CRITIC-TOPSIS Method: Design of hybrid renewable energy systems based on multi-criteria decision-making

Original Scientific Paper

Ade Gafar Abdullah*
Universitas Pendidikan Indonesia,
Fakultas Pendidikan Teknologi dan Kejuruan,
Program Studi Pendidikan Teknik Elektro
Jl. Dr. Setiabudhi No. 207 Bandung, Indonesia
ade_gaffar@upi.edu

Nanin Trianawati Sugito
Universitas Pendidikan Indonesia,
Fakultas Pendidikan Ilmu Pengetahuan Sosial, Program Studi Survei Pemetaan dan Informasi Geografis
Jl. Dr. Setiabudhi No. 207 Bandung, Indonesia
nanintrianawati@upi.edu

Yusril Nurhikam
Universitas Pendidikan Indonesia,
Fakultas Pendidikan Teknologi dan Kejuruan,
Program Studi Pendidikan Teknik Elektro
Jl. Dr. Setiabudhi No. 207 Bandung, Indonesia
yusrilnurhikam@upi.edu

Diky Zakaria
Universitas Pendidikan Indonesia,
Program Studi Mekatronika dan Kecerdasan Buatan
Jl. Dr. Setiabudhi No. 207 Bandung, Indonesia
dikyzak@upi.edu

Dadang Lukman Hakim
Universitas Pendidikan Indonesia,
Fakultas Pendidikan Teknologi dan Kejuruan,
Program Studi Pendidikan Teknik Elektro
Jl. Dr. Setiabudhi No. 207 Bandung, Indonesia
dadanglh@upi.edu

*Corresponding author

Abstract *– The increasing demand for electricity has driven the development of hybrid renewable energy systems (HRES) in developing countries and remote areas. HRES combines various renewable energy sources to overcome the limitations of each source by utilizing their respective strengths. Although HRES has advantages such as flexibility and low pollution, the development of renewable energy needs to consider environmental impacts and principles of sustainable development. This study aims to find the optimal configuration of a hybrid renewable energy system in the new capital region of Indonesia, namely IKN Nusantara in East Kalimantan province. We conducted a geospatial approach and literature review to gather relevant information, such as solar radiation data, hydropower potential, and biomass potential. We utilized the hybrid optimization model for electric renewables (HOMER) software to design the HRES, and we optimized the results using the multi-criteria decision-making (MCDM) method. The experimental results show that the combination of PV and hydro is the optimal configuration in terms of energy and environmental aspects, with a relative closeness value of 0.675 compared to the ideal solution. Therefore, the implementation of MCDM to evaluate and determine the best configuration of HRES in the IKN Nusantara region is worth considering for further research and development.*

***Keywords**: hybrid renewable energy system, energy, environment, HOMER, CRITIC, TOPSIS*

Received: October 23, 2023; Received in revised form: May 2, 2024; Accepted: May 3, 2024

1. INTRODUCTION

The growing demand for power, particularly in developing nations and isolated locations with limited electrical access, has pushed the development of hybrid renewable energy systems (HRES) over the past few decades [1, 2]. The issue of energy scarcity in emerging nations has emerged as a significant global concern in contemporary times. The depletion of fossil fuels and the threat of global warming have compelled the global community to transition towards renewable energy sources [3]. However, the inherent stochasticity of renewable energy hinders it, making it unpredictable and less dependable. Hence, the inclusion of HRES is very important because it can combine numerous renewable energy sources [4], thereby reducing the problems connected with individual sources while taking advantage of the benefits of others [5]. The utilization of renewable energy resources for electricity generation offers a multitude of benefits, including its widespread accessibility, long-term viability, and contribution to environmental conservation. HRES offers numerous advantages, such as versatility, dependability, minimal environmental impact, and the capacity to provide power to distant settlements, major urban areas, and tiny municipalities [6]. Despite the potential for energy creation and their emission-free status, renewable energy sources such as solar power, wind power, and hydropower development still have environmental repercussions. The non-compliance of renewable energy technologies with sustainable development principles can give rise to a range of consequences, encompassing both advantageous and detrimental impacts on human health and climate change. Considering the principles of sustainable development, it is imperative to prioritize the development of renewable energy technologies [7, 8].

The field of HRES has garnered significant interest from researchers, leading to the conduct of numerous investigations [9]. Several prominent studies evaluating HRES using the HOMER software have been carried out. For instance, a study in Iran identified the optimal off-grid HRES model from environmental and economic perspectives using the hybrid optimization model for electric renewables (HOMER) [10]. The researchers conducted a separate study to assess the technical, load, environmental, and economic factors in residential regions, yielding favorable outcomes [11]. The Nigerian Space Research Laboratory has utilized HOMER to evaluate environmental and economic factors [12]. The findings of a study indicate that off-grid HRES have the potential to provide the whole energy requirements of six isolated settlements while also having minimal environmental consequences [13]. In a separate study, the University of Lethbridge employed the particle swarm optimization (PSO) algorithm to optimize the design of an on-grid HRES. This approach yielded a significant reduction in carbon emissions, exceeding 75%, and a power supply outage probability of 5% [14]. Researchers in India found that using the multi-objective genetic algorithm (NSGA-II) in MATLAB software can develop a hybrid system that can meet the electrical needs of rural areas near the Sundarbans region at a cost of 0.1967 $/kWh. Additionally, this system has the capability to reduce CO_2 emissions by 75,832 kg/year [15]. A separate investigation conducted a comparison between the NSGA-II and Interactive Decision-Making Approach (IDEA) methodologies, revealing that the NSGA-II performed superior optimization in terms of both environmental and economic aspects [16]. Researchers have conducted numerous studies to evaluate the economic and energy aspects of HRES. However, the energy and environmental aspects of HRES in emerging urban or settlement regions continue to receive insufficient attention.

