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Prototype Development and Experimental Validation for Wind Energy Harvesting from HVAC System for A Charging Station

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Abstract: The Heating, Ventilation, and Air Conditioning (HVAC) system is commonly found in buildings such as industrial, commercial, residential, and institutional buildings. This HVAC system generates a significant speed of wind flow from its condenser unit. Surprisingly, this wind energy remains unexploited and thus dissipates into the surroundings. This project aims to leverage this unused wind energy from the condenser unit by developing an energy harvesting prototype that harnesses the HVAC system's wind for a practical charging station. Specifically, a wind turbine is connected to a three-phase 12 VAC generator motor. This connection would efficiently convert wind energy into electrical power. An energy storage module is also incorporated to ensure uninterrupted functionality for the developed charging station prototype. The energy storage module has a substantial capacity of 25Ah, equivalent to a standard socket outlet. This ensures that the energy storage system can fully charge within three hours if there are no interruptions in the turbine's operation. An experimental validation was conducted by supplying different wind speeds to this project prototype, and it was observed that only when the wind speed is above 10 ms^{-1} does the energy storage system charge, and sockets provide a consistent output. The final output at the socket provided both 230VAC voltage and a USB charging option, making it versatile for users to charge commonly used electrical appliances such as smartphones and laptops. By repurposing this otherwise wasted wind energy, the developed system prototype contributes to cleaner and more sustainable energy utilization. It also converts unused energy into valuable, cleaner energy.

Keywords: Charging Booth/Station, Power Generation, Renewable Energy, Sustainable Environment.

1 Introduction

RENEWABLE energy refers to energy generated from natural sources that is considered sustainable and environmentally friendly because it is naturally produced and continuously regenerated. Various types of renewable energy sources exist, including solar energy, wind energy, tidal wave energy, hydro energy, geothermal energy, and biomass energy. All of these renewable energy sources face challenges in maintaining their consistent availability. For instance, Auväärt et al. [1] stated that solar energy depends largely on astronomical factors which would be significantly affected by cloudiness, atmospheric transparency, and snow cover. Although it is known that implementation of renewable energy solutions is essential to cutting down carbon emissions and reaching every country sustainability goal, there are a lot of regulatory hurdles

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that slowing down the growth and implementation of renewable energy projects. It has been outlined by Aggarwal and Usapein in [2] that efficient licensing processes, well-defined regulatory frameworks, enhanced cooperation between public and private sectors, and upgraded grid infrastructure are pivotal in advancing the development of renewable energy. Meanwhile, Byrnes et al. in [3] highlighted that the obstacles at both federal and state levels continue to impede the effective deployment of renewable technologies and the development of a skilled workforce although Australian renewable energy policy has advanced.

Equally important for the implementation of renewable energy are the challenges associated with the regulation of electronic waste (e-waste) management. Rautela et al. in [4] and Ikhlayel in [5] found that this is due to the management of e-waste being constrained by inadequate technical skills and insufficient infrastructure, particularly in developing countries. Consequently, this leads to improper recycling practices, which can have detrimental effects on both human health and the environment. For that, this paper focuses on wind energy as a prospective electricity source. The authors of this paper agree with Akorede et al. [6], who suggested that small-scale wind energy systems could be economically feasible in Peninsular Malaysia despite the challenges posed by low, weak, and inconsistent wind speeds in several areas for large-scale installations.

One of the factors that limits the natural gust of wind is urbanization. Liu et al. [7] state that the wind gust in urban areas was reported to be less than 0.3 ms^{-1} during daytime as compared 0.6 to 0.9 ms^{-1} during the nighttime. It was also reported by Saberi et al. in [8] that an annual average of wind speed in Kuala Terengganu, Malaysia is only 2.01 ms^{-1} while higher wind speeds could only be observed during the Northeast Wind Monsoon season. Rather than concentrating solely on Malaysia's naturally weak and variable wind resources, the authors of this paper are excited to explore alternative methods to access significant and consistent wind speeds that may be underutilized yet present in our surroundings.

