate the economics of photovoltaic wind energy systems, which directly reflects the ratio of benefits and costs generated by the system over the whole life cycle. By calculating the cost-benefit ratio, you can quickly determine whether a project is economically viable. Photovoltaic wind energy systems typically involve a high initial investment, and decision makers need to choose the best of many options. The cost-benefit ratio quantifies the economic performance of each option, providing an intuitive comparison.

Cost-benefit ratio formula:

$$\mathrm{CBR} = \frac{\mathrm{ESB}}{\mathrm{TC}} \tag{14}$$

CBR: Cost-Benefit Ratio

ESB: Economic or Energy System Benefits

TC: Total Cost

By calculating the cost-benefit ratio of centralized and distributed photovoltaic wind energy, the cost-effectiveness of different arrangements can be obtained.

3. Result

3.1. Optimal Inclination Angle of Photovoltaic Panel

In this study, LONGi Hi-MO 6 Explorer photovoltaic panel was selected for research. It has high power output, excellent low light resistance, strong temperature adaptability and high reliability.

The latitude ψ of Holiday Village, Brisbane is 27.4698° south (or -27.4698°). The ground is asphalt ground, according to research of Kotak et al., the ground albedo ρ=0.1[9]. Select each month as the unit and analyze the average value of each month. Combined with the formula (1)-(6), the number of days n, the solar declination δ and the daily Angle ωs are respectively shown in Table 1.

Table 1: Monthly Solar Angles and Declinations in Brisbane

Month	ωs(°)	δ(°)	n
January	101.5705013	-21.09634389	16
February	97.14519169	-13.45495968	45.5
March	91.25782145	-2.417734805	75
April	84.95555813	9.599397234	105.5
May	79.66952273	19.03059093	136
June	77.03933284	23.33521955	166.5
July	78.27229252	21.35367858	197

Table 1: (continued).

August	82.85480831	13.45495968	228
September	88.95146106	2.01587453	258.5
October	95.24163675	-9.966257972	289
November	100.4685038	-19.26362517	319.5
December	102.9837275	-23.37165125	350

In order to ensure that the inclination of the photovoltaic panel maximizes the absorption of solar radiation throughout the year, the solar radiation amount on the surface of the photovoltaic panel is used for the solar radiation amount on the surface of the photovoltaic panel throughout the year. Through the data in table x combined with formula (1) to (6), the relationship between PV panel inclination βand the annual solar radiation HT on the PV panel surface can be obtained by input of different PV panel inclination values, as shown in Figure 2. According to the relationship between PV panel inclination β and the annual solar radiation HT on the PV panel surface, the optimal inclination of PV panel is about 24.8 degrees, and the corresponding solar radiation on the PV panel surface is about 85758.33Wh/m^2.

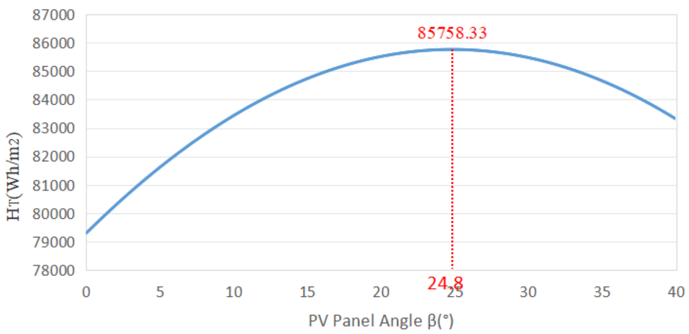

Figure 2: Relationship Between Photovoltaic Panel Inclination Angle and Annual Solar Radiation

3.2. Power Generation of Photovoltaic Panels

Each building of Holiday Village in Brisbane is a two-story small villa with a roof area of 120-144m^2. In order to avoid the energy conversion rate reduction caused by the mutual occlusion of photovoltaic power generation panels, the actual photovoltaic panel area of each building is 100m^2.

Panel area A=100m^2, unit area irradiation G=85758.33Wh/m^2.

According to actual measurements, the panel conversion efficiency of the LONGi Hi-MO 6 Explorer photovoltaic panel is about 22.8%, the inverter efficiency is about 97.5%, and other losses are about 80%. According to formula (13), the comprehensive efficiency yita of the system can be calculated as 17.784%. Based on formula (12) and (13), the annual power generation of the solar panel is about 73206KW/m^2.