Numerous scholarly investigations have demonstrated the wide-ranging utilization of HRES in various geographic regions, applying multi-criteria decision making (MCDM) techniques to achieve optimal design and implementation. The energy requirements of an academic township in Sikkim, India, are addressed by an autonomous HRES that incorporates solar, wind, biogas, syngas, and hydrokinetic energy sources. We also utilize batteries as a backup power source. The system successfully attains a competitive levelized cost of energy (LCOE) of 0.095 kWh/kWh by utilizing the analytical hierarchy process [3]. In Kenya, a methodical decision-making framework employing geographic information systems (GIS) and the best worst method (BWM) assesses solar, wind, and hybrid systems for energy access, with a preference for solar/wind/diesel/battery HRES due to its efficiency and cost-effectiveness [17]. Optimized HRES planning is advantageous for airports since it involves the use of MCDM models to estimate the appropriate size of renewable energy and storage devices. This planning takes into account both environmental and social benefits simultaneously [18]. Moreover, Cameroon is implementing grid-connected HRES in residential buildings across various climatic zones. By employing sophisticated optimization techniques, this study aims to identify configurations that exhibit reduced costs and greenhouse gas emissions. These findings have significant potential for addressing energy deficiencies in developing regions. These studies highlight the adaptability and effectiveness of MCDM-based methods in creating HRES customized to particular situations, hence supporting sustainable energy transitions and tackling global energy concerns [19].

The utilization of MCDM techniques plays a crucial role in the development of HRES in diverse settings, as demonstrated by numerous research initiatives. To address the issue of gas flaring in oil and gas fields, a novel approach called combinational MCDM has been developed. This approach incorporates various techniques, such as equal distribution, intuitive distribution, and the Analytical Hierarchy Process (AHP), to determine the weights assigned to different criteria. Additionally, a modified technique for ordering preference by similarity to the ideal solution (TOPSIS) is employed to accurately rank appropriate locations for gas flares [20]. In the context of off-grid power solutions in Malaysia and South Africa, the implementation of a complete approach that incorporates numerical approaches, multi-objective principles, and group decision-making processes is crucial to achieve optimal designs. This approach aims to minimize the probability of load loss and minimize life cycle costs [21]. The ideal configuration for a HRES in Faro-Poli, Cameroon, is determined by MCDM. This process takes into account performance ratings while also considering social and environmental restrictions.

MCDM is advantageous for hospitals as it allows for the identification of a cost-effective mix of PV, WT, and DG systems using the TOPSIS approach [22]. Furthermore, the evaluation of the appropriateness of renewable energy systems in the southern region of the Philippines is conducted through the utilization of fuzzy-AHP and GIS methodologies, with a particular focus on the significance of energy production. The utilization of a multi-objective framework in the operation of on-grid PV-PHS hybrid energy systems exhibits notable dependability and cost-effectiveness, as evidenced by the evaluation of MCDM [23]. This framework facilitates optimal decision-making inside intricate energy systems. These studies jointly emphasize the importance of MCDM approaches in effectively resolving various issues and enhancing the performance of HRES designs in different geographical and operational settings.

The utilization of MCDM techniques has been demonstrated to yield significant advantages in the optimization of decentralized energy systems, with the identification of 1945 best designs for ensuring a dependable, cost-effective, and environmentally sustainable energy supply [24]. MCDM approaches such as TOPSIS, combined with weighing methods, were employed to select cost-effective and ecologically sustainable designs, emphasizing the significance of MCDM in enabling efficient decision-making processes for energy systems [25]. Favourable prospects for remote regions without grid connectivity are presented by decentralized HRES. The study showcases how MCDM assists in identifying the most cost-effective and environmentally friendly solutions [26]. The integration of photovoltaic, wind generators, and lithium-ion technologies proves to be both technically and economically feasible. The prioritization of dependability over economic efficiency in the integration of PV and WT (wind turbine) systems for rural energy distribution leads to enhanced reliability and decreased costs for standalone hybrid renewable energy systems [27]. Moreover, the significance of providing clean energy to underserved locations is emphasized, demonstrating that the combination of PV, WT, bio, and batteries is the optimal solution for areas in Iran. [28] Furthermore, a thorough examination of energy system designs for a geographically isolated rural community in India underscores the significance of MCDM in the process of determining the most advantageous configuration, considering technical, economic, and environmental considerations [29]. In general, the aforementioned findings highlight the significant importance of MCDM in the progression of sustainable energy solutions and the resolution of energy requirements in rural and underprivileged populations [30].

In determining the appropriate renewable energy sources for use in HRES, the decisions made are often not directly related to the core issues. This is due to the complex criteria involved in determining HRES. Currently, there is limited research on the development of HRES design for new development areas, such as the new capital city of Indonesia located in IKN Nusantara, East Kalimantan province. This is because the current focus of HRES development is mainly on providing energy for remote, off-grid areas. However, there has been relatively little research conducted on the development of grid connected HRES designs with a focus on energy and environmental aspects. Some studies tend to be partial and focus on only one aspect, while others are more centered on economic analysis. Therefore, it is necessary to adopt an approach that combines suitable methods and software when designing grid connected HRES. This is especially important for selecting hybrid renewable energy options suitable for the development of new residential areas, such as the IKN Nusantara region, which is planned to become the new capital city of the Republic of Indonesia. In this research, the contribution lies in the design of HRES using the proposed HOMER software combined with the MCDM CRITIC-TOPSIS (Criteria Importance Through Intercriteria Correlation-Technique for Order of Preference by Similarity to Ideal Solution) method in the grid-connected area of IKN Nusantara, with a specific focus on energy and environmental aspects.

2. METHODS

2.1. RESEARCH PROCEDURE

The present study encompasses two unique phases, both of which contribute to a full analysis of the adoption of renewable energy. The primary stage of the process is the processing of data using the HOMER tool. During this phase, the procedure begins with a thorough identification of the optimal location for the deployment of the proposed renewable energy system. Following this, a thorough compilation of pertinent data from renowned international journals ensues. The provided data not only serves to inform the project, but also acts as a fundamental resource for making well-informed decisions. Subsequently, a comprehensive evaluation is undertaken to determine the extent of renewable energy capacity within the designated geographical area. Simultaneously, a comprehensive assessment of the electricity demand in the IKN region is being conducted to guarantee that the suggested renewable energy solutions are customized to adequately address the unique requirements of the local community. In addition, robust data validation protocols are implemented to guarantee the precision and dependability of the collected information. The research progresses to the subsequent level alone once the validation of the data has been confirmed. During the second phase, a thorough design process is undertaken to create various combinations of on-grid renewable energy sources. Each combination is carefully tuned to maximize energy production and delivery within the specific region. The phase encompasses the novel element of the study, as it aims to establish the optimal and environmentally friendly approaches to meet the energy requirements of the IKN region.