In HVAC system, a condenser unit comprises of a condenser coil, compressor, and fan. This important part of HVAC is used to release air into the outdoor environment. The emitted airflow from the HVAC system through a condenser unit is consistent and may somehow exceeds the natural wind speeds, especially from the condenser units installed outside the commercial buildings such as office buildings, universities, hotels, and supermarkets. The airflow is continuously generated throughout the operation of air-conditioning systems within these buildings. Fig. 1 shows the installation quantities of condenser units positioned outside a management building in Terengganu, Malaysia. These units are associated with high-horsepower HVAC systems and would indeed emit stronger airflow from their condenser units.

Fig. 1 A group of condenser units installed outside a management building in Kuala Terengganu, Malaysia.

On 23rd November 2023, wind speed emitted from a HVAC condenser unit outside an academic building of UniKL British Malaysian Institute were measured during operational hours at 12:36 pm, as shown in Fig. 2. The recorded data indicates a consistent average wind speed of 10.70 ms^{-1}, with the highest recorded speed reaching 14.10 ms^{-1}. The emitted airflow, heated to temperatures between 37.30°C and 39.40°C presents an opportunity for utilizing it for a small-scale wind turbine system to generate electricity. As suggested by Kreith and Goswami in [18], the HVAC systems designed for commercial and institutional buildings typically require cooling capacities ranging from 0.6 to 1.2 horsepower per 100 square feet of spaces. Therefore, larger building spaces require air-conditioning systems with higher horsepower ratings. These systems must be equipped with bigger condenser units to increase the air flow capability for an effective heat dissipation [19].

There were significant number of prior works that focused on producing electricity from the air-conditioning systems. For instance, Mano et al. in [9] managed to produce the electricity with a potential of 14.1 W per day from mechanical energy of rotor motor in the condenser unit of air conditioner. In a study by researchers [10], the concept of recycling wind energy from air conditioning condenser fans in outdoor buildings was demonstrated. Their small, low-cost, and portable prototype employs a DC motor generator, achieving a maximum charging capacity of 13.04V within 45 minutes. Likewise, Slamet et al. in [12] had successfully developed an energy harvesting system using a DC generator attached to the fan of one horsepower air-conditioning unit's compressor. The prototype managed to fully charged the small battery storage with maximum charging capacity of 2.28V in 25 minutes. On the contrary, Goh and Duan in [11] designed a prototype micro wind turbine aimed at enhancing mechanical efficiency. Their prototype focused on increasing rotor solidity and minimizing generator resistance to optimize power generation.

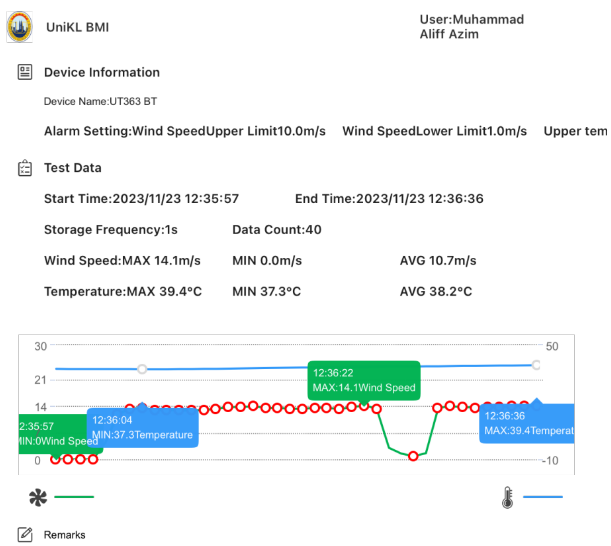

Fig. 2 The wind speed recorded from a HVAC condenser unit outside the academic building of Universiti Kuala Lumpur British Malaysian Institute.

Previous studies predominantly utilize DC motor generators and limited battery storage to establish small-scale electricity sources suitable for low-power applications. It is known that DC generator motor requires regular maintenance due to the presence of carbon brushes that can wear out over time. Hence, these systems are only capable of powering devices such as LEDs, desk fans, desk lamps, and other appliances that can be charged via USB cable. As differ from what has been highlighted by previous research works, this paper will exploit the usage of a three-phase AC generator motor to harness wind energy and convert it into electrical power. This AC voltage is then transformed into suitable DC voltage for battery charging using a Maximum Power Point Tracking (MPPT) wind turbine charge controller.

To match with the standard domestic voltage output, a 500W inverter is incorporated in the proposed charging station prototype as it converts 12V DC from the battery into 230V AC at 50Hz for charging purposes, fitting well with the needs of three-pin plug and socket system for electrical appliances and devices such as smartphones, laptops and others. Specifically, this paper aims to develop a prototype charging station capable of harnessing electricity from airflow emitted by a condenser unit in a HVAC system. The effectiveness of this prototype in charging real electrical appliances will be validated, assessing its feasibility across various wind speeds that activate the commercial wind turbine integrated into the prototype.

2 Methodology

2.1 Block Diagram and Operational Flow Description

Fig. 3 shows the proposed block diagram. In this work, airflow from the HVAC condenser unit will be used to move a wind turbine blades that are connected to a three-phase AC generator motor. A primary limitation of this project is its applicability to HVAC units exceeding 3 horsepower. Larger units produce wind speeds sufficient to drive the turbine, whereas smaller units (1 to 2 horsepower) generate insufficient airflow. As stated in [13], wind turbine requires at least 10 ms^{-1} gust of wind to move its wind turbine blades. The rotation of the blades will produce an angular velocity that will affect the value of the generated power [14]. The blades are attached directly to the three-phase AC generator motor. In this project, the length of the wind turbine blade is 550 mm. This blade length appears to be suitable for rotation and requires a small angular velocity to generate power.

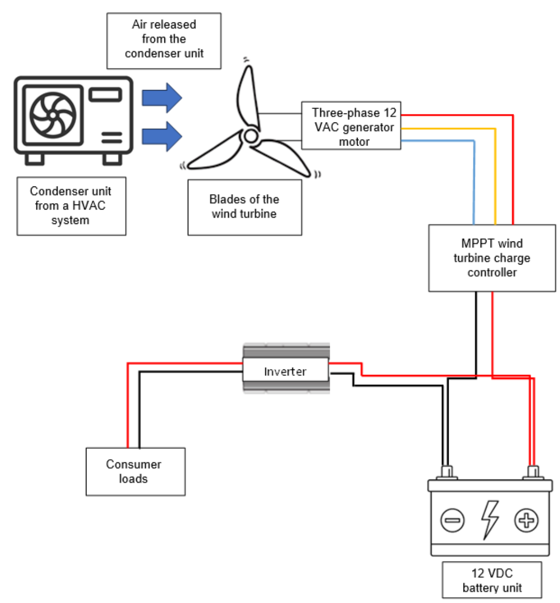

Fig. 3 Proposed block diagram.

For efficient power generation, this proposed work uses a three-phase AC generator motor. This generator motor will generate 12V AC and produce a rated power of 100W. Based on Ohm's Law, the calculation of the rated current produced is according to the P/V formula. Hence, the rated current produced is 8.33A. Next, the MPPT wind turbine charge controller is used to control the input voltage so that it is suitable for charging the battery. It will automatically convert the AC voltage supply to DC voltage to charge the attached battery storage unit. When the turbine reaches maximum rotation and generates excessively high voltage unsuitable for battery charging, the MPPT wind turbine charge controller incorporates a braking function to restrict further rotation. This intervention ensures that only the appropriate voltage levels are applied to effectively charge the battery.

In this project, the main function of 12V battery unit is to act as energy storage system for uninterruptible and emergency use and power supply to a DC to AC inverter. According to Xuewei et al. [17], incorporating an energy storage system into wind power generation allows for the utilization of its charging and discharging capabilities to maintain a relatively stable output power which helps to mitigate power fluctuations and enhance power quality. The selected battery voltage is 12V, and the chosen battery capacity is 25Ah due to its reasonable price and suitability for small-scale use at a charging station. The 25Ah capacity is seen to be suitable for use for approximately 1.5 hours with full loads on socket outlet and USB ports outlet without charging from the input voltage from the rotation of the wind turbine. This is based on calculation Ah/A [15], so the full current rated on standard socket outlet is 13A while the full current rated on USB ports outlet is 3.4A (based on seller specifications). The total current from these two loads is 16.4A, and after dividing it by the battery capacity of 25Ah, the time rate of usage is 1.5 hours. These rechargeable batteries have an efficiency of 80-85%. They are less expensive compared to lithium-ion batteries but have a shorter lifespan [16].

Then, the inverter will convert the DC 12V from battery and convert it to provide a standard 230V AC voltage to the socket outlet. Furthermore, DC power supplied by the battery has no sine wave, no frequency, and only 12V DC. Therefore, to make a socket outlet work, it needs to receive the same AC waveform power coming from the grid (sine wave) to ensure that the generated output matches the grid electricity supply. This inverter is rated at 500W, meaning that it can support loads up to 500W. The output describes the last component in the project system. This component will produce output that will be used by the user. The output must be according to the standards and specifications of the supply voltage because the output is a project system that connects to the load and as a charging station, the consumer load is the majority of sensitive electronic devices that have very sensitive ICs.

In this project, there are two types of socket outlets used called the standard socket outlet and USB ports socket outlet. The standard socket outlet is installed for general purposes use such as charging laptops and other devices such as the Nintendo Switch, MP3 players and devices that come with an embedded charger with a plug top. These outlets have safety mechanisms such as insulated covers on the live and neutral contacts to keep the user safe from accidental contact. It also has a fuse to cut off the live supply if there is any short circuit occurred in the circuit. The USB port socket outlet is an advanced electrical outlet that follows the shape of a traditional plug socket. This outlet is designed to provide convenient direct charging for various electronic devices, such as smartphones, tablets and other USB-powered devices, without the need for a separate adapter. The USB port socket is designed with six USB ports, and this enables multiple charging of multiple devices, allowing multiple users to charge their devices at the same time and this can save their time. The USB port is designed with features such as overcurrent protection and fast charging capabilities. It also supplies stable and efficient power.

2.2 Actual Prototype Development Cost

Table 1 outlines the actual expenses incurred during the prototype development of the proposed project. This table captures all costs associated with the components used, as well as any unforeseen expenses that emerged throughout the development phase. The total actual cost of developing the prototype amounts to RM 930.15 (nine hundred thirty Ringgit Malaysia and fifteen cent). Note that the deviation that might be occurred in cost of reconstruction of prototype development may be attributed to several key factors such as:

i. The unavailability of components from preferred suppliers necessitated purchases at higher prices;
ii. The need for supplementary components, which were not initially anticipated, contributed to the increased cost;
iii. Enhancements to component specifications, including higher current ratings and increased power ratings, resulted in additional expenses;
iv. Several components were damaged during development, requiring their replacement; and
v. Errors in component measurements led to further purchases to rectify these issues.

Additionally, wind turbines can utilize either single-phase or three-phase AC generator motors. However, the authors of this paper decided to utilize three-phase AC generator motor because three-phase systems are durable for warmth air released from the HVAC condenser unit. Besides that, this type of motor generator is capable of achieving balanced loading and tracking the peak power point, both of which are crucial for optimizing wind turbine performance. This leads to more stable and efficient power output compared to single-phase systems. This statement is supported by the significant findings by Arthishri et al. (2019) in [20].

Table 1 Actual prototype development cost in Malaysian currency unit (i.e., Malaysia Ringgit).

No.	Item	Cost Per Unit	Unit	Cost Per Item
1.	Three-Phase 12V Wind Generator Motor	RM 288.20	1	RM 288.20
2.	Turbine Blades Holder	RM 21.54	1	RM 21.54
3.	MPPT Wind Turbine Charge Controller	RM 86.90	1	RM 86.90
4.	Turbine Blades	RM 28.05	3	RM 84.15
5.	Sealed Lead Acid 12V 25AH	RM 121.99	1	RM 121.99
6.	Inverter 500W	RM 110.20	1	RM 110.20
7.	13A Socket Outlet	RM 5.00	1	RM 5.00
8.	USB Ports Socket Outlet	RM 19.67	1	RM 19.67
9.	PVC 1-Side Plywood 600mm x 600mm	RM 27.50	7	RM 192.50
		Total Cost		**RM 930.15**

3 Results and Discussions

3.1 Prototype Development of The Proposed Charging Station

Fig. 4 illustrates the development of the proposed charging station prototype, which harvests electricity from the airflow emitted by the HVAC compressor in an academic building. A three-blade wind turbine, connected to a three-phase generator motor is employed in this prototype. It can be seen that the wind turbine is positioned on the opposite side as it will be facing the HVAC compressor to harness electricity from the emitted airflow and thereby ensuring users safety by preventing accidents or injuries while utilizing the socket outlets. The prototype's interior comprises the following wiring routes:

i. from the generator motor to the MPPT wind turbine charge controller;
ii. from the MPPT wind turbine charge controller to the battery storage;
iii. from the battery storage to an inverter; and
iv. from the inverter to the socket outlets.

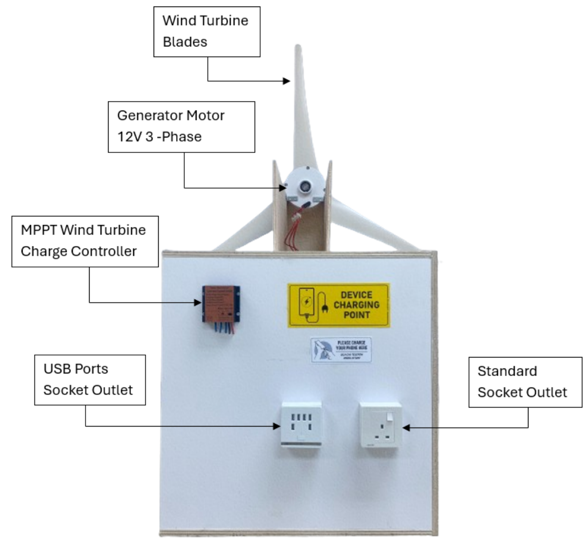

Fig. 4(a) Exterior view of the charging station prototype.

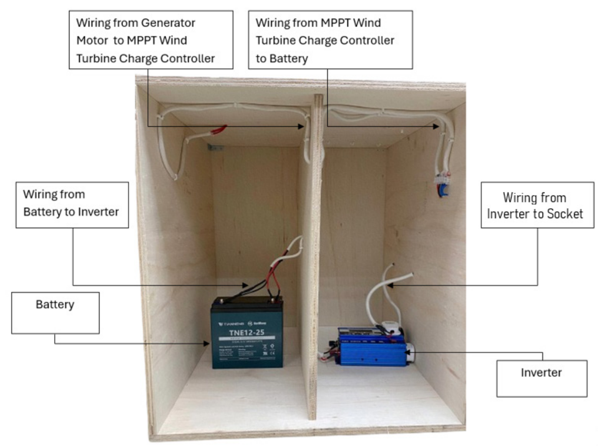

Fig. 4(b) Interior view of the charging station prototype.

3.2 Experimental Validation on Electricity Harvested Based on Various Wind Speed

The measurement of the motor-generator's rotational speed and generated voltage provided crucial insights into the performance of the wind turbine prototype. The tachometer and multimeter readings were systematically recorded, and the resulting data, tabulated in Table 2, offer a comprehensive view of the operational parameters. By calculating the power output as the product of measured voltage and current, the efficiency and capability of the system could be better understood. Specifically, the fast-charging charger and lightning cable draw currents of 3A and 1.8A, respectively, from the outlets, cumulatively providing a total current of 4.8A. This is consistent with Kirchhoff's Current Law, which confirms that in a parallel circuit configuration, the total current is indeed the sum of the currents through each parallel branch. This configuration ensures that each load receives the full system voltage while varying the current distribution according to its requirements. Fig. 5 illustrates the electrical loads configuration during prototype testing, showing a smartphone connected to a fast-charging charger with its charging indicator illuminated. This had visually confirmed the functionality of the developed prototype.

Table 2 Data for various wind speed and generated power from an experimental setup during prototype testing.

RPM	Wind Speed (ms^{-1})	Voltage Generated (V)	Power Generated (W)	Charging Status
127.4	7.32	1.70	8.16	No
145.6	8.36	2.30	11.04	No
164.2	9.43	3.90	18.72	Yes
184.0	10.56	4.00	19.20	Yes
187.1	10.75	4.10	19.68	Yes
208.7	11.99	6.50	31.20	Yes
235.8	13.55	6.60	31.68	Yes
289.3	16.62	6.90	33.12	Yes
309.1	17.76	7.10	34.08	Yes
314.1	18.05	7.20	34.56	Yes
327.2	18.80	7.50	36.00	Yes
339.3	19.50	7.60	36.48	Yes

The wind speed in the unit of meters per second (ms^{-1}) that rotates the wind turbine blades can be theoretically calculated as in Eq. (1) by considering the recorded motor-generator's RPM values on a tachometer, the diameter (D) of the turbine blade in feet. This online wind speed calculator can be obtained at https://calculator.academy/fan-wind-speed-calculator/ whereby the above three values shall be multiplied by 60 to convert to hours and finally need to be divided by 5280 to convert the fee per hour unit becoming miles per hour unit. The Eq. (1) was utilized to derive the wind speed, which was then converted to meters per second by multiplying by 0.447.

$$\text{Wind speed} = (\pi \times \mathrm{D} \times \mathrm{RPM}_{\text{value}} \times 60) \div 5280 \quad (1)$$

The data presented in Table 2 were further analyzed by plotting the relationship between wind speed and generated power. The graph in Fig. 6 reveals a notable trend i.e., as the wind speed increases, the generated power also rises, demonstrating a positive correlation between the two variables. The observed sharp increase in power output after wind speeds exceed 10.75 ms^{-1} indicates that the turbine's efficiency improves significantly at higher wind speeds. This finding aligns with the minimum wind speed requirement of 10 ms^{-1} for effective turbine operation as mentioned in [13]. The analysis confirms that the prototype is capable of producing sufficient power to charge batteries efficiently when subjected to adequate wind conditions.

Fig. 5 Electrical loads configuration during prototype testing.

Furthermore, the implications of these results suggest that optimizing turbine design to operate effectively at higher wind speeds could enhance overall performance. The prototype ability to meet and exceed the power generation requirements at increased wind speeds highlights the potential for its application in real-world scenarios where high wind conditions are prevalent. Future research could focus on exploring aerodynamic improvements to the turbine blades and assessing the long-term reliability of the system under varying environmental conditions. Overall, the experimental validation of the wind turbine prototype has demonstrated its capability to harness wind energy effectively. The increasing power output with rising wind speeds confirms the turbine's operational efficiency and validates the theoretical models used for performance prediction.

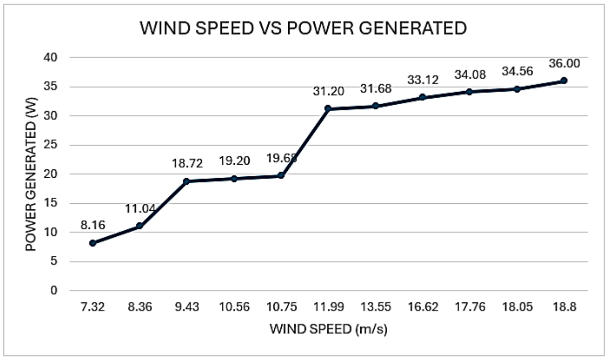

Fig. 6 Correlation between wind speed and electrical power produced.

4 Conclusion

The proposed wind energy harvesting charging station from HVAC system demonstrates the feasibility of transforming unexploited wind source into usable electricity. By converting waste heat from HVAC systems into clean electricity, the project offers a dual benefit of reducing greenhouse gas emissions and decreasing reliance on traditional, fossil fuel-based power generation. The potential for substantial energy savings and long-term economic advantages for businesses and communities is significant. To enhance the system's performance, future research should focus on several key areas. Employing a generator motor with a higher output voltage, such as a 24V model, could improve energy capture, especially under low wind conditions. Optimizing turbine blade design through increased width for efficient low-speed operation and reduced length for improved airflow capture is essential. Moreover, downsizing the prototype and exploring the use of vertical-axis wind turbines would facilitate integration into the constrained space of HVAC condenser units.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This work was collaboratively conducted by all authors. Siti Marwangi Mohamad Maharum, who also serves as the corresponding author, contributed to the overall manuscript writing, including summarizing the related literature review, providing the overall project description, and conducting the analytical analysis. Meanwhile, Muhammad Aliff Azim Hamzah led the design and development of the project prototype from scratch. Muhammad Ridzwan Ahmad Yusri assisted Muhammad Aliff Azim Hamzah in testing the functionality of the project. Lastly, Izanoordina Ahmad was responsible for project monitoring and proofreading of the manuscript. All authors reviewed and approved the final version of the manuscript, agreeing to be accountable for all aspects of the work.

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Biographies

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