3.3. Centralized Arrangement of Turbine Fans

Centrally arranged turbofans are placed on the central lawn of Holiday Village, Brisbane. The area of the central lawn is about 134,000 square meters, the lawn is relatively broad, the shape is about oval, no other buildings shelter, the wind is abundant. Therefore, Northern Power Systems NPS 100C-24 wind turbine is chosen as the research object. Northern Power Systems NPS 100C-24

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Wind turbine is a medium-sized generator, Table 2 is the Northern Power Systems NPS 100C-24 wind turbine data[10].

Table 2: Specifications of Northern Power Systems NPS 100C-24 Wind Turbine[10]

Manufacturer	Northern Power Systems
Rated Power	100 kW
Rotor Diameter	24 meters
Swept Area	452 square meters
Cut-in Wind Speed	3 m/s
Rated Wind Speed	13 m/s
Cut-out Wind Speed	25 m/s
Rated Rotational Speed	28.5 RPM
Tower Height	30 meters
Noise Level	Maximum 55 dB
Design Lifetime	20 years
Price	AU$59,200

According to the above data, RW=33m can be obtained by calculation. The wind speed in the wake area of the fan is uniformly distributed, while the width of the wake area is linearly expanded. In order to make each fan can receive the maximum wind of the main wind direction. The wind speed of Holiday Village in Brisbane can be obtained through climate documents, as shown in Table 3[11].

Table 3: Monthly Average Wind Speeds in Brisbane

Month	Wind speed(m/s)
January	3.8
February	3.1
March	4.2
April	2.9
May	2.3
June	3.1
July	3.1
August	3.0
September	3.4
October	3.6
November	2.9
December	4.2

The data of wake velocity at downstream distanceU2, wind wheel axial induction factor α, atmospheric inflow velocity $U\infty$ and turbine thrust coefficient C_r can be obtained by combining formula (7)-(11), as shown in Table 4.

Table 4: Wind Speed and Wake Characteristics of Centralized Wind Turbines

U2(m/s)	α	$U\infty$(m/s)	C_r
1.967706355	0.482182538	3.8	0.93
1.590837981	0.486826458	3.1	0.948

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Table 4: (continued).

2.196727677	0.476969601	4.2	0.91
1.485227934	0.487852437	2.9	0.952
1.21509217	0.471699057	2.3	0.89
1.590837981	0.486826458	3.1	0.948
1.590837981	0.486826458	3.1	0.948
1.537980848	0.487339717	3.0	0.95
1.754421075	0.483993802	3.4	0.937
1.861345348	0.482959626	3.6	0.933
1.485227934	0.487852437	2.9	0.952
2.196727677	0.476969601	4.2	0.91

After comprehensive consideration of wind speed and spacing, the arrangement is shown in Figure 3.

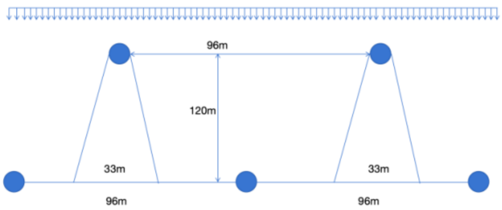

Figure 3: Centralized Wind Turbine Arrangement Plan

3.4. Distributed Arrangement of Fans

Distributed turbines will be installed on the roofs of each building in Brisbane's Holiday Village. In order to minimize the impact of the wind turbines on the photovoltaic panels and other impacts, each wind turbine will be installed at the southwest corner of the top of the building. Distributed turbines, especially those installed on rooftops, require the use of small turbines, so the ECO-25 was chosen as the object of study. Table 5 shows the data of ECO-25 fan[12].

Table 5: Specifications of ECO-25 Wind Turbine

Manufacturer	EcoCycle
Rated Power	2.5kW
Rotor Diameter	2 meters
Swept Area	12.6 square meters
Cut-in Wind Speed	3 m/s
Rated Wind Speed	12 m/s
Cut-out Wind Speed	25 m/s
Tower Height	10 m
Design Lifetime	20 years
Price	AU$1,400

Because the distance between each building in Holiday Village in Brisbane is far greater than the influence distance of the fan wake, each fan can receive the maximum wind power.

3.5. Fan Power Generation Calculation

The simulation analysis of Northern Power Systems NPS 100C-24 wind turbine and ECO-25 wind turbine under the climatic conditions of Holiday Village in Brisbane was carried out by RETScreen. After adjustment, both centralized and distributed wind turbines can maximize the use of wind energy. The fans of the two arrangement modes are not affected by the wake or occlusion of other fans, and there is a big difference in the power loss during the transmission process, so we carry out a separate study on each fan. Through the simulation of RETScreen, Table 6 shows the actual energy supply of individual wind turbines of Northern Power Systems NPS 100C-24 wind turbine and ECO-25 wind turbine to the building.

Table 6: Monthly Energy Output of Centralized and Distributed Wind Turbines

Month	NPS 100C-24(kwh)	ECO-25(kwh)
January	19620	687.6
February	15840	606.6
March	22320	595.8
April	19800	396
May	20610	311.4
June	24120	304.2
July	17460	340.2
August	18900	325.8
September	19710	315
October	22860	415.8
November	18180	635.4
December	18720	685.8

3.6. Cost-Benefit Analysis

According to formula (14), the cost-benefit ratio needs to calculate the amount of energy saved relative to the total cost. In addition to the cost of fan purchase, details of other costs are shown in Table 7.

Table 7: Annual Maintenance and Operational Costs of Wind Turbines

Projects	NPS 100C-24	ECO-25
Maintenance and repair	AU$1,200	AU$300
Insurance expense	AU$700	AU$150
Grid access cost	AU$400	AU$75
Labor cost	AU$1,000	AU$200
total	AU$3,300	AU$725

The average unit price of electricity in Brisbane is AU$0.2kWh. On a one-year basis, Table 8 and Figure 4 show the total cost and cost-benefit ratio.

Table 8: Yearly Total Costs and Cost-Benefit Ratios for Centralized and Distributed Wind Turbines

Year	Total cost($)		Cost-Benefit Ratio	
	NPS 100C-24	ECO-25	NPS 100C-24	ECO-25
1	299300	67500	0.845	1.016

Table 8: (continued).

2	302600	67800	1.671	2.023
3	305900	68100	2.479	3.022
4	309200	68400	3.270	4.011
5	312500	68700	4.044	4.992
6	315800	69000	4.803	5.964
7	319100	69300	5.545	6.928
8	322400	69600	6.272	7.884
9	325700	69900	6.985	8.831
10	329000	70200	7.683	9.771
11	332300	70500	8.368	10.702
12	335600	70800	9.039	11.625
13	338900	71100	9.697	12.541
14	342200	71400	10.342	13.449
15	345500	71700	10.975	14.349

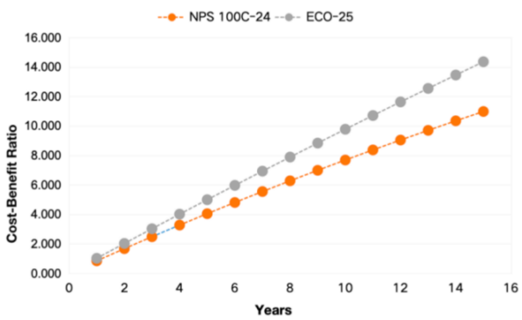

Figure 4: Cost-Benefit Ratio Over 15 Years for Centralized and Distributed Systems

4. Conclusion

This study provides a comprehensive analysis of centralized versus distributed photovoltaic (PV) and wind energy systems for the climate and geography of Brisbane, Australia. By optimizing the inclination of photovoltaic panels and the placement of wind turbines, the study provides valuable insights into maximizing energy efficiency while also being economically viable. The results show that the centralized layout has higher energy output, but the initial investment and maintenance costs are higher. In contrast, distributed systems have lower energy output, but are more flexible, less costly, and enable localized energy production, which is more suitable for small-scale or urbanized scenarios. In contrast, the cost-benefit ratio of a distributed layout system is better. The results of the study provide a scientific basis for optimizing the renewable energy system and have practical guiding significance for Brisbane and other similar subtropical regions. This study does not deeply explore the integration of hybrid energy systems combining photovoltaic and wind energy or the potential impact of advanced storage technologies. Additionally, it lacks an analysis using dynamic simulation methods to account for real-time variations in energy demand and climate conditions. Future research can be further expanded to explore hybrid energy systems and incorporate advanced technologies to further improve energy capture efficiency and system performance.

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