Within the scope of this study, the evaluation of alternative designs for renewable energy systems (HRES) involves a series of key steps in the application of the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) algorithm process, as seen in Fig. 1.

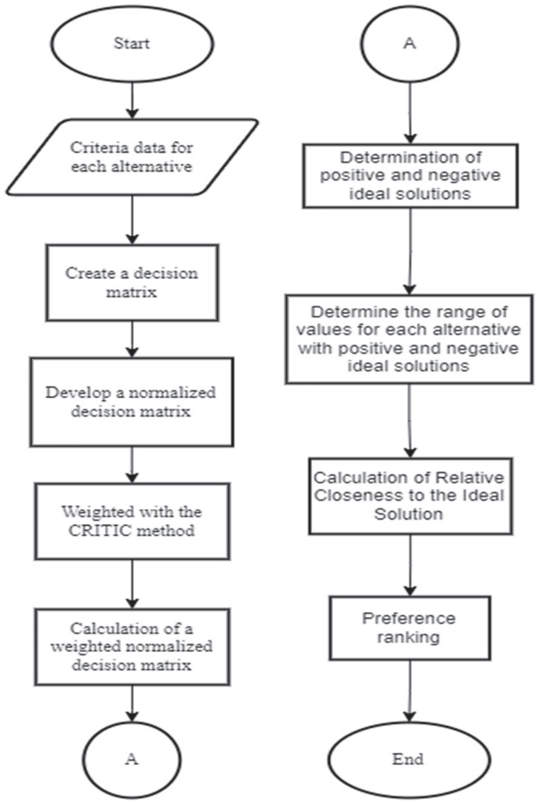

Fig. 1. TOPSIS procedure

The initial stage of the TOPSIS algorithm involves the identification of criteria that will be utilized for the evaluation of HRES alternatives. These criteria often encompass performance factors, including energy efficiency, environmental effect, cost, and additional considerations. The criteria frequently rely on optimization outcomes obtained by software applications like HOMER, which is utilized for the purpose of designing renewable energy systems. After the establishment of the criteria, the relevant data pertaining to each design choice for the Hybrid Renewable Energy System (HRES) is inputted into the decision matrix. The matrix provides a comprehensive representation of the performance of each alternative across all criteria. To enhance the accuracy of decision-making, the matrix then undergoes a process of assigning weights. During the weighting stage, the CRITIC approach is employed to ascertain the relative weight assigned to each criterion. The methodology employed in this approach is founded upon the intercorrelation among criteria, resulting in the derivation of weights that accurately represent the relative significance of each criterion in relation to the desired objective. The outcome of the weighting phase yields a decision matrix that has undergone both normalization and weighting processes. The matrix presented herein provides a more accurate evaluation of the performance of each alternative in relation to pre-established criteria. The matrix also serves as a reflection of the researcher's choices about each criterion. Subsequently, the normalized and weighted matrix is examined to ascertain the positive and negative ideal solutions. The positive ideal solution refers to the optimal combination of values for each criterion, whereas the negative ideal solution represents the converse, namely the least favorable combination of values. By utilizing positive and negative ideal solutions, it is possible to determine the proximity of each alternative to the positive ideal solution and the distance it deviates from the negative ideal solution. These values offer a more comprehensive perspective on the degree to which each alternative aligns with the researcher's preferences. In general, the performance of an alternative tends to improve as it approaches the positive ideal solution and moves away from the negative ideal solution.

2.2. STUDY AREA

IKN Nusantara, situated in the North Penajam Paser and Kutai Kartanegara Regencies of East Kalimantan, is designated as the future National Capital. This designated area encompasses a total expanse of 256,142.74 hectares, with the central city covering 56,180.87 hectares, and the administrative center occupying 5,664 hectares [31, 32]. The development of IKN Nusantara is expected to pose environmental challenges, which the government plans to address by implementing the concepts of a smart city and forest city. These concepts aim to create a sustainable and eco-friendly urban environment by harmonizing nature and technology, thereby preventing ecological degradation resulting from development [33]. Furthermore, there's a strong emphasis on utilizing renewable energy sources to meet the energy demands of IKN Nusantara. The East Kalimantan Province boasts a significant renewable energy potential, estimated at around 23,841 MW [34]. To cater to the power needs of the research site, a priority is placed on harnessing locally available renewable energy sources. This approach aligns with the core principle of IKN Nusantara's development - the integration of nature and technology. Solar energy, hydropower, wind energy, and biomass represent a few examples of renewable energy sources that can be effectively deployed within IKN Nusantara. Leveraging locally sourced renewable energy not only reduces reliance on nonrenewable resources but also promotes a path toward sustainable development.

The researchers opted for a site situated near the Sepaku Semoi Dam, with precise coordinates at 0°54'32.01" Southern Latitude and 116°50'25.72" East Longitude, located in Tengin Baru Village, Sepaku District, North Penajam Paser Regency. As seen in Fig.2, this location was chosen due to its substantial renewable energy potential and a land area spanning 6,230.87 hectares, rendering it suitable for the establishment of a hybrid power plant integrating hydro power with other renewable energy sources. Furthermore, the selection of this site was influenced by its proximity to the zero point of IKN Nusantara, located approximately 16.3 kilometers away.

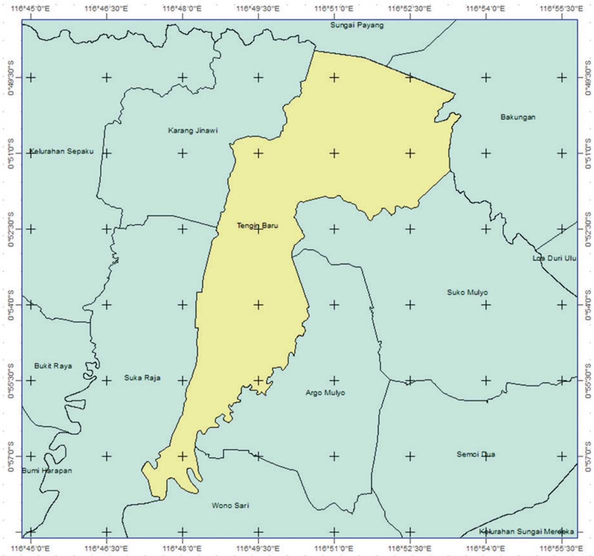

Fig. 2. The research site map

2.3. CRITIC METHODS

The Criteria's Significance the through inter criteria correlation (CRITIC) technique is an analytical method that employs correlation analysis to investigate significant decision criterion specifications. This method can determine the appropriate weight by employing contrast strength and conflicting criteria [35]. The initial step in applying the CRITIC method is to normalize the initial decision matrix using the following equation:

$$r_{ij}= \frac{x_{ij}-x_j^{min}}{x_j^{max}-x_j^{min}} \tag{1}$$

Using the standard deviation and the correlation between one criterion and other criteria, determine the weight of the wj criteria using the following equation:

$$wj = \frac{Cj}{\sum_{i=1}^{m} Ci} \tag{2}$$

Where, Cj is the quantity of data contained in the j-th criterion established in:

$$Cj = \sigma_j \sum_{i=1}^{m}(1 - r_{ij}) \tag{3}$$

Where, σ_j the standard deviation of the j-th criteria and r_{ij} is the correlation coefficient of the j-th and i-th criteria. A higher Cj value indicates that more information is obtained from a given criterion, thereby indicating that the criterion has a higher level of significance in the decision-making process [36].

2.4. TOPSIS METHODS

TOPSIS was chosen as the MCDM method due to its efficacy in decision-making processes for energy systems.

The TOPSIS method is well-suited for scenarios in which it is necessary to simultaneously consider numerous criteria to assess and prioritize different solutions. TOPSIS enables the optimization of decentralized energy systems by considering multiple criteria, including cost-effectiveness, environmental sustainability, and technological feasibility. The study seeks to determine the most advantageous designs that achieve a balance between these requirements by utilizing TOPSIS in conjunction with weighing methodologies. Therefore, the selection of TOPSIS was based on its capacity to offer thorough assessments and enable well-informed decision-making in intricate energy system optimization endeavors.

TOPSIS is a practical and valuable technique for ranking and selecting alternative options based on Euclidean distance that arises from various multicriteria decision making techniques. It is a straightforward, conceptually, and practically simple ranking method. This methodology's objective is to identify ideal solutions and negative ideal solutions to compare the relative performance of alternatives and to identify alternatives that are closer to the ideal solution. The first step in implementing this strategy is to create a normalized decision matrix. [37]:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_i^m x_{ij}^2}} \tag{4}$$

Then calculate the normalized and weighted matrices:

$$v_{ij} = w_j r_{ij} \tag{5}$$

The positive ideal solution is derived from the optimal performance of the normalized and weighted matrix to formulate ideal and anti-ideal solutions:

$$A^* = \{v_1^*, v_2^*, \dots, v_n^*\} = \begin{Bmatrix} \underset{j}{max} & v_{ij}|i \in I' \\ \underset{j}{min} & v_{ij}|i \in I'' \end{Bmatrix} \tag{6}$$

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} = \begin{Bmatrix} \underset{j}{min} & v_{ij}|i \in I' \\ \underset{j}{max} & v_{ij}|i \in I'' \end{Bmatrix} \tag{7}$$

Determine the D_i* and D_i^- value values for each alternative using the formulas:

$$D_i^* = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^*)^2} \tag{8}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \tag{9}$$

Lastly, the Relative Closeness to the Ideal Solution calculation:

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-} \tag{10}$$

C_i* is always between 0 and 1 and an alternative is best if it is close to 1. This is calculated for each alternative and is defined as the above equation [38].

3. DATA AND HOMER DESIGN INPUT

3.1. DATA INPUT

Before starting to optimize the design of the HRES, there is an important first step that needs to be taken: gathering and analyzing data about the potential of solar radiation, the viability of water sources, the availability of biomass, and the needs of the electrical load. This information is very important for making sure that the HRES design can meet the location's energy needs effectively. If we know how much potential solar radiation there is, we can guess how much solar energy can be turned into electricity. In the same way, looking at how easy it is to get to water sources and biomass, along with electrical load data that accurately shows energy needs, gives a full picture of the resources available and the energy needs.

Indonesia boasts significant potential for the advancement of solar power as a viable alternative energy source, owing to its equatorial location and the abundant solar radiation it receives. The East Kalimantan region, in particular, benefits from an exceptional level of solar radiation, rendering it ideally suited for the efficient harnessing of solar energy. Within this geographical area, solar energy stands out as the predominant renewable energy source, constituting a substantial 74.89 percent of East Kalimantan's overall renewable energy potential. [39, 40].

The data provided in Table 1 applies to the solar energy capacity in the village of Tengin Baru Sepaku, which is one of the chosen locations within the IKN Nusantara region. The data utilized in this study was obtained from NASA POWER and encompasses information regarding the mean solar radiation levels seen during the months of January to December during a duration of 21 years, specifically spanning from 2000 to 2021. The average solar radiation possesses the capability to generate a monthly electricity output of 4,661 kWh/m^2/day.

Table 1. Average solar radiation

Month	Daily Radiation (kWh/m^2/day)	Month	Daily Radiation (kWh/m^2/day)
January	4.555	July	4.481
February	4.914	August	4.699
March	4.898	September	4.775
April	4.800	October	4.608
May	4.633	November	4.609
June	4.406	December	4.563
Average		**4.661**	

East Kalimantan, characterized by its abundant river flow and substantial water discharge, presents a highly auspicious prospect for the development of hydroelectric power plants. Additionally, the government's National Energy General Plan (NEGP) supports this claim, saying that East Kalimantan has a large energy potential of 13,479 MW thanks to its many water and solar resources [41, 42]. Within the scope of this study, we leverage the region's substantial water resources, with a particular focus on harnessing the water discharge from the Sepaku Semoi Dam for the establishment of a hydroelectric power plant.

Table 2. Water discharge of the Sepaku Semoi dam

Month	Discharge m^3/s	Month	Discharge m^3/s
January	2.21	July	3.07
February	2.06	August	2.35
March	1.75	September	2.17
April	2.78	October	1.96
May	3.26	November	1.99
June	3.58	December	2.21
Average		**2.45 m^3/s**	

Table 2 provides data indicating that the maximum water discharge occurred in June at 3.58 m3/s, while the minimum discharge was observed in March at 1.75 m3/s. The annual mean discharge stands at 2.45 m3/s. Based on precipitation calculations spanning the previous two decades, it is ascertained that water availability remains consistently adequate. Given a hydraulic head of 15.85 meters, the total electricity generation potential amounts to 2,593,140 kWh annually [43].

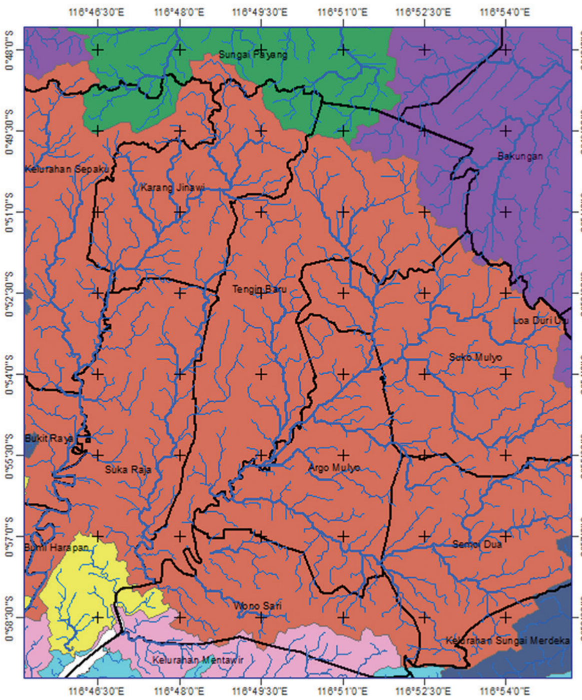

Fig. 3. Tengin Baru village river flow

Fig. 3 presents a comprehensive visualization of the river flow distribution within Tengin Baru Village. This visualization was meticulously analyzed using the robust ArcGIS software. The primary objective of this analysis was to precisely evaluate and quantify the hydropower potential inherent to the specific study site under investigation. The utilization of ArcGIS software allowed for a thorough examination of the geographic and hydrological factors influencing the hydropower prospects in the area, enhancing the accuracy and reliability of the results obtained.

Indonesia, recognized as one of the world's leading palm oil producers, grapples with a significant volume of palm oil waste. Based on the results of the thorough survey, there is a huge potential for making electricity from palm oil waste, which adds up to an impressive 12,654 megawatts (MW). Among the regions assessed, Sumatra exhibited the highest potential, with a capacity of 8,812 MW, while Kalimantan demonstrated the lowest potential at 3,384 MW. This remarkable revelation underscores the immense opportunity to harness palm oil residue as a sustainable and renewable energy source within the region [44]. Moreover, Table 3, which is presented herewith, offers a detailed breakdown of palm oil waste production in the East Kalimantan Province, a province within the Kalimantan region. This dataset was collected in 2019, revealing that ten regencies and local communities in East Kalimantan collectively generate approximately 800 million tons of palm oil solid waste annually [45].

Table 3. Production of palm oil waste

No	Districts	TKKS (ton)	Serat (ton)	Cangkang (ton)
1	Kutai Kartanegara	808265	464323	171971
2	Kutai Timur	1866382	1072177	397103
3	Kutai barat	263456	151347	56.055
4	Mahakam Hulu	29871	1716	6356
5	Penajam paser utara	219584	126144	46720
6	Paser	563094	323479	119807
7	Berau	557463	320245	118609
8	Samarinda	2501	1437	532
9	Balikpapan	110	63	23
10	Bontang	79	45	17

3.1. HRES DESIGN USING HOMER

The research site is where the modeling and simulation of the HRES takes place. This is done by gathering and analyzing relevant data. The visual representation in the Fig.4. showcases four distinct HRES design models, each meticulously developed using HOMER software. While these design schemes share common load requirements and component ratings, their uniqueness lies in the combination of renewable energy sources employed within each design. Design 1 embrace a blend of biomass and photovoltaic (PV) sources, whereas the design 2 integrates hydropower with PV. In the Design 3, biomass and hydropower come together, and the design 4 stands out by combining hydropower, biomass, and PV sources. These diverse combinations of renewable energy sources have been strategically chosen to optimize the simulation outcomes, with a primary focus on enhancing energy efficiency, promoting sustainability, and mitigating the environmental impact of the energy generation process. By running these simulations, the researchers hope to find the best HRES configuration—one that not only meets the site's energy needs but also fits with the main goals of reducing damage to the environment and promoting long-term energy solutions. Fig. 4 shows the four HOMER designs in this study.

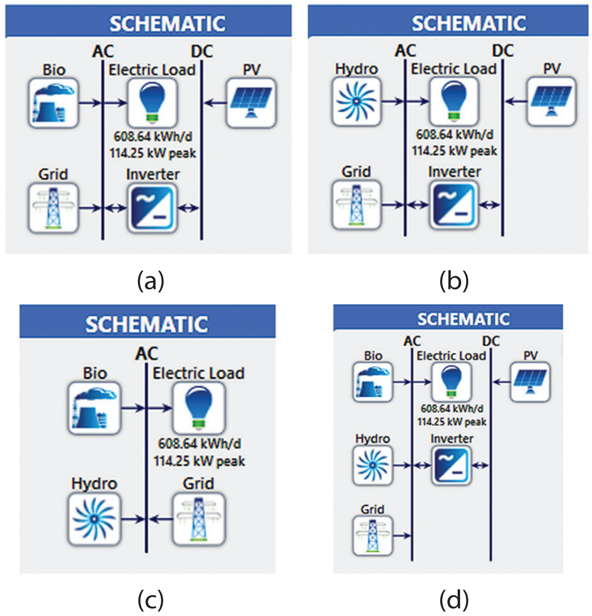

Fig. 4. HOMER Design (a) PV-Biomass (b) PV-Hydro (c) Biomass-Hydro (d) PV-Biomass-Hydro

The load profile implemented at the research site is initially assumed to be representative of the Bali Provincial DPRD (Regional People's Representative Council) office building [46] (see Fig.5).

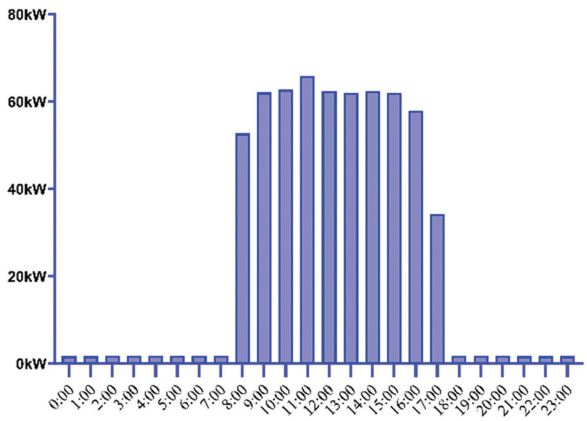

Fig. 5. Daily load profile for the research location

This assumption is based on the premise that such an office facility may offer a reasonable approximation for the energy usage patterns encountered in the area under study. However, to enhance the accuracy and relevance of the load profile, further adjustments are made to align it with the specific daily load characteristics observed at the Office of Highways and Irrigation located in Badung Regency [47]. This meticulous calibration process ensures that the load profile accurately reflects the real-world energy consumption patterns observed in the study location. This considers the Office of Highways and Irrigation's unique operational needs and scheduling quirks, which may be different from those of the Bali Provincial DPRD Office building. This fine-tuning of the load profile is essential for the reliable modeling and simulation of the hybrid renewable energy system (HRES) under consideration, facilitating more precise and context-appropriate results.

Figure 5 shows the daily load data used in the IKN region in a visual way, which helps us understand how energy use changes over time. On average, the daily energy consumption stands at a noteworthy 608.64 kWh. Notably, a discernible spike in electricity usage is observed during the hours spanning from 08:00 to 17:00. This time frame corresponds to the conventional working hours, and as a direct consequence, it leads to a substantial surge in energy demand. This data reveals the prominent role of daily work routines in shaping the energy consumption pattern within this region.

The annual load profile at the study site is depicted in Fig. 6. By analyzing this load profile, trends, and patterns of energy consumption over a certain period can be identified, forming the premise for designing and optimizing renewable energy systems that can efficiently meet energy demands.

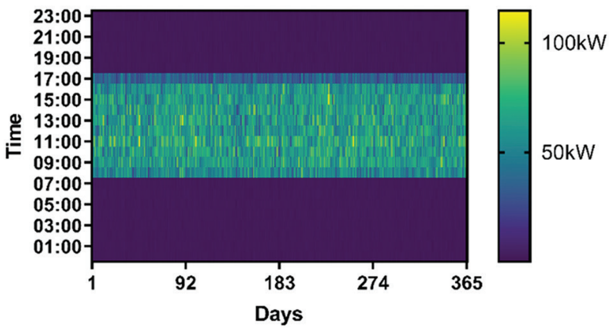

Fig. 6. Annual load profile for research site

The components used in this study have been adapted to the potential and environment of the research site. Where the following components are used:

- The Tirani Solar Vertex 500 WP is a flat panel with a DC current output and a capacity of 0.5 kW. The initial investment and replacement costs for this component are USD 1726,74. The operational and maintenance expenses are 20% of the initial investment, or USD 50 [48]. This PV component has a depreciation factor of 80% and a useful life of 25 years.
- Francis's turbine model HL110-WJ-30 This turbine has a minimum head requirement of 10 m and a capacity of 10 kW. The initial investment cost and replacement cost of this water turbine are USD 4759,60, and operational and maintenance costs are 12% of the initial investment, which is USD 571,15 [49, 50].
- A 15-kW biogas generator with the model number 15GFT-J. With an initial investment cost and replacement cost of USD 6712,25, this generator has operational and maintenance costs of USD 50 [51]. A generator with a lifespan of 20,000 hours.
- 50-250kW Growatt inverter with 99% efficiency and a 15-year service life. Initial investment and replacement expenses total USD 4116,51 while operational and maintenance expenses total IDR USD 82 [52].
- The grid is used to sell excess electrical energy produced by hybrid generators so that it is not wasted. With an electricity purchase price of USD 0,098 per kWh and a selling price of electricity to PLN of USD 0,075 per kWh [53].

4. RESULTS AND DISCUSSION

4.1. RESULTS

After simulating alternative designs using HOMER software, results are obtained that include various parameters related to economic, energy, and environmental aspects. However, in the context of this study, the main emphasis is placed on energy and environmental aspects. The results of the optimization of the four designs that have been made are then presented in detail in Table 4. Furthermore, these data are used as input to calculate the weight of each criterion using the CRITIC method.

Table 4. Homer Pro optimization results for four HRES designs

Criteria	System configuration			
	Design 1	Design 2	Design 3	Design 4
C1: Renewable Fraction (%)	85.7	93.4	79.9	94.4
C2: Max Renewable Energy Penetration (%)	111	109	100	108
C3: Production (Kwh/Y)	266613	377188	276704	345762
C4: Energy Sold (Kwh)	86965	179780	124160	143044
C5: Energy Purchased (Kwh)	44201	26385	69609	20310
C6: Carbon Dioxide (Kg/Y)	27993	16675	44022	12858
C7: Sulfur Dioxide (Kg/Y)	121	72.3	191	55.6
C8: Nitrogen Oxides (Kg/Y)	59.6	35.4	93.5	27.4

At this stage, the CRITIC method is applied to determine the weight of the criteria. The first step in this process is to create a normalized decision matrix using equation (1). Then the standard deviation values for each criterion will be obtained as follows: σ_j = (0.47201, 0.43913, 0.48453, 0.41661, 0.4486, 0.44882, 0.44848, 0.44922).

After the standard deviation is obtained, determine the value of the correlation coefficient. The final step in the decision-making process, where the weights for each criterion are determined using equations (2) and (3). The weight calculation results for each criterion are then presented in Table 5.

Table 5. Weight of each criterion

C1	C2	C3	C4	C5	C6	C7	C8
0.0727	0.2341	0.146	0.2464	0.0752	0.0751	0.0753	0.0749

The decision matrix normalization table shows how different designs perform against the criteria. Design 4 has the highest scores in most criteria (C3, C4, C5, C6, C7, and C8), as shown in the Table 6. Due to its better energy production, energy sales, and greenhouse gas emissions, Design 4 may be a better choice. Design 2 has high energy production (C4) but low purchased energy (C5). Design 3 has a high purchased energy (C5) but lower renewable fraction and maximum renewable energy penetration. Design 1, which scores well in some criteria, has the lowest production score (C3), suggests it may not produce energy efficiently. The final decision about which design is best must take weighting criteria and decision-makers' preferences into account.

Table 6. Normalization of the decision matrix

	C1	C2	C3	C4	C5	C6	C7	C8
Design 1	0,484	0,518	0,417	0,316	0,497	0,498	0,496	0,498
Design 2	0,527	0,509	0,589	0,688	0,342	0,342	0,342	0,341
Design 3	0,451	0,467	0,432	0,655	0,960	0,960	0,960	0,960
Design 4	0,533	0,504	0,540	1,000	1,000	1,000	1,000	1,000

Table 7 displays the weighted normalization matrix, in in which the corresponding criteria weight multiplies each value in the decision matrix. The criteria weights indicate the importance of each criterion in the decision-making process. By examining this table, we can observe the relative contribution of each criterion to the overall assessment of each design. From the table, criterion C4 has the highest weight among all criteria for all designs. This indicates that C4 has a significant influence on the final assessment. Furthermore, criterion C2 also holds a relatively high weight for all designs, suggesting its importance in the decision-making process.

Table 7. Construction of weighted normalization matrix

	C1	C2	C3	C4	C5	C6	C7	C8
Design 1	0,035	0,121	0,061	0,078	0,037	0,037	0,037	0,037
Design 2	0,038	0,119	0,086	0,169	0,026	0,026	0,026	0,026
Design 3	0,033	0,109	0,063	0,161	0,072	0,072	0,072	0,072
Design 4	0,039	0,118	0,079	0,246	0,075	0,075	0,075	0,075

Table 8 provides the positive ideal solution (V+) and negative ideal solution (V-) for each criterion. The positive ideal solution represents the best possible values for each criterion, while the negative ideal solution represents the worst possible values. From Table 8, we can observe that the positive ideal solution (V+) has higher values compared to the negative ideal solution (V-) for all criteria. This indicates that higher values are desirable for criteria such as C1, C2, C3, and so on, while lower values are desirable for criteria such as C4, C5, and others.

Table 8. Identify positive ideal solutions and negative ideal solutions

	C1	C2	C3	C4	C5	C6	C7	C8
V+	0,039	0,121	0,086	0,246	0,075	0,075	0,075	0,075
V-	0,033	0,109	0,061	0,078	0,026	0,026	0,026	0,026

Table 9 provides the Euclidean distance (S+) from each alternative to the positive ideal solution (V+), the Euclidean distance (S-) from each alternative to the negative ideal solution (V-), and the proximity score (Pi) calculated based on these distances. The proximity score represents how close each alternative is to the positive ideal solution relative to the negative ideal solution. From Table 9, we can see that Design 4 has the shortest Euclidean distance to the positive ideal solution (S+), indicating that it is closest to the ideal solution among all alternatives. On the other hand, Design 1 has the longest Euclidean distance to the positive ideal solution. Similarly, Design 4 has the shortest Euclidean distance to the negative ideal solution (S-), while Design 1 has the longest Euclidean distance.

Table 9. Calculation of Euclidean distance, proximity score, and alternate ranking

	Design 1	Design 2	Design 3	Design 4
S+	0,1862	0,1251	0,0890	0,0079
S-	0,1880	0,1574	0,1534	0,1963
Pi	0,5025	0,5572	0,6328	0,9614
Alternative ranking	4	3	2	1

The proximity scores (Pi) are then calculated by dividing the distance to the positive ideal solution by the sum of the distances to both the positive and negative ideal solutions. Better performance relative to other alternatives is indicated by a higher proximity score. Based on the proximity scores, the highest score is attained by Design 4, indicating that it is the most preferable alternative among all designs. Conversely, the lowest proximity score is achieved by Design 1, suggesting that it is the least preferable alternative.

A sensitivity analysis was performed to verify the outcomes of decision-making using the CRITIC-TOPSIS approach. The experiment was conducted by manipulating the weight of each criterion by 25% and 50%, respectively. The outcomes of this manipulation are depicted in Fig. 7. The importance of sensitivity analysis in this work lies in its ability to provide a deeper understanding of how changes in the weight of evaluation criteria affect the choice of HRES design. This allows for the identification of designs that exhibit greater resilience to change, facilitates the exploration of trade-offs across criteria, and incorporates uncertainty into the decision-making process. Through the utilization of sensitivity analysis, the decision-making process can be enhanced, and multiple pertinent factors can be considered when implementing renewable energy.

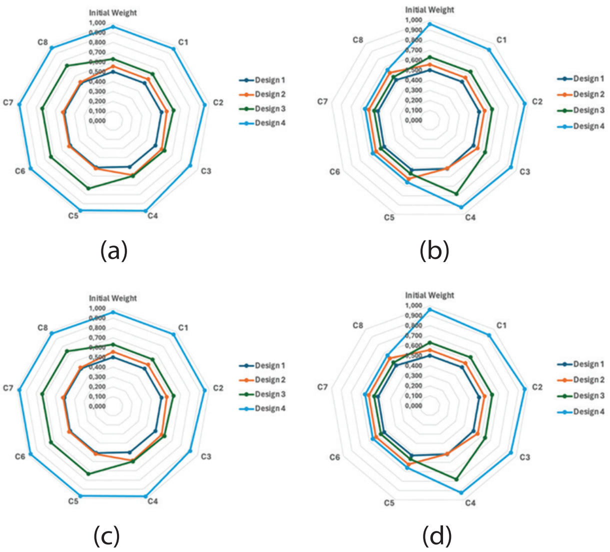

Fig. 7. Sensitivity to changes in performance score: (a) Experiment 1:25% weight gain; (b) Experiment 2: 25% weight reduction; (c) Experiment 3: 50% weight gain; and (d) Experiment 4: 50% weight reduction

Different responses to weighting the evaluation criteria were observed for each design. In Experiment 1, with a 25% weight gain, Design 1 was found to be performing consistently, while renewable energy penetration and production were increased in Design 2, but energy sales decreased. Design 3 was associated with higher emissions of carbon dioxide and sulfur dioxide, whereas Design 4 saw an increase in the utilization of purchased energy. Experiment 2 revealed a different response pattern with a 25% weight loss. Energy purchases increased in Design 1; sulfur dioxide emissions increased in Design 2; energy production increased but nitrogen oxide emissions decreased in Design 3; and energy production and sales decreased in Design 4. Analysis of experimental results with weight addition and reduction by 50% showed significant changes in the evaluation of HRES designs. In experiments with a 50% weight increase, it was seen that some designs experienced increased values on several evaluation criteria, such as energy production (C3) and renewable energy penetration (C2). However, the increase in weight also led to increased emissions of carbon dioxide (C6) and sulfur dioxide (C7) in some designs, suggesting that increased focus on certain criteria could have a negative impact on environmental aspects. Meanwhile, in experiments with a 50% weight reduction, it was seen that there were designs that improved in some criteria, such as energy production (C3), but also decreased in other criteria, such as energy sales (C4). This suggests that weight reductions on certain criteria can change design priorities and result in trade-offs between different criteria. From the experimental results provided, Design 1 shows good relative consistency in performance relative to weight changes. Despite fluctuations in some criteria, such as energy purchase (C5), Design 1 tends to maintain stability in its relative performance.

4.2. DISCUSSION

This study aims to obtain the best configuration of HRES design in accordance with the environmental and energy potential of Indonesia's new capital region, namely the IKN Nusantara area in East Kalimantan province. The results of multi-criteria analysis using the CRITIC TOPSIS method and sensitivity analysis determined that design 4 (a combination of hydropower, biomass, and PV sources) became the main choice to be implemented in the case study area. We have proven this design to provide the optimal performance in various aspects, and the results of sensitivity testing demonstrate its robustness against variations in criterion weight. The incorporation of various renewable energy sources in Design 4 enables improved energy efficiency, sustainability, and a holistic reduction of environmental impact [54,55]. By harnessing the power of water, biomass, and solar energy, this design can provide a reliable and sustainable energy supply to meet electricity needs in the country's capital, IKN Nusantara.

However, it's important to remember that the final decision about a more robust design also depends on your preferences and specific goals. For example, if the top priority is reducing emissions of carbon dioxide and sulfur dioxide, then Design 1 may not be the best choice, as Design 1 is likely to increase emissions of both pollutants under some conditions. In this case, we may need to look at other designs that are more consistent in reducing those emissions. Increased or reduced weights on evaluation criteria can have significant consequences on the relative performance of HRES designs [56], [57], by affecting economic, environmental, and technical aspects [17]. Therefore, in decision-making related to the implementation of HRES, it is important to consider the impact of weight changes on the evaluation criteria thoroughly and choose the design that best suits the needs and desired goals.

The potential for the implementation of HRES that combine PV, hydropower, and biomass at research sites in East Kalimantan is very large. High solar radiation throughout the year, with a daily average of 4,661 kWh/m2/day, creates opportunities to build solar panel installations and expand the use of solar energy in the power sector. In addition, the existence of abundant river flows, with water discharge reaching 3.58 m3/s in several months, allows the construction of hydropower plants that can provide a stable and sustainable supply of electricity. Indonesia also has great potential to produce energy from palm oil waste, which is one of the largest producers in the world. The research site in Kalimantan, which generates significant amounts of palm oil waste, enables the development of biomass power plants to expand the renewable energy portfolio in the region [58]. By harnessing all these potentials together, the implementation of HRES, which combines solar, water, and biomass energy sources, can be an effective solution to meet the sustainable energy needs of East Kalimantan.

In this study, which introduces a new alternative combination method between the HOMER software and MCDM CRITIC-TOPSIS, this methodology functions as a highly effective, comprehensive, and dependable instrument for determining the viability of a hybrid power plant in a specific region. Among the limitations of this study is its reliance solely on expert opinions gathered through content analysis studies of international journals, as opposed to obtaining field data directly. This can result in less accurate research results compared to research involving direct participation. In addition, the limited availability of data on other renewable energy potential limits alternative solutions for hybrid generation to waterpower, biomass, and solar panels. And finally, in this study, the plan alludes only to a prototype government building.

5. CONCLUSION

This study has identified the best configuration for HRES design in Indonesia's new capital region, the IKN Nusantara area in East Kalimantan province. Through multi-criteria analysis using the CRITIC TOPSIS method and sensitivity analysis, Design 4 emerged as the optimal choice, combining hydropower, biomass, and PV sources. This design offers superior performance across various aspects and demonstrates robustness in sensitivity testing. By integrating diverse renewable energy sources, Design 4 enhances energy efficiency, sustainability, and environmental impact reduction. The potential for implementing HRES in East Kalimantan is substantial, leveraging high solar radiation, abundant river flows, and palm oil waste. However, decision-makers must carefully consider their priorities and goals when selecting the most suitable design. Despite limitations like reliance on expert opinions and limited data availability, this study's methodology effectively assesses hybrid power plant viability, providing a comprehensive and reliable approach for sustainable energy solutions in the region.

The implications of these findings highlight the urgency of optimizing renewable energy resources to meet sustainable energy needs in the East Kalimantan region and beyond. Design 4 stands out as an approach that has the potential to reduce dependence on fossil energy sources and reduce environmental impact. Therefore, we recommend that governments and stakeholders take these findings into account when planning and implementing energy projects in the region. Further research may include an investigation of social, economic, and political factors that might influence HRES implementation, as well as technological development and innovation in the field of renewable energy. To ensure the achievement of long-term sustainability goals, we need to carry out continuous monitoring and evