Modeling of solar and wind energy using MATLAB/Simulink: a review

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Article Info	ABSTRACT
	This paper presents a concise review of solar (photovoltaic (PV)) and wind (horizontal axis) energy systems, focusing on their modeling and simulation using MATLAB)/Simulink. The advantages, disadvantages, strengths, and weaknesses of each system are discussed, providing a comprehensive overview of their characteristics. The review explores the mathematical modeling approaches for PV cells and modules specific for single diode model, as well as horizontal-axis wind turbine systems, highlighting the key equations and parameters involved. Furthermore, the paper discusses the emerging trend of hybrid solar-wind energy systems and their potential for optimizing power output, efficiency, and reliability. The review emphasizes the importance of accurate modeling based on fundamental knowledge, which serves as a practical implication for readers to understand the mechanism. Future research directions and challenges in the field of renewable energy modeling and simulation are also outlined. This review serves as a valuable resource for researchers, engineers, and decision-makers involved in the development and implementation of solar and wind energy systems.

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1. INTRODUCTION

Energy is an important aspect for living beings as it is the basis for doing all kinds of activities. Humans, especially, have used energy since the prehistoric era for heating and lighting using fire sources. After the technological revolution, marked by the use of the steam engine, energy was used more frequently [1]. Now, with the rapid demand for energy resources, the use of fossil fuels as one of the most dominant sources due to their output characteristics has become depleted significantly [2], [3]. Hence, an alternative is proposed, which is using renewable energy. Renewable energy is an efficient source that can meet the requirements of the environment, and energy is also considered clean by reducing CO_2 emissions only if it surpasses a certain threshold of renewable energy consumption [4]–[6]. Examples of this energy are solar energy, wind energy, hydropower energy, geothermal energy, biomass, ocean thermal energy, and tidal energy.

The significance of renewable energy is that it produces electricity that will supply the energy demand needed. The other advantages of renewable energy in general are its availability, land usage, safety (minimizing the risk of man-made disaster), development of technology, employment, environmental friendliness, and reducing fossil fuel dependency [4], [7], [8]. It will also help supply energy to

underdeveloped areas [4]. However, the disadvantage of these sources lies in power production due to weather conditions (unpredictability and volatility), low efficiency, and/or the presence of reserves that will provide energy when energy deficiency occurs [4], [8]. The limitation can be countered by carefully planning and selecting specific renewable energy choices. Hence, the phase of research and design becomes one of the important parts due to the need for complementary studies, designing, and testing.

A strategic way to support the development of renewable energy in the research phase is to use energy models, as they help in providing suitable designs for decision-making [9]. The method used, namely simulations, has become a powerful tool to create virtual experiences as the answer to real-physical performance [10]. It acts as a replication, linking theories and experimental investigation based on systems, processes, and laws for random known parameters [10]. In the case of renewable energy, simulation enables people to analyze the estimated results before directly installing systems to reduce losses such as cost, time, and quality, as well as consequences such as environmental damage. Many types of renewable energy implementations use simulation before implementation. In the future, the era where renewable energy must become the main source, solar and wind energy have become the top choices for utilization. This is due to the popularity of both sources that have been implemented and their huge potential compared to other renewable energy sources (solar by 8,300 TWyr and Wind energy by 1,500 TWyr) [11]. With the capacity generation for both types increasing, uncertainties with the availability of the supply must be carefully considered to avoid system reliability quality loss or even power outages [12]. Thus, detailed planning must be done to assess how far the systems can reach the desired output comparable to the potential.

Since simulation acts as the key step in the planning stages, it is important to see how the solar and wind energy implementation will result. Solar energy systems mainly consist of several parts, including models of photovoltaic (PV) cells and modules, storage systems, trackers, direct current to direct current (DC/DC) converters, and inverters. Several elements that affect the final output of the system include rated power, cell internal resistance, operating voltage and current, short circuit current, and open circuit voltage [10]. For wind energy, the whole system may consist of a turbine system, generator, and electronic power system. Not to mention that, each system has reciprocating complex subsystems such as blades, nacelle, and rotor. With unsupportive weather conditions, the complexity of both energies undoubtedly poses the potential for inefficiencies and losses. Therefore, the use of simulation may significantly help in suggesting the outcome under simulated conditions based on physical world behavior.

Several simulation software used for energy modeling includes retscreen expert (RETSCREEN), PVsyst, hybrid optimization of multiple energy resources (HOMER), power systems computer aided design (PSCAD), dynamic modeling laboratory (DYMOLA), power system simulator for engineering (PSS/E), thermal library (ThermoLib), open analysis platform for real-time laboratory verification (OPAL-RV), and MATLAB. MATLAB is programming, analysis, and computation software for mathematics and engineering purposes with matrices as the basis [13]. This software is used to support scientific programming using toolboxes such as Simulink.

Several advantages of this software compared to others are its flexibility and customization (block-based environment), advanced control system design, hardware-in-the-loop (HIL) simulation for hardware integration, and availability for co-simulation. Simulink can simulate the energy system that has been designed and estimate the output as part of the consideration and planning before decision-making for real system installation. For solar and wind energy, several studies have conducted experiments using this software. However, most articles directly show mathematical approaches and jump into results and discussions by only describing the methods narratively, without any guide for readers to try.

Thus, based on this, the use of simulations can be a solution for energy modelling, specifically for solar and wind energy, due to its popularity in the middle of the increasing renewable energy capacity installation as the answer for a cleaner transition. In this article, a brief review of related articles on renewable energy simulation using MATLAB/Simulink is presented, specifically on solar (PV) and wind (horizontal axis) energy. Additional explanations of advantages, disadvantages, strengths, weaknesses, and hybrid models will also be included to serve as an introduction for this article in the context of solar and wind energy.

The scope of the review will be limited to solar energy based on a single diode and wind energy based on the turbine system. Other specifics and additional systems will not be elaborated. The purpose of the review is to give an introduction and basic guidelines for researchers who need a quick summary of modeling and simulation for solar and wind energy based on MATLAB/Simulink. The innovation of this paper is to present the simulation architecture. Relevant reviews had shown case by case for solar and wind energy with the mentioned scope, proving the use of MATLAB/Simulink as a source for energy model simulations while also producing results.

2.   METHOD

In conducting the literature review on renewable energy simulation using MATLAB/Simulink, the methodological steps followed are as follows. First, research was conducted through various academic databases such as IEEE Xplore, ScienceDirect, and Google Scholar. Keywords used included "renewable energy simulation," "MATLAB/Simulink," "solar energy simulation," and "wind energy simulation." Additionally, the research also involved related articles, books, and conferences relevant to the topic. Next, articles found in the searches were evaluated to ensure their relevance to renewable energy simulation using MATLAB/Simulink, with a specific focus on solar and wind energy. Articles that did not meet these inclusion criteria were excluded from the review. After identifying relevant articles, the analysis process began by extracting information on the advantages, disadvantages, strengths, weaknesses, and hybrid models in the context of solar and wind energy from each article. Relevant information from each article was then synthesized to provide a comprehensive overview of subsystem modeling and simulation setup details for readers who wish to study and experiment with MATLAB/Simulink on solar and wind systems.

3.   RESULTS AND DISCUSSION
3.1. Advantages and disadvantages of solar and wind energy in general

Before choosing the right renewable energy sources, several considerations must be taken and analyzed before decision-making. Knowing and assessing the advantages and disadvantages of renewable energy can be helpful in making the right choice carefully. In this article, the advantages and disadvantages of solar and wind can be explained briefly, as shown in Table 1. Thus, based on the prior explanation of the advantages and disadvantages, general knowledge regarding the reference for energy suitability is provided. Thus, based on the prior explanation of the advantages and disadvantages, general knowledge regarding the reference for energy suitability is provided.

Table 1. Solar energy advantages and disadvantages

Type of energy	Key characteristics	Advantages	Disadvantages
Solar	Solar energy comes from the sun's radiation, which is utilized and converted to heat, electricity, and other energy forms using conversion technology [14]. This energy, in general, is divided into solar PV (converts absorbed light that moves electrons to electricity) and thermal solar energy (collects direct normal irradiance and transports the heat to storage) [14], [15].	The advantages of solar energy are that it can convert solar energy directly to electricity without causing pollution, helping in mitigating climate change, has low operational and maintenance costs, and can be used for heating/cooling purposes in industry or other sectors [14], [16]–[18].	Despite those benefits, solar energy also has many disadvantages, such as high investment cost, low efficiency, the need for area, weather, and latitude dependency, as well as complex systems (specifically for solar thermal technology) [14], [16]–[18].
Wind	Wind energy is a source of energy that results from the movement of air from a higher temperature region to a lower one due to pressure differences [19], [20]. The conversion of wind to electricity can be based on two different types of turbines, which are horizontal axis (blade parallel to wind flow) and vertical axis (blade perpendicular to wind flow) [21]. Based on the location type, it can be classified into onshore and offshore [22].	The advantage of wind energy is that, aside from being environmentally friendly since no greenhouse gas is emitted during operation, it also stimulates job creation (installation and manufacturing), and it also supplies electricity.	The disadvantages of this energy include high investment cost, complex maintenance, difficulty in the transportation of components, noise, visual effects, and temperature rise around the surroundings, which cause habitat change and animal death [18], [21], [23].

3.2. Strengths and weaknesses of PV system and wind power system

Moving on from general advantages and disadvantages, the strengths and weaknesses of solar (PV) and wind systems can be depicted as follows [24]:

i)   Strength: renewable energy source that has a relatively predictable pattern, can be scaled to increase energy, low operating and maintenance costs, decentralized generation (specific to PV), high energy yield (specific to wind energy in some regions with constant and strong wind), reduces greenhouse gas emissions and pollution, technological advancements, grid support, and energy independence (on fossil fuels).

ii) Weakness: both energies are limited (PV by weather and wind by wind speed), limited energy production (PV is limited by weather and does not produce at night/least light conditions whereas wind causes low production on calm conditions), shading impact (specific on PV that reduce energy production), aesthetic considerations, geographical and land use limitations, resource limitations, maintenance challenges (especially for the offshore system), high initial costs, visual impacts, and energy storage requirements.

Hence, each system presents similar strengths and weaknesses that must be considered before designing, planning, and executing the overall installation of the systems. Additionally, the choice between solar and wind systems often depends on local environmental conditions and specific energy needs. Effective integration of these systems requires addressing their respective limitations while maximizing their benefits.

3.3. Studies on solar and wind energy modelling using MATLAB/Simulink

Recent studies from the last 5 years on renewable energy integration using MATLAB/Simulink have focused on creating more accurate and efficient models for PV and wind turbine systems, such as developing advanced control strategies like maximum power point tracking (MPPT) and inverters to improve grid stability and power quality. For PV arrays, models are now being designed to accurately capture the effects of real-world conditions like partial shading, where some PV cells are exposed to less sunlight, creating multiple power peaks [25]. These models are crucial for developing effective control algorithms. Similarly, wind turbine modeling has progressed to include detailed representations of different generator technologies, like the permanent magnet synchronous generator (PMSG) and doubly-fed induction generator (DFIG) [26], [27]. These advanced models simulate complex mechanical and electrical dynamics, such as blade pitch control and rotor aerodynamics, to predict performance under varying wind speeds.

As for MPPT, the field is shifting from traditional algorithms to more advanced hybrid methods, primarily developed and tested using MATLAB/Simulink. Researchers simulate algorithm performance under varying irradiance and temperature conditions to validate their effectiveness before hardware implementation. While conventional methods like perturb and observe (P&O) and incremental conductance (INC) are still common, they struggle with rapid changes and partial shading. As a result, recent research has focused on enhancing P&O methods with variable step sizes to reduce oscillations and improve tracking speed [25], [28]. Moreover, a significant trend is the integration of intelligent algorithms like fuzzy logic controllers (FLC) and neural networks (NN). These intelligent controllers are particularly effective in handling the complex, multi-peak power curves created by partial shading, as they can adapt without requiring a precise system model. The Simulink environment enables a side-by-side comparison of these intelligent controllers with conventional methods, demonstrating their superior tracking speed and efficiency. A study by Melhaoui *et al.* [29] used Simulink to show that a hybrid P&O-FLC method had a faster tracking speed and higher efficiency, while another method by Dahmane *et al.* [30] utilized the platform to test a hybrid P&O and neural network approach for wind energy systems.

The integration of renewable energy sources into the power grid is a vital research area, focusing on inverter control for maintaining power quality and system stability. MATLAB/Simulink is an essential tool for modeling and testing advanced inverter strategies safely. A key advancement is the shift from grid-following to grid-forming inverters. While grid-following inverters rely on the grid for voltage and frequency references, grid-forming inverters can generate these references autonomously. This is crucial for microgrids and low-inertia power systems, enabling them to provide essential services like voltage and frequency support. Researchers use Simulink to test these control strategies, particularly for fault ride-through capabilities, ensuring inverters remain connected during disturbances [31], [32]. Additionally, Simulink's advanced analysis tools are utilized to design and evaluate filters that reduce total harmonic distortion (THD), ensuring that the power supplied to the grid complies with strict quality standards. Studies like that by Nguyen *et al.* [33] and Rao *et al.* [34] used Simulink to design and simulate control systems, analyzing the dynamic operation of microgrids. This demonstrates the platform's vital role in ensuring reliable and high-quality power delivery from renewable sources.

Despite advancements in complex and intelligent systems, it is essential to recognize that these systems are built on fundamental models. A solid understanding of how to create basic PV and wind turbine models in Simulink is important for several reasons. These foundational models, which are often based on the mathematical equations of equivalent circuits and aerodynamic forces, provide insight into the core principles of renewable energy conversion. They serve as building blocks for more complex systems, enabling researchers and students to progressively incorporate features such as MPPT algorithms, battery storage, and grid-forming inverters. Additionally, basic models are invaluable for educational purposes, helping students comprehend the physics and engineering concepts of renewable energy before advancing to more complex, pre-built library blocks in Simulink. Thus, this article will elaborate on the modelling process, specifically on solar and wind energy systems using Simulink.

3.4. Solar energy-photovoltaic cell modelling using MATLAB/Simulink

The design of PV energy systems depends on the performance of their cells and panels. The cell can be represented using either a single-diode or two-diode circuit model (however, the two-diode model has complexity with equations and parameters) [35]. The single diode circuit model in Figure 1 is preferable in most relevant articles since it presents fewer complex calculations while providing lower computational errors compared to the two diode circuit models [35], [36]. Overall, the simulation steps involve finding irradiance profiles based on the desired location, modelling based on PV governing equations, determining load conditions, and finally integrating storage, power electronics, and control loops. However, this paper will discuss limited to PV modelling.
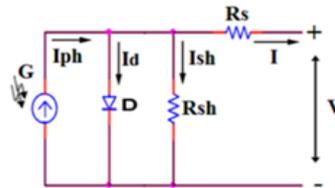
Figure 1. Single diode circuit representation for PV cell [36]

The governing equation of the current source of this model is given as (1)-(6) [35]–[37].

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I_{ph} = \frac{G}{G_{ref}} \left[I_{sc} + K_I \left(T_{op} - T_{ref} \right) \right] \tag{2}$$

$$I_d = I_{sat} \left[\exp\left(\frac{V + IR_S}{nV_t} \right) - 1 \right] \tag{3}$$

$$I_{sh} = \frac{V + IR_S}{R_{sh}} \tag{4}$$

$$I_{sat} = I_{RS} \left(\frac{T_{op}}{T_{ref}} \right)^3 exp\left[\frac{qE_g}{nk} \left(\frac{1}{T_{ref}} - \frac{1}{T_{op}} \right) \right] \tag{5}$$

$$I_{RS} = \frac{I_{sc}}{\exp\left(\frac{qV_{oc}}{N_s nk T_{op}} \right) - 1} \tag{6}$$

In which I is output current, I_{ph} is the current source, G is insolation, G_{ref}, and T_{ref} as insolation and temperature at STC, I_{sc} is short circuit current, K_I is the current temperature coefficient, I_d is the diode current, I_{sh} is current through R_{sh}, I_{sat} as reverse saturation current of diode, V as terminal voltage, n ideality factor of the diode, V_t is thermal voltage ($V_t = (k)(Top)/q$ for q by $1.6×10^{-19}$ C and k by $1.38×10^{-23}$ J/K or Boltzmann' constant), E_g as band gap energy of semiconductor, I_{rs} as reverse saturation current at STC, and V_{oc} as open circuit voltage. (V+IR$_s$) the PV cell connection is usually in a series and parallel combination for higher power, combining it into a tool called modules (36 or 72 combinations of cells). The governing equation of the PV module is as (7).

$$I = N_p I_{ph} - N_p I_{sat} \left[\exp\left(\frac{\frac{V}{N_s} + \frac{R_S I}{N_p}}{nV_t} - 1 \right) \right] - \frac{\frac{N_p}{N_s} V + R_S I}{R_{sh}} \tag{7}$$

In which N_p is an equivalent circuit in parallel strings, and N_s is for series arrangement.

The known equation can now be converted to an energy system model in Simulink. For a simpler understanding, some assumptions are made. First, based on Figure 1, R$_s$ and R$_{sh}$ are both resistant for series (current path and act as losses by Joule effect) and parallel (correlated with seepage of current) aspects [37]. Although both variables must not be overlooked, with the purpose of simplicity, R$_{sh}$ can be ignored (becomes conspicuous if many modules are considered) while R$_s$ is still taken into account due to its multiplication effect, making it more prominent [37]. This will result in a newer equation, which is (8).

$$N_p I_{ph} - N_p I_{sat} \left[\exp\left(\frac{q(V+IR_S)}{N_s n k T_{op}} - 1 \right) \right] \tag{8}$$

Then, with these equations, PV can be modeled based on the desired catalogue and type. As a reference, a study by Vinod *et al.* [37] uses this approach to model a PV system based on the determined parameters of JAP6-72-320/4BB. The values of the parameters are given in Table 2.

Table 2. JAP6-72-320/4BB PV module parameters [37]

Variable	Values	Variable	Values
P_m (maximum power at STC)	320 W	N_s (total series cells)	72
V_{mp} (maximum power voltage)	37.38 V	N_p (total parallel cells)	1
I_{mp} (maximum power current)	8.56 A	n (ideality factor)	1.3
V_{oc} (open circuit voltage)	46.22 V	Ki (cell short circuit temperature coefficient of I_{sc})	0.058%/C
I_{sc} (short-circuit current)	9.06 A	T_{ref} (reference temperature)	25 C
N_s (total series cells)	72	G_{ref} (solar irradiance)	1,000 at STC

The next step is to make subsystems based on smaller equations that are not dependent on other subsystem equations. This can be done first for the operating temperature conversion model as shown in Figure 2 and products of $N_s k n T_{op}$ as shown in Figure 3, in which the variable n is equivalent to A [37]. Then the modeling can be focused on obtaining I, which depends on I_{ph} and I_d (Gain from I_{sat} in (5) through I_{Rs}). Hence, using (2) and (6) to find I_{ph} and I_{Rs} as shown in Figures 4 and 5, then using I_{Rs} to find I_s (or I_{sat}) shown in Figure 6. Then, I can be produced based on the resulting value of the mentioned subsystems based on (1), which is shown in Figure 7. The final system models are shown in Figures 8 and 9.

Several other studies offer improved equations tailored to specific needs and purposes. These new equations result in different mathematical formulations depending on the requirements. One example is from the Berlini studies (seen in Figure 10) that shows the approaches as (9)-(15) [38]–[40].

$$I_y = I_{sc} \left[1 - K_1 \left(\exp^{\frac{V_y}{K_2 V_{oc}}} - 1 \right) \right] \tag{9}$$

$$K_1 = \left(1 - \frac{I_{MP}}{I_{sc}} \right) \exp^{\frac{-V_{MP}}{K_2 V_{oc}}} \tag{10}$$

$$K_2 = \left(\frac{\frac{V_{MP}}{V_{oc}} - 1}{\ln\left(1 - \frac{I_{MP}}{I_{sc}}\right)} \right) \tag{11}$$

$$I_{sc}(G, T_c) = I_{scs} \cdot \frac{G}{G_s} \left[1 + \alpha(T_c - T_s) \right] \tag{12}$$

$$I_{MP}(G, T_c) = I_{MPs} \cdot \frac{G}{G_s} \left[1 + \alpha(T_c - T_s) \right] \tag{13}$$

$$V_{oc}(T_c) = V_{ocs} \left[1 + \beta(T_c - T_s) \right] \tag{14}$$

$$V_{MP}(T_c) = V_{MPs} \left[1 + \beta(T_c - T_s) \right] \tag{15}$$

In which I_y is PV current. While K_1 and K_2 are parameters dependent on irradiance and temperature. After that, I_{sc}, I_{MP}, V_{oc}, and V_{MP} are values given in the datasheets of PV module manufacturers.
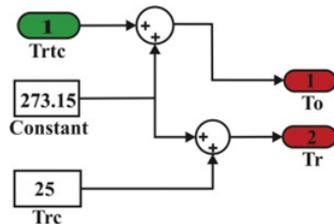

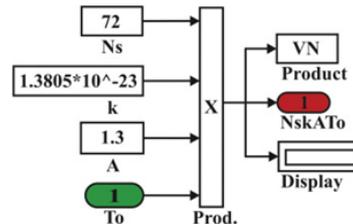Figure 2. Subsystem for operating temperature conversion model [37]

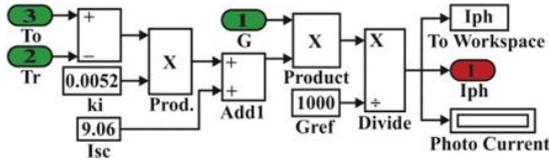Figure 3. Subsystem for $N_s k n T_{op}$ [37]

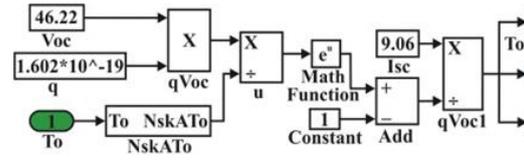Figure 4. Subsystem for Iph [37]
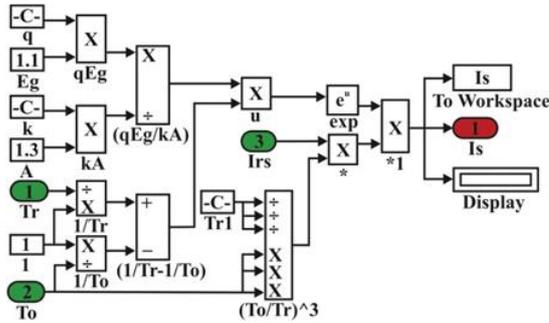

Figure 5. Subsystem for IRs [37]

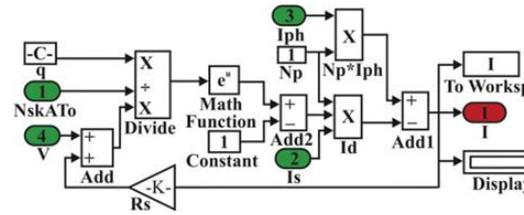Figure 6. Subsystem for Is [37]

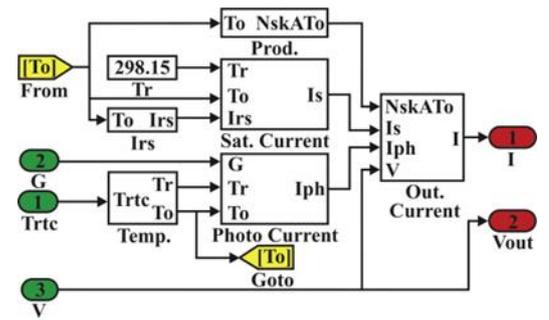Figure 7. Subsystem for I [37]

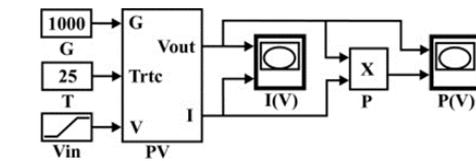Figure 8. Final system integrated based on designed subsystems [37]
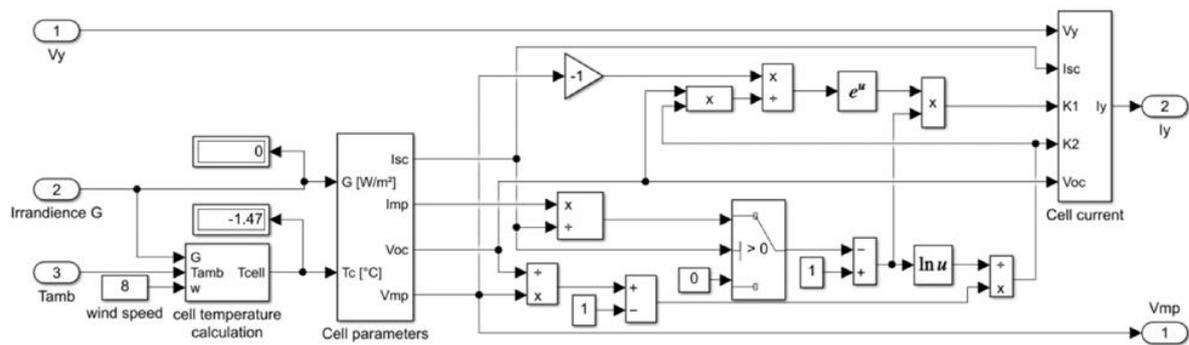

Figure 9. Simplified final system [37]

Figure 10. Simulink model by Möller and Krauter [40], based on Ayaz et al. [38] and Berlini et al. [39] approaches

Corresponding to the reviewed literature provided, it can be highlighted that the modelling based on the Simulink can be made by using the equation that governs the solar cell operations. However, the studies given have several limitations, which can be further progressed by including several other considerations aside from the mathematical models of PV cells and modules, such as storage systems, tracking algorithms (generally MPPT), DC/DC converters, inverters, and other additional systems, such as temperature adjustment systems.

3.5. Wind energy-turbine and generator modelling using MATLAB/Simulink

For a wind energy system, the simulation steps involve finding wind velocity profiles based on the selected area, modelling based on wind energy governing equations, determining load conditions, and integration with storage, power electronics, and control loops. However, similar to the PV section, this article will discuss limited to wind energy modelling. The main components of wind energy systems consist of a blade turbine, generator, power converter, and controller [41]. Wind energy turbine modeled in MATLAB/Simulink. It can be based on (16).

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda, \beta) \tag{16}$$

In which P_m is mechanical power (W). While R is the radius of the turbine blade (m), v is the wind velocity, C_p is the power coefficient, λ is the tip speed ratio, and β is the pitch angle. Obtaining λ will be based on (17).

$$\lambda = \frac{\omega R}{v} \tag{17}$$

The λ acts as the ratio of tangential velocity to wind speed, in which ω is the angular speed [42]. The C_p is dependent on several aspects. For the horizontal axis type, factors that are affecting consist of several blades, λ, and β. Therefore, in making the system of wind energy, the C_p significantly impacts the power output based on the λ and β. Several mathematical approaches to C_p are based on three main functions, which are polynomial, sinusoidal, and exponential functions. One of the most general functions used to design a Simulink model is using the exponential function based on Ovando *et al.* equations [42], [43]. The equation is as (18) and (19).

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1 + \beta^3} \tag{18}$$

$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4.\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} + 0.0068\lambda \tag{19}$$

Using the given equations, the mathematical model can be designed in Simulink. First, subsystems must be created for (18). This process is illustrated in Figure 11, in which eq1 represents $\frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1 + \beta^3}$ and eq2 as $0.5176\left(\frac{116}{\lambda_i} - 0.4.\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} + 0.0068\lambda$. Now that the model for (18) is known, a power factor can be obtained. This power factor can then be used to complete the calculations based on (16), as shown in Figure 12. This model can now be simplified to a final system, as shown in Figure 13. The parameters for the blade radius, wind velocity, beta, and angular velocity should match the real conditions and preferences. The angular velocity can be obtained from (17).

Many other mathematical approaches are presented to show different designs of Cp in Simulink such as polynomial function (third order, fourth order, fifth order, and sixth order [44], [45]–[47]), sinusoidal function ([44], [48]–[51]) as well as exponential ([43], [52]–[57]). The steps to design the models are the same since they only rely on the given mathematical models. Aside from Cp considerations, choosing the right turbine in which the data of speed in a selected area is suitable as the cut-in speed for the turbine. In addition to the turbine selection and mathematical approaches, the use of a generator is adequately important due to the turbine selection, which can be classified into fixed-speed wind turbines and variable-speed wind turbines. For fixed-speed turbines, the squirrel cage induction generator is suitable, whereas the doubly fed induction generators and permanent magnet generators are used for variable-speed turbines [41]. The generator can be classified into asynchronous and synchronous types based on the grid supply requirement for the asynchronous type, in contrast to synchronous. The squirrel cage induction generator and doubly fed induction generator are both categorized as asynchronous types while the permanent magnet is classified as synchronous. According to the study conducted by Chong *et al.* [41] a simulation using the mentioned generator in the variation of speed (0-9 m/s) from 1 to 10 s shows that the permanent magnet synchronous generator performs better at lower wind speed (which means better efficiency) in Malaysia since the other two generators must draw reactive power from three-phase alternating current (AC) source, which consumes energy before the generator starts working. The model of each generator based on the prior study can be shown in Figures 14-16.
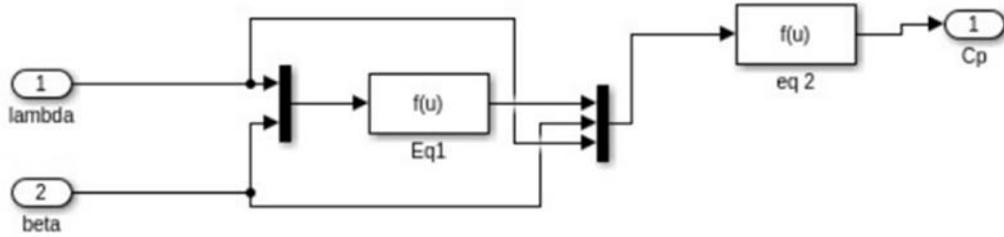
Figure 11. Subsystem for (18) provided by researcher
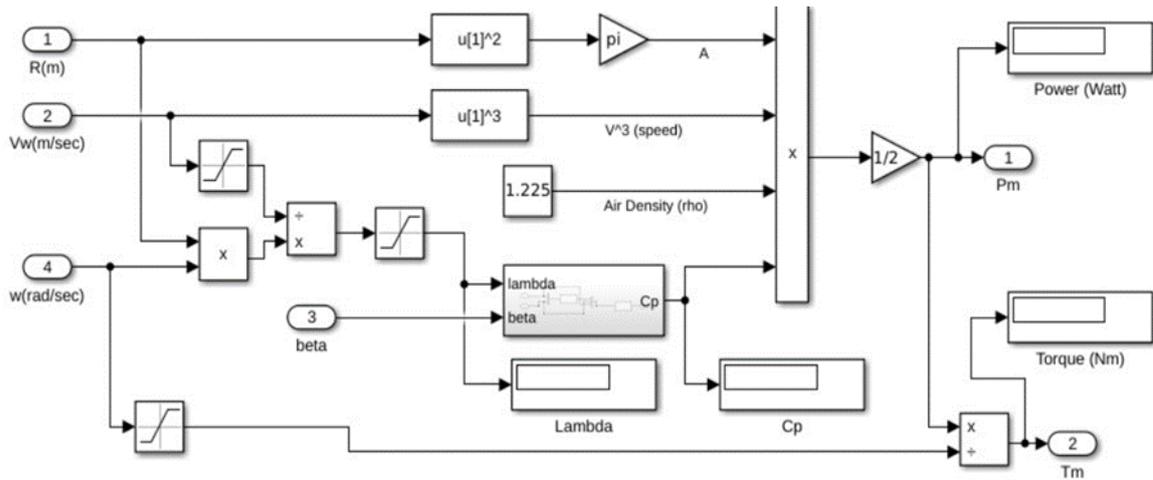

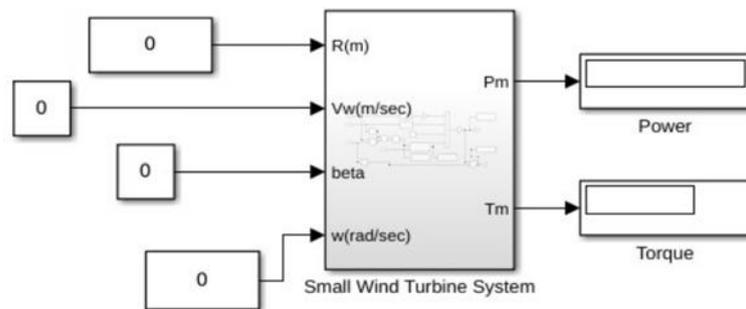Figure 12. Subsystem for (16) provided by researcher

Figure 13. Wind turbine final system provided by researcher
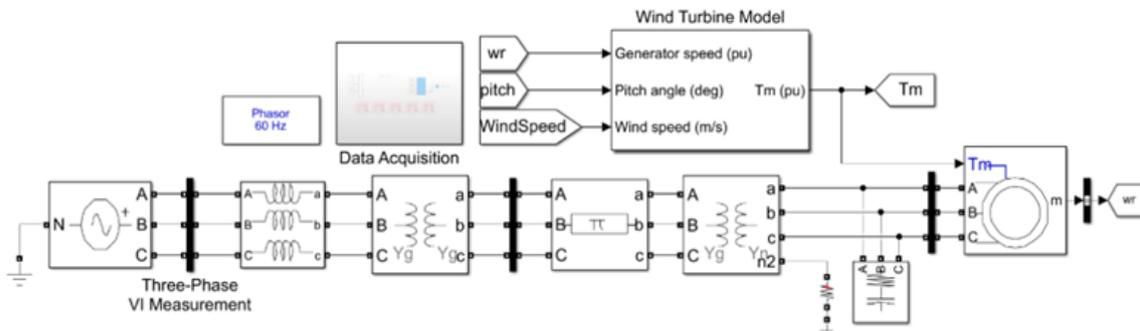

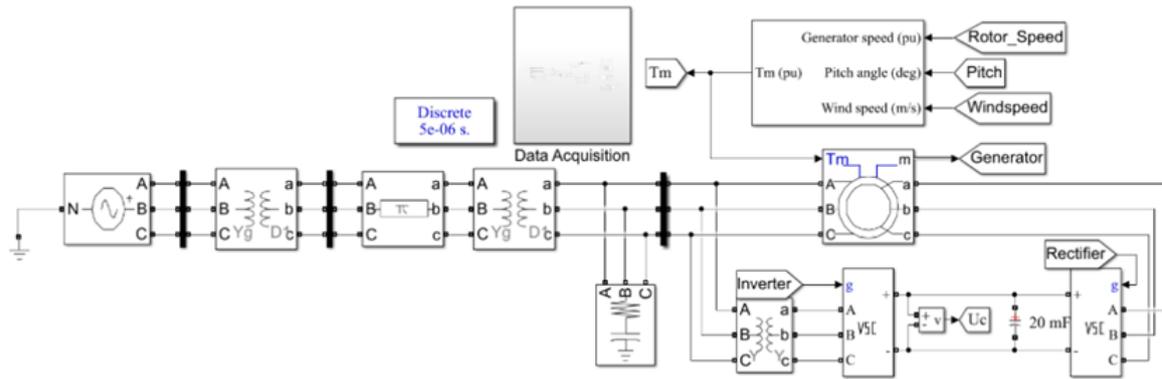Figure 14. Simulink model of a squirrel cage induction generator [41]

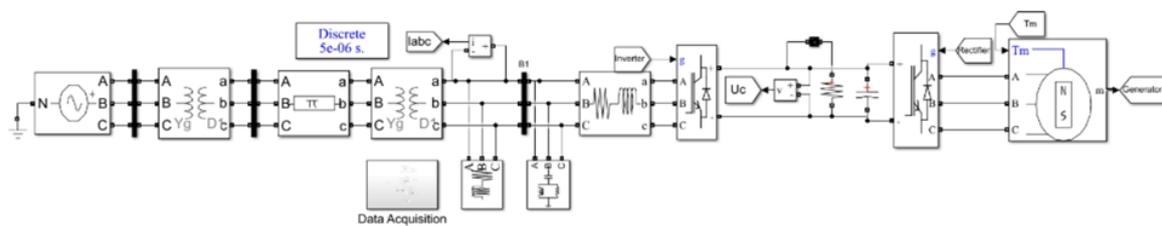Figure 15. Simulink model of a doubly-fed induction generator [41]

Figure 16. Simulink model of permanent magnet induction generator [41]

Based on all those considerations, upon designing the system of wind energy, designated and well-planned components and selection of turbines and generators must be compatible with the wind speed data of the chosen location, in which the cost-benefit analysis must not be overlooked. Moreover, the consideration for a grid-connected system based on the oscillation factors that may happen must not be overlooked, which is also shown by the study by Behabtu *et al.* [58] comparing the squirrel cage induction generator and a doubly fed induction generator in Figures 17 and 18. The results of the study show that the performance of a doubly fed induction generator is better than the other during variable wind speed swell, as well as active-reactive power control capability during steady-state and transient operating conditions.

3.6. Model evaluation

The evaluation of PV and wind turbine model performance in MATLAB/Simulink is a critical process that focuses on two key aspects: accuracy and computational efficiency. Researchers have developed a variety of methods to ensure that their models are both reliable and practical for a wide range of applications, from academic research to real-time control.

Accuracy is the primary metric for model validation and is typically assessed by comparing simulation results with real-world data. The most common approach is experimental validation, where the output of a Simulink model is compared against data collected from a physical PV array or wind turbine system under the same operating conditions. For PV models, this involves using measured values of solar irradiance and ambient temperature as inputs and comparing the simulated voltage, current, and power output against the measured values. The difference is often quantified using metrics like root mean square error (RMSE) or percentage error, which provides a clear measure of the model's fidelity. For wind turbines, models are validated by comparing simulated power curves and torque-speed characteristics with data from real turbines at varying wind speeds.

Some studies also use theoretical validation, where the model's output is compared against established mathematical principles or existing, highly validated models. For instance, the single-diode model for PV cells is a well-understood theoretical basis, and new Simulink models are often validated by showing that their I-V and P-V curves match the theoretical curves under standard test conditions [59], [60]. This approach is particularly useful for verifying the fundamental physics of the model before moving on to more complex simulations. While the accuracy of individual components, such as the aerodynamic block's Cp or the electrical generator's output, is also verified to ensure the overall model's correctness [57].

Aside from accuracy, computational efficiency is a critical consideration for models used in real-time applications, such as HIL simulations or for large-scale grid studies [61]. Researchers often compare the simulation time of their proposed model against that of simpler or older models to demonstrate performance improvement. A faster simulation time allows for more extensive testing, including long-term simulations and real-time control. A key challenge is the trade-off between accuracy and efficiency. Highly detailed models that include every parasitic resistance or aerodynamic nuance can be computationally expensive and slow down simulations.

To address this, researchers are developing simplified models that strike a balance. These models use reasonable assumptions or lump certain parameters to reduce the number of equations and computational steps. For example, a reduced-order model for a PV system may simplify the equivalent circuit to a single-diode model without a shunt resistance to speed up simulation time with a minimal impact on accuracy [62]. The evaluation of efficiency often involves running models on a standardized computer system and reporting the simulation time for a specific duration to allow for fair comparisons across different studies [28]. The use of machine learning models integrated with Simulink also provides a pathway to enhance efficiency by creating fast-to-predict, yet physically consistent, models for real-time forecasting [63].

3.7. Future trends-hybrid energy system

Both solar and wind energy systems, with limitations imposed by the components, geographical situation, weather, costs, and other factors, have caused losses and inefficiencies, casting doubt on the worthiness of these renewable energy sources. Due to technology's rapid advancement, an innovation in that combines both PV and wind systems is developed to optimize energy output production, efficiency, and reliability. Several techniques that have been used are co-located installations (both systems are connected to one grid), integrated controllers (control systems for power and battery charging diversion), microgrids (combinations for energy storage solutions), power electronics (using devices to adjust voltage and frequency parameters for stabler power), optimization algorithms (computational algorithms that have considered weather, demand, and storage capacity) and demand response systems (automatic adjusting supply-demand response) [24].

In the case of MATLAB/Simulink implementation, most of the related studies show that hybrid model (seen in Figure 17) is usually completed with a PMSG generator, an inverter, a boost converter, MPPT, solar panels, and a wind turbine, the power output of the combination is more effective compared to each PV or wind system [64]–[66]. One of the examples is the study by Bangura *et al.* [66], which shows the output in Figure 18. MATLAB/Simulink is an invaluable tool for the initial design and simulation of hybrid PV-wind systems, enabling rapid prototyping, detailed controller testing, and system optimization. Its modular, block-based environment allows engineers to quickly build and test different system configurations, from simple DC/DC converters to complex grid-connected inverters [67]. The ability to simulate various control algorithms, such as MPPT and intelligent energy management strategies, is essential for fine-tuning performance before deployment [68].

The ability of MATLAB/Simulink to integrate with real-world systems is a significant advantage. This is achieved through rapid prototyping and HIL simulations, where the control algorithms developed in Simulink can be directly deployed to a real-time hardware processor. This is essential for applications such as microgrids and grid-tied configurations, where real-time control and interaction with the electrical grid are necessary. A study on a grid-connected solar-wind hybrid system demonstrated the use of MATLAB/Simulink to design a system that not only ensures optimal energy transfer but also enhances power quality and reduces harmonic distortion to meet grid compliance standards [34]. For standalone PV-wind setups, this integration validates the effectiveness of the control system in managing power flow, battery charging, and load balancing under dynamic and unpredictable weather conditions [67].

However, as a system's complexity grows with the addition of generators, multiple converters, and intricate grid connections, the simulation models can become overwhelming. Building these models from thousands of interconnected blocks can be a complex and time-consuming task, even with the latest versions offering pre-built system blocks. Furthermore, publicly available resources often lack the detailed guidance needed to reconstruct advanced models that account for real-world phenomena like the shading effect on PV panels and wind variability, limiting researchers' ability to replicate and build upon existing work [67].

Another major limitation of Simulink for holistic system analysis is its lack of integrated, real-world weather data. To overcome this, a multi-software approach is often required. Specialized tools like PVSyst and WindPRO (or other advanced wind modeling software) are essential for providing accurate meteorological data inputs. PVSyst, for example, is a dedicated PV simulation software that excels at detailed solar energy analysis, including modeling complex shading effects and calculating system losses and inefficiencies. For wind energy, tools like WindPRO provide robust wind resource assessment and turbine placement optimization [67].

Future extensions for hybrid PV-wind systems will focus on integrating advanced technologies to enhance performance and reliability. These innovations include AI-based control, digital twin modeling, and co-simulation with other platforms. These intelligent controllers can analyze vast amounts of data from weather forecasts and energy demand to make real-time decisions, optimizing power dispatch and energy storage strategies and ensuring both high efficiency and resilience against unexpected events [68]. Building on this, the concept of a digital twin is a significant future extension. This is a high-fidelity virtual replica of a physical system that is continuously updated with real-time data from sensors, providing a powerful tool for monitoring, predictive maintenance, and operational optimization [69]. By creating a digital twin of a hybrid system, operators can simulate various scenarios in a risk-free virtual environment, which is crucial for improving reliability and reducing downtime, which can also inform decisions on component selection, potential area analysis, and cost-benefit analysis [70].

To address the limitations of a single software platform, co-simulation will also be essential. This involves running two or more simulators together to combine their strengths. For instance, while MATLAB/Simulink is excellent for control system design, it can be combined with platforms like PSCAD or LabVIEW to perform more comprehensive analyses. Co-simulating with PSCAD allows engineers to analyze power quality and electromagnetic transients in a detailed grid model, ensuring the control algorithms from Simulink are robust enough for real-world grid conditions [71]. This comprehensive approach allows researchers and engineers to model and optimize not just the technical performance of a hybrid system, but also its economic viability and overall efficiency.
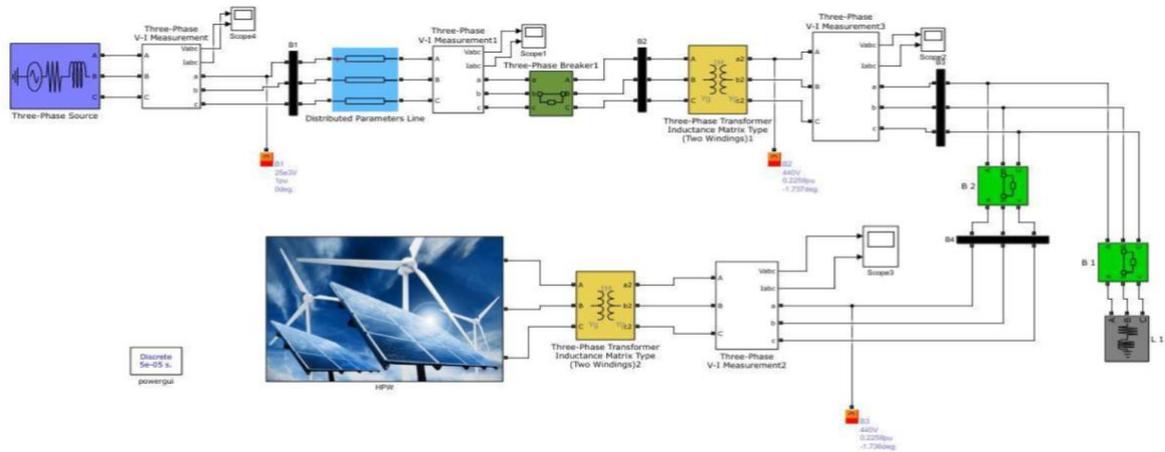

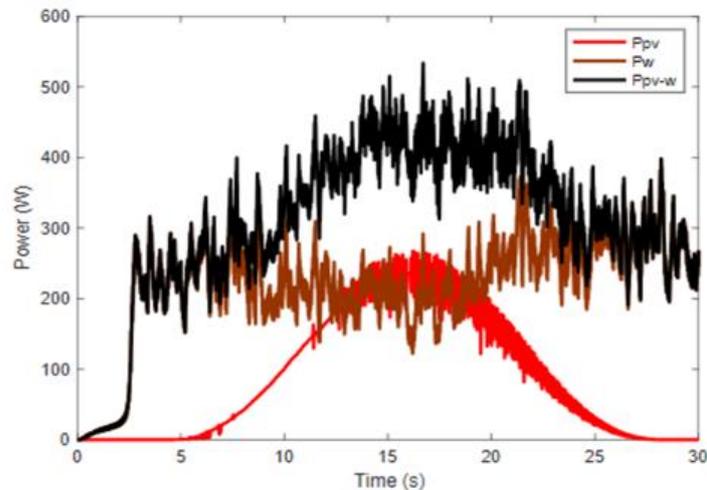Figure 17. PV-wind hybrid system based on Lodin *et al*. model [65]

Figure 18. Output of hybrid system compared to PV and wind system [66]

4.   CONCLUSION

This article provides a guideline for the modeling of PV and horizontal wind systems using MATLAB/Simulink, which is appended with complementary information such as the advantages and disadvantages, strengths, and weaknesses for each energy type. Categorizing it as a renewable energy source, the conversion system usually faces inefficiency and losses due to components, geography, weather, and many other factors. Using tools such as MATLAB/Simulink will help in giving the most suitable design before going to the implementation stages to avoid unnecessary losses. In the case of PV, the Simulink model relies mainly on the mathematical models of PV cells based on a single diode, whereas the wind system relies on the power equation based on Cp variation for horizontal-axis type, though other factors such as converter, generator, and inverter. must not be overlooked to increase more accurate results; however, complexity increases. Due to the limitations of each system, an alternative, which is a hybrid system for both, can be utilized to give optimization, reliability, efficiency, and higher power production. Therefore, this article is intended as an introductory reference on the design of solar and wind energy systems for researchers and engineers, and the decision to help avoid risks for cost and time before real-time implementation. Future research will lead to variations and additional integration for other systems, such as storage and converters. Additional actions, such as implementing other software, can also be done to give a comprehensive analysis for the overall system on costs, potential areas, component selections, and losses/inefficiencies reduction.

AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Fahmy Rinanda Saputri	✓									✓		✓	✓	✓

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support this study's findings are openly provided by all scientific articles that have been discussed and shown in the references.

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