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The Advancement of Artificial Intelligence's Application in Hybrid Solar and Wind Power Plant Optimization: A Study of the Literature

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ABSTRACT

The harnessing of solar, wind, and hydroelectric energy sources has rendered them easily accessible renewable resources, owing to their abundant availability. There is a growing body of research evincing interest in the deployment of hybrid renewable energy systems. Over recent decades, adopting hybrid technologies has engendered a positive trend, marked by broader considerations of configurations and applications within these systems. This study analytically examines the potential of hybrid solar and wind energy harvesting devices. As such, the project aims to extensively evaluate relevant literature and statistical analysis of data extracted from journal papers published between 2004 and 2023. A specific objective is to develop a complete database matrix surrounding multiple categories, including component configurations, methodological approaches, and supporting software infrastructures. Moreover, an assessment of the socio-economic, environmental, and ecological impacts of these systems is undertaken to ascertain their salience. Furthermore, this inquiry delves into the optimization strategies of these systems leveraging artificial intelligence methodologies. Critical lacunae identified during this review pertain to more emphasis on optimization metrics for PV-wind hybrid energy systems, impeding a holistic understanding of their implications on energy, economics, environment, and society. Our findings underscore prevalent methodologies such as computational modelling utilizing software suites like MATLAB/Simulink, HOMER, and others to derive empirical data. Additionally, parametric analyses emerge as the predominant approach, characterized by the application of algorithms such as Particle Swarm Optimization (PSO), Fuzzy Logic Control (FLC), and Genetic Algorithms (GA), among others. PV-wind hybrid energy systems are classified into autonomous and grid-interconnected configurations, with primary components comprising PV-wind generators. The anticipated trajectory suggests a burgeoning development of these hybrid energy harvesting systems, underpinned by their potential as clean, sustainable, and eco-friendly energy sources.

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1. Introduction

This study focused on applying renewable resources for energy purposes due to the concern for environmental issues and fuel limitations. The electricity generated by the Indonesia State Electricity Corporation (PLN) is sourced from coal and processed through combustion, leading to long-term severe environmental problems. Moreover, the electricity cannot be stored in large quantities, leading to energy wastage when not consumed [1]. This shows an urgent need for alternative energy sources due to the increasing electrical burden of PLN each year, which can cause a power supply crisis. One of the potential alternatives suggested is the management of renewable resources such as solar, wind, and water as future energy sources. To provide a workable alternative, earlier research suggested that microgrids (MGs) integrate hybrid renewable sources such as solar and wind photovoltaic systems backed by electrical energy storage devices [2]. This is due to higher energy production by integrating photovoltaic (PV) systems and wind power plants compared to individual energy systems with a low economic impact and a balance of energy availability [3]. Using sunlight as an alternative source of electrical energy can assist communities in achieving independent power supplies, thereby reducing reliance on electricity from PLN.

Moreover, Indonesia is located near the equator, with the whole country lit up by sunlight during the day, indicating the suitability of PV power plants for generating energy [4]. Due to their low cost and simplicity of installation, photovoltaic systems are growing in popularity as a renewable energy source. The trend shows that the collaboration between PV and wind energy systems can be an optimal and stable solution for hybrid power grids in the present world as part of the efforts to implement modern energy systems using diverse sources [5]. This innovation is needed. After all, additional sources such as diesel generators are often used to cover disruptions, system failures, and other issues in individual energy systems to increase the overall energy system costs. Meanwhile, well-designed renewable energy systems can save costs, be highly reliable, and improve overall quality of life.

Solar and wind energy have been observed to complement each other, but the availability of the two sources is unpredictable due to the possible fluctuations at any time. The characteristics of these sources also depend on weather conditions, leading to unreliability when adequate storage devices such as batteries or generators are not provided. Several studies focus on optimizing PV systems to determine the ideal number of PV modules, storage battery capacity, inverter capacity, and the tilt angle of PV arrays. Other studies also consider the optimal size of diesel generators and wind turbines required in hybrid PV systems [6]. Recent trends in the optimization of hybrid renewable energy have suggested the inclusion of artificial intelligence to ensure effectiveness without the need for extensive long-term weather data [7].

Digital transformation drives innovation in environmentally friendly technology, reduces energy financing constraints, and attracts government subsidies. However, the supportive role of this phenomenon in environmentally friendly technology has yet to be fully used, mainly due to financing limitations [8]. Previous studies about the government's impact on this technology primarily focused on environmental regulations, with most identified as impeding green technology innovation. It was also reported that the technology faced serious funding obstacles [9], specifically hybrid PV and wind plant energy systems requiring significant investment for further development to replace depleting energy sources.

The growth of environmentally friendly technology, particularly in water and wastewater treatment, solar PV energy, lighting, chemicals, pharmaceuticals, electric vehicles, and other areas, has reached significant milestones [9]. Most of the discussions on green economic policies have focused on designing public policies to promote low-carbon technologies to promote investment in new technologies that can assist the transition from destructive practices [10]. These were observed to have led to the significance of Green Technology Innovation (GTI) and environmentally friendly energy to achieve carbon neutrality goals [11].

The world expects significant subsidies to promote and develop clean energy technologies to replace carbon-based electricity sources. These subsidies were observed to have hindered several green initiatives, leading to bankruptcies, such as the closure of solar panels (PV) [12]. Meanwhile, the automation of wind power systems has accelerated due to the growing usage of artificial intelligence (AI) algorithms in wind energy technologies. Prior research has shown that artificial intelligence (AI) and advanced data analysis might optimize wind power plant operations and significantly increase the efficiency of wind power systems. An empirical examination of the development of AI algorithm implementation in wind energy technology using text mining and network analysis based on machine learning was conducted, and the findings revealed dynamic patterns in the application process [13].

Several studies examined the development of hybrid PV and wind plant energy with relevant data on general information and the impact of reviews, keywords, system configurations, optimization indicators, methods, and software used presented in Table 1. For example, Sinha & Chandel [14] focused on optimizing PV-wind hybrid energy systems using both traditional and state-of-the-art methods such as algorithms. The trend analysis results showed that AI algorithms were utilized due to the brief computation time and higher accuracy. The application of two algorithms also assisted in overcoming the limitations of a single algorithm.

In 2023, Sahri *et al.,* [15] suggested using intelligent control to enhance system performance and the calibre of produced currents in hybrid PV-wind battery systems. This was accomplished by applying an MPPT algorithm to the grid-side converter to regulate active and reactive power using neurofuzzy direct power regulation (NF-DPC). Zero reactive power was applied to provide a unit power factor and monitor the operational power flow. An energy management algorithm was also created to preserve energy balance, satisfy DC load specifications, lessen weather-related fluctuations, and reduce battery overcharging and discharging.

The physical modelling of renewable energy systems was covered by Bhandari *et al.*, emphasizing techniques and standards for optimizing hybrid renewable energy systems (HRES). These systems were observed to be gaining popularity in addressing energy and environmental crises. Therefore, using artificial intelligence, the study provided a comprehensive review of the trending optimization methods without extensive long-term weather data [7].

A Demand Response-Fuzzy Inference System Controller (DR-FIS) is used to regulate load operations and optimize the size of an autonomous system, as described by Mbouteu Megaptche *et al.,* [16]. The optimization was done with the MOPSO and MOGA methodologies, and the system included PV, wind turbine, supercapacitor, battery, and generator. Wasted Energy (WE), Renewable Generation (REG), Total Greenhouse Gas Emission (TGE), Cost of Energy (COE), Net Present Cost (NPC), and Loss of Power Supply Probability (LPSP) were among the assessment criteria for the optimization. Abdolrasol *et al.,* reported on an off-grid photovoltaic inverter that produced three-phase electricity to supply nearby loads in the same year. An improved fuzzy logic controller (FLC) with particle swarm optimization (PSO) was used to operate the inverter to regulate the output of PV systems. The mean square error (MSE) for voltage at the output was used as the objective function in PSO's subsequent application to improve the three-phase inverter's membership functions (MFs). The PWM inverter's gate driver was turned on using the best PSO results. MATLAB/Simulink was utilized to simulate and model the system to verify the effectiveness of the suggested techniques and ascertain the optimal control output of the inverter for varying load scenarios [17]. Moreover, the FLC preferred to maintain the shape of MFs to save the time used during the trial and error.

In 2012, Hong *et al.,* [18] examined diesel generators, wind turbines, and photovoltaic systems to determine unit sizes for stand-alone plant systems. The investment expenditures, including gasoline, installation, and unit prices, were minimal. Reliability standards and CO emissions limitations were upheld concurrently. Initially, the operating condition of the system load, wind turbine generator (WTG), and photovoltaic (PV) generation in 8760 hours were classified using fuzzy-c-means (FCM). The next step involved building a Markov model that included the system load, WTG, and PV. This model was then integrated into a genetic algorithm to ascertain the ideal sizes for the diesel generators, WTG, and PV. The following year, however, Hong *et al.,* [19] also introduced a fresh approach to deal with the drawbacks of planning active power from a stand-alone hybrid energy system. The goal was to satisfy all operating requirements while reducing the cost of diesel unit fuel and CO2 emissions. Fuzzy sets were utilized to simulate the maximum power of solar and wind PV with uncertainty, and adaptive chaos clonal evolution programming (ACCEP) was employed to solve the resulting interactive multi-objective issue. Priority lists, reference level choices, and various degrees of uncertainty were also covered for the diesel generator.

To get a collection of Pareto-optimal hybrid system configurations with good variety in price and emissions, Abul'Wafa [20] suggested an elitist NSGA-II handled multi-objective approach. Fuzzy cardinal priority ranking was used to find the best compromise alternatives, which were then shown for various input parameter values. It was demonstrated that multipliers associated with overestimated predicted risk and underestimated costs to the availability of solar and wind energy affected how much system generation capacity was allocated. As a result, this investigation aimed to offer quantitative measures of various previously published data about hybrid energy systems. The project aimed to create a thorough information framework by merging the data about installing PV and wind plant energy systems. The literature review identified energy and economic indicators utilized for optimization, classified systems based on relationships, and displayed mathematical models of system components. It was remarkably advised that artificial intelligence be used in modern energy systems that are being created increasingly, such as Artificial Neural Network (ANN) algorithms and fuzzy devices. This was made feasible by the vast amount of research done worldwide on the design and optimization of renewable hybrid energy systems, most of which used computational methods because of their dependability.

PV and wind turbine integration has grown in importance as a research area in attempts to improve sustainable energy systems due to the quick rise in the use of renewable energy [21]. However, there are still several areas where further research is needed to address challenges and improve system efficiency. One of these is researching the development of hybrid technology integrating PV and wind turbines with other renewable energy technologies such as hydro, biomass, or geothermal, which can enhance system flexibility and reliability. This literature review aims to create a comprehensive database and analyse statistical trends in articles related to renewable energy systems, focusing on developing PV-wind power plants.

Table 1
Literature review

Configuration System	Indicators	Methods	Algorithm	Software	Ref.
Stand-alone	LPSP, LLP/LOLP, UL, SPL, LOLH, LOLR, LA, NPC, LCC, COE	Modelling	PSO, GA, SA	MATLAB	Sinha & Chandel [14]
Connected	Not Studied	Modelling	EMA	MATLAB/ Simulink, ANFIS Tool	Sahri *et al.,* [15]
Stand-alone	LPSP, LOLP	Modelling	GA	HOMER	Bhandari *et al.,* [7]
Grid-connected	LPSP, NPC, COE, TGE, WE, REG, Npv	Simulation	MOPSO, MOGA	MATLAB	Mbouteu Megaptche *et al.,* [16]
Stand-alone	COE, LPSP, PE, RF	Simulation	PSO, GA	MATLAB	Sawle *et al.,* [22]
Stand-alone	MAE, MSE	Simulation	PSO, FLC	MATLAB/ Simulink	Abdolrasol *et al.,* [17]
Stand-alone	TLCC, LPSP	Simulation	ANN	MATLAB	Zhang *et al.,* [23]
Stand-Alone	LOLP, LPSP	Simulation	GA	Markov Model	Hong & Lian [18]
Stand-Alone	Fuel cost, CO2 Emission	Simulation	GA	MATLAB	Hong & Lin [24]
Not specified	Emission output, fossil fuel-fired, WECS	Modelling	MODE, PDE, NSGA-II, SPEA2	MATLAB	Abul'Wafa [20]
Connected	Not explained	Simulation	PSO	MATLAB	Hong *et al.,* [19]
Grid-connected	EIR, PE, Cost	Modelling	PSO, HNN	Not Mentioned	Ganesan *et al.,* [25]
Not specified	Operating cost, objective constraints, emission level	Simulation	BSA	Not Mentioned	Chauhan & Kaur [26]
Grid-connected	Not explained	Modelling	PSO, FLC, TLBO	MATLAB	Anilkumar & Srikanth [27]
Grid-connected	Cost minimization objective	Study Case	MOJA, Single objective Jaya algorithm	MATLAB	Salkuti [28]
Stand-alone	economy of energy	Modelling	FL, P&O	MATLAB	Belmili *et al.,* [29]
Grid-connected		Simulation	PSO	MATLAB	Rezaei & Esmaeili [30]
Grid-connected	Not studied	Modelling	FLC	GWOA	Giri & Bera [31]
	LCOE, EENS, LOLP	Simulation	ECSS	SAMS	Huang *et al.,* [32]
Grid-connected	Not studied	Simulation	FLC	MATLAB/ Simulink	Jomaa *et al.,* [33]
Stand-alone	ACO	Simulation	FLC, PSO	dSPACE	Priyadarshi *et al.,* [34]
Grid-connected	Not studied	Modelling	MOPSO	HOMER	Uddin & Islam [35]

2. Methods

This literature review study analysed articles published between 2004 and 2023 on optimizing PV and wind generator systems. Each article was categorized based on the methods, analysis, system configurations, optimization indicators, and the software and algorithms applied. Moreover, Microsoft Excel was used to develop a database to facilitate the classification process, and the results were presented as pie charts.

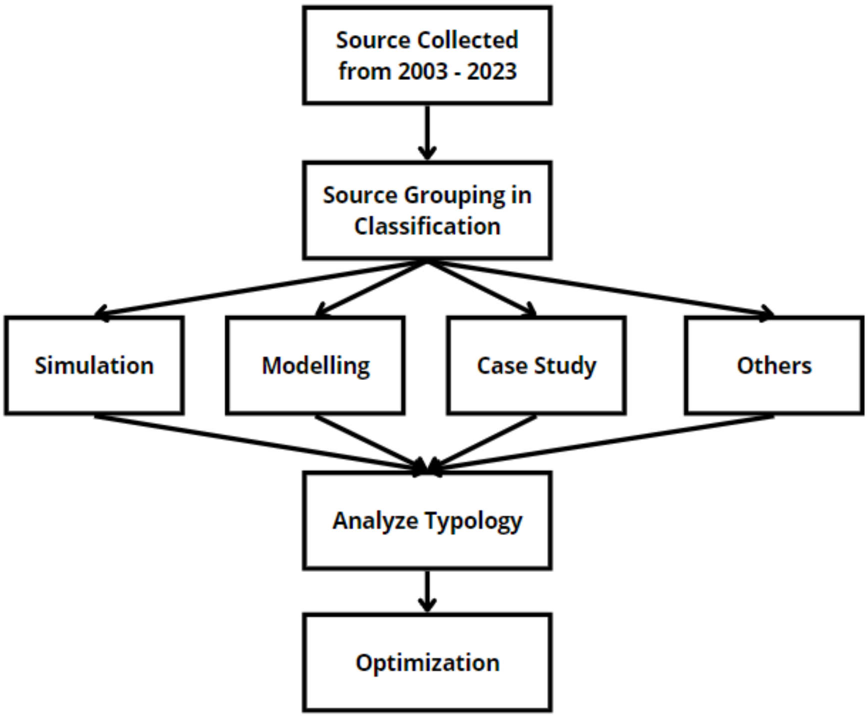

Fig. 1. Analysis system flow

The methods applied in the articles analysed were observed to be different. The most famous two methods were simulation and modelling or experimentation, as presented in the following statistics:

i. 85 articles were in the form of simulations.
ii. 53 articles provided a modelling overview.
iii. 5 articles presented case studies.
iv. 7 articles did not use any of the two methods.

The review showed the preference for numerical simulation in hybrid energy systems due to factors such as time constraints and the simplicity of tools compared to experimental simulations, which required installation and operation of systems.

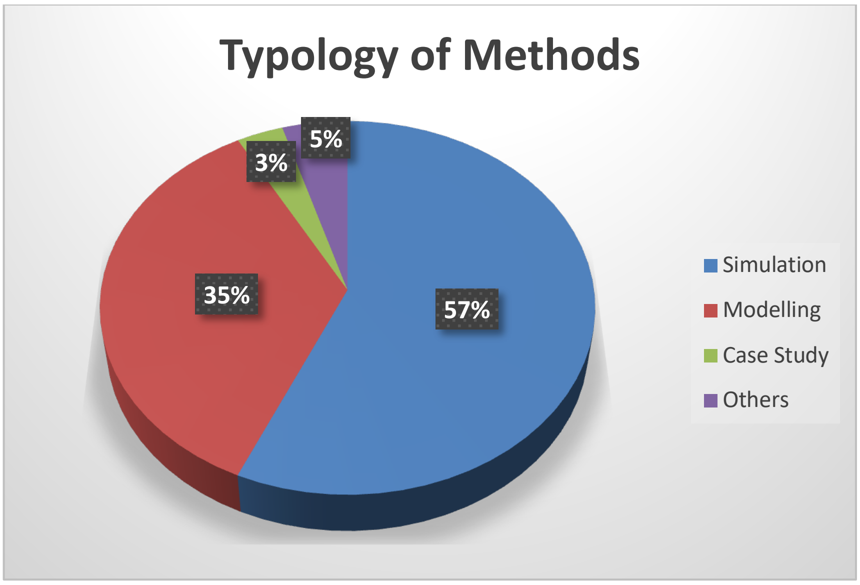

Fig. 2. Methods

Figure 3 shows that the simulation method was most widely used for hybrid energy studies in 2018 and peaked in 2019 and 2022. Meanwhile, the modelling method was primarily applied in 2015, 2017, and 2019. The case study method was mainly used in 2020, while the others were discovered to be more uniform.

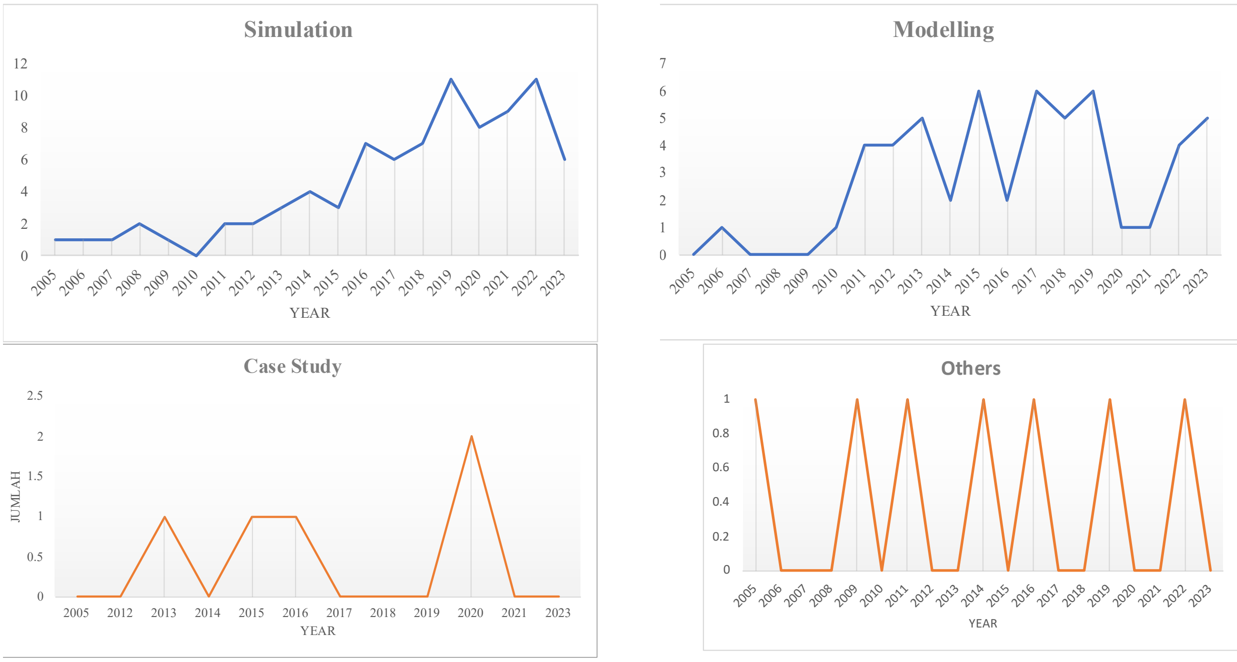

Fig. 3. Graph of methods

3. Results

3.1 Analysis

The articles analysed were grouped based on the type of analysis conducted with a focus on the following:

i. Parametric analysis for optimizing parameters using algorithms
ii. Non-parametric analysis to assess how well hybrid systems function in terms of the environment, social factors, energy, and economy
iii. The results obtained are presented as follows:
iv. 137 articles proposed parametric analysis
v. 89 articles developed non-parametric analysis
vi. 6 articles developed other types of analysis
vii. 143 articles used one software tool
viii. 29 articles used more than one software tool

Figure 4 shows that most of the studies proposed applying parametric analysis to evaluate the performance and reliability of hybrid systems, while 59 used non-parametric. It was discovered that the generation of the parametric analysis was complex due to several influencing factors, such as the availability of renewable energy, location, and others.

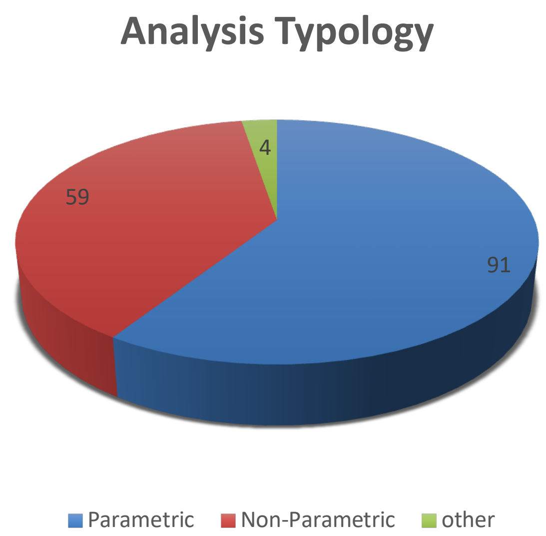

Fig. 4. Analysis typology

3.2 Supporting Software

The review showed that all the articles applied software in studying hybrid systems, and 18 different types were identified, as presented in Figure 4. MATLAB was observed to be used majorly by 27.03% of articles systems studying PV-wind generator hybrid systems, while 23.65% did not specify the software used. Hybrid energy systems were modelled or simulated using these techniques.

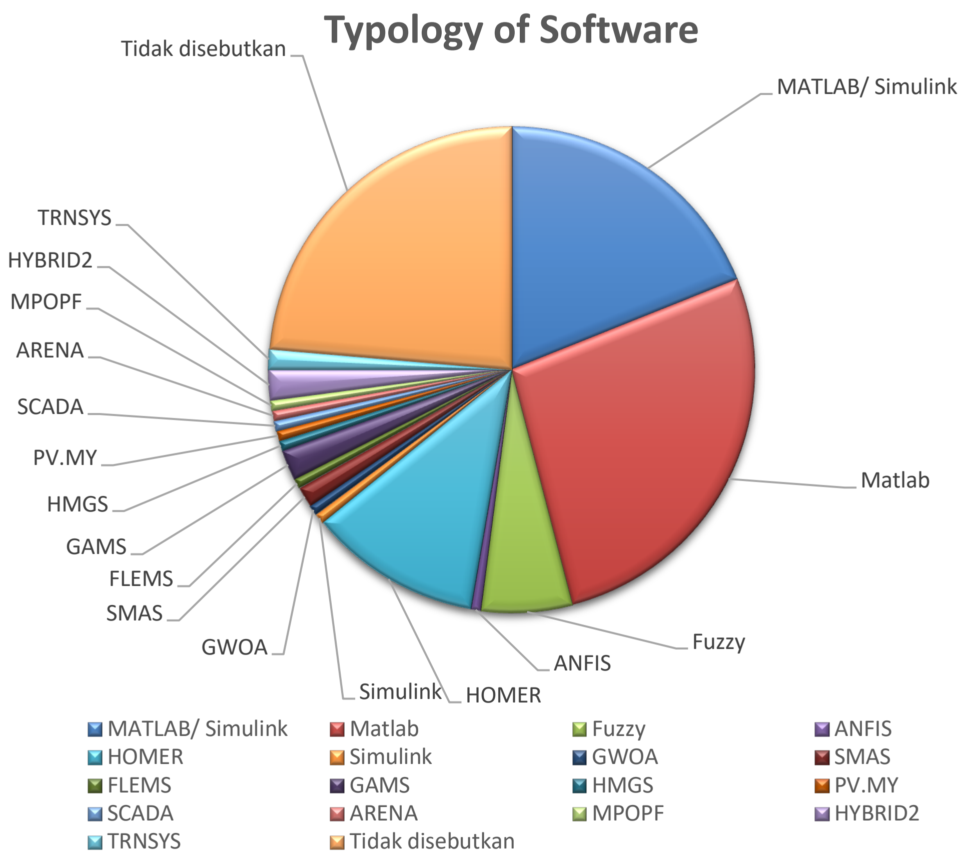

Fig. 5. Typology of software

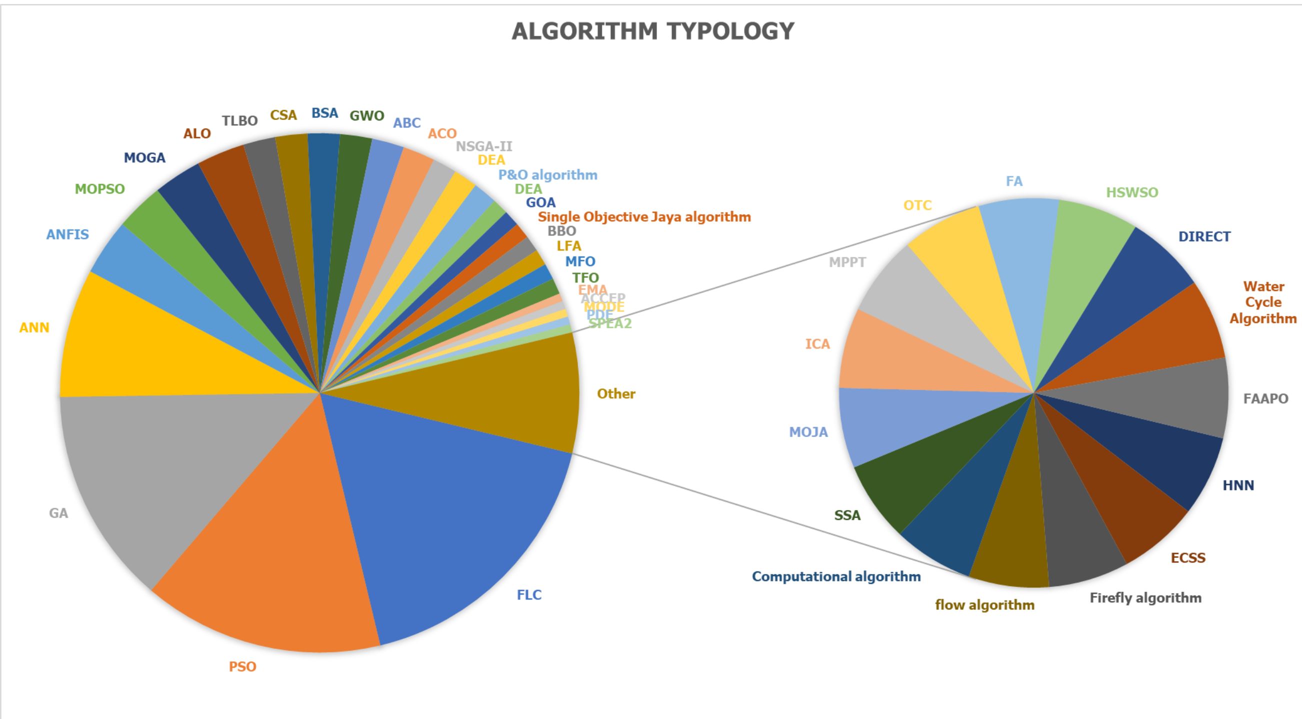

Fig. 6. Typology of algorithms

The results further showed that 18% of the articles used the FLC algorithm, 15% used the PSO algorithm, 14% applied the GA algorithm, 8% opted for the ANN algorithm, and the rest used other algorithms in optimizing PV and wind power plant systems due to certain advantages and reasons. For example, some studies [36-40] explained that the ANN algorithm was effective in predicting weather conditions, such as wind speed, temperature, humidity, and solar intensity, and consider suitable due to the ability to produce time series data. However, all algorithms used in each study can be applied to predict weather factors and determine turbine angles and other components.

3.3 Optimization Indicators and Algorithms

The results showed that 17 energy, 22 economic, 1 social, and 7 environmental indicators were used in the articles analysed, in addition to 139 optimization algorithms.

i. LPSP, LPS, and LLP were used as energy indicators to gauge the system's capacity to handle the load. This demonstrated that the study prioritized developing a dependable hybrid system while considering the quantity of renewable energy generated, surplus power, and unserved load.
ii. NPC (system cost) and COE (cost of energy) characteristics were used to measure economic indicators. In certain studies, the metrics were presented differently: TAC, LCC, and NPV reflected the system cost, whereas LCOE and LCE showed the cost of energy. Payback time (PBT), a metric used to describe the project's investment recovery period, was also incorporated in specific other parameters.
iii. Environmental indicators were addressed by analysing carbon and other equivalent carbon-declared gas emissions.
iv. Social indicators were analysed based on the effects on community well-being.
v. The results showed that the algorithms most commonly used were genetic, fuzzy logic, ANN, and PSO. Comparative studies also used the algorithms to determine the best hybrid system configuration.

3.4 Photovoltaic (PV) System

PV systems' probability power density distribution was split into grid-connected and stand-alone groups. It has been shown that PV distribution systems (PCs) often have low to medium installed power levels with more than 2500 kW frequencies.

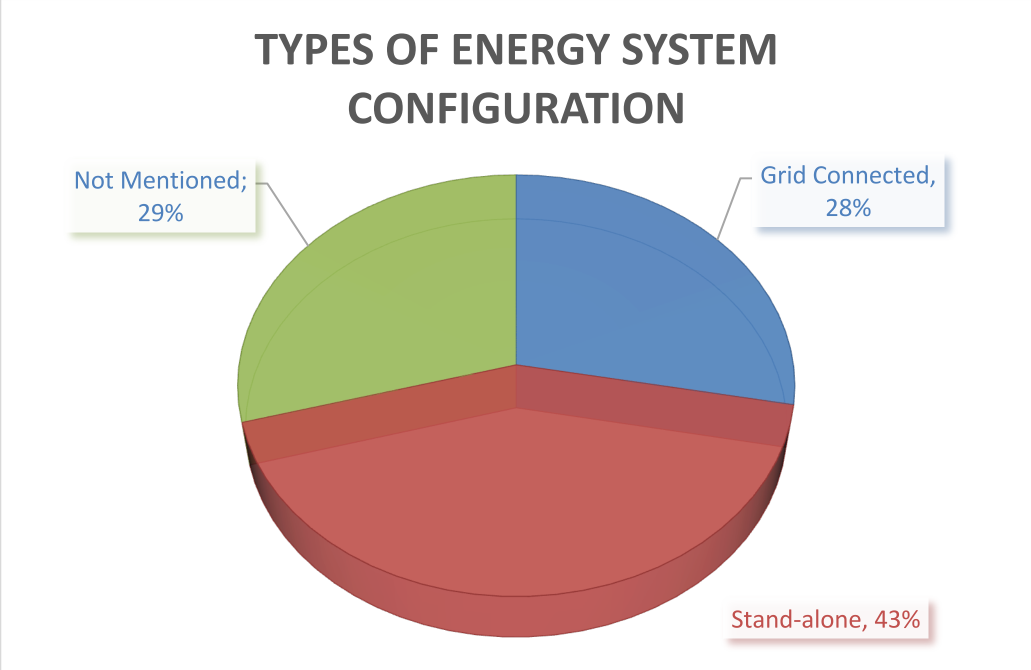

Fig. 7. Typology of hybrid energy system configurations

The analysis revealed that the most popular PV distribution system designs were stand-alone and grid-connected. However, 9% or approximately 14 studies did not specify the configuration used, leading to the categorization of others.

Figure 8 shows that several articles did not specify the components used in the hybrid power generation system design. A detailed analysis of these articles showed variations in the components used. Meanwhile, some cores were batteries, solar PV, diesel generators, wind turbines, and fuel cells. The supporting components were converters, electrolysers, hydrogen tanks, biomass, and others.

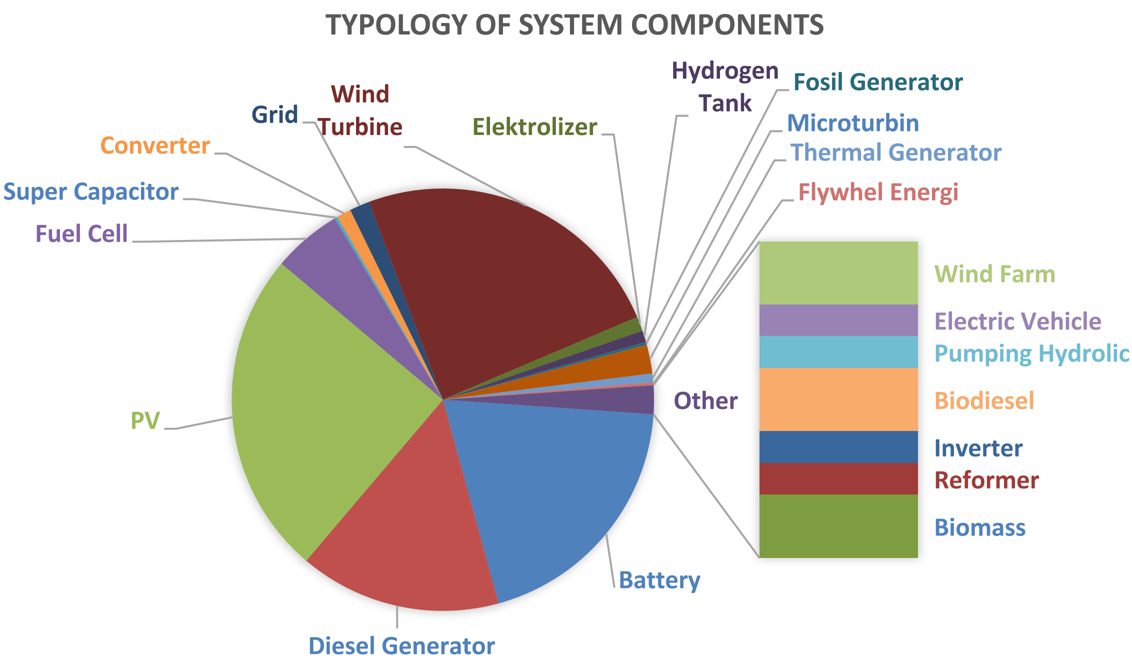

Fig. 8. Typology of hybrid energy system components

Several methods, including stand-alone and grid-connected configurations, can be utilized to optimize hybrid PV and wind power plant systems, according to the discussion of the results. The essential parts were batteries, fuel cells, diesel generators, wind turbines, photovoltaic panels, and additional supporting components. Algorithms like GA, PSO, FLC, SWAM, and others were typically employed to enhance the optimization process further. Also suggested were neural network techniques that may be applied, including ANN, CNN, and RNN, three different forms of neural network structures. Meanwhile, CNN architecture is less effective because the input layer uses images. The ANN and RNN architectures are highly recommended and considered suitable because they use time series data as input and can predict unstable weather conditions, considering the lack of statistical data for long-term weather predictions.

3.5 Artificial Intelligence in Optimization of Hybrid Solar and Wind Power Plants

Artificial Intelligence (AI) has become increasingly applied in optimizing hybrid solar and wind power plants, improving their efficiency and reliability. Essential functions and methods include predictive modelling, optimization techniques, energy conversion efficiency, design optimization, and energy management systems. Predictive modelling involves using Artificial Neural Networks (ANN) to predict the significance of experiments and attributes of various solar and wind prediction models. This helps scientists and engineers analyse the characteristics of different multiple models, assisting them in selecting the most suitable model for a given application. Optimization techniques, such as Particle Swarm Optimization (PSO), can be combined with AI to choose the best hybrid model.

Improving energy conversion efficiency is another key benefit of AI in hybrid solar wind power plants. Research has shown that using a single-axis solar tracking system with a solar panel can boost solar energy conversion efficiency by improving the power output generated by solar-wind hybrid production systems. To reduce expenses and increase efficiency, design optimization entails optimizing factors, including the number of photovoltaic modules, wind turbine height, wind turbines, and turbine rotor diameter. AI also benefits energy management systems; it aids in the conceptual framework, modelling, and optimization of renewable energy sources, control elements, and integration. An analysis of a case study about artificial intelligence's influence on integrating renewable energy sources revealed that AI enhanced the electrical grid's efficiency.

Technical concerns with wind-drive hybrid systems have been investigated in research on hybrid renewable energy systems, and potential solutions that may come from process integration in both grid-connected and off-grid modes have been offered. Special attention was paid to modelling, design, and optimization, as well as sensitivity analysis problems and control techniques to reduce risk and energy waste. Future AI research for optimizing hybrid solar and wind power plants could focus on several areas: improving predictive models, advanced optimization techniques, integration of renewable energy sources, energy management systems, environmental impact, and fault analysis. As AI in renewable energy continues to evolve, there are likely many other potential areas for future research.

4. Conclusions

In summary, a comprehensive data matrix foundation compiled from previous articles deemed most pertinent to optimizing Photovoltaic (PV) and wind generator systems using artificial intelligence techniques spanning the past two decades served as the basis for conducting rigorous quantitative statistical analysis. The findings unveiled that the predominant methodology employed across these studies involved modelling techniques, with a notable proportion leveraging simulation methodologies to generate numerical test data utilizing software platforms such as MATLAB/Simulink and HOMER. Moreover, a considerable proportion of the literature adopted parametric analysis methodologies, employing algorithms like Particle Swarm Optimization (PSO), Fuzzy Logic Control (FLC), and Genetic Algorithms (GA). Additionally, the results elucidated that the configurations of these systems predominantly fell into two categories: stand-alone and grid-connected setups, with the primary components comprising PV-wind generators, while some studies augmented these configurations with auxiliary elements such as diesel generators, fuel cells, and storage batteries. These hybrid systems are projected to undergo substantial advancements in the foreseeable future owing to their promising potential as eco-friendly, renewable energy sources.

Furthermore, applying neural network algorithms, such as Artificial Neural Networks (ANN) and Recurrent Neural Network (RNN) architectures, is recommended for measurement purposes. This recommendation stems from using time-series data as input, facilitating the prediction of long-term weather patterns essential for determining optimal operational schedules for hybrid generation systems. As expounded in this article, optimizing PV-wind hybrid systems is anticipated to be further refined by considering alternative energy sources with superior hybridization prospects while carefully considering geographical parameters.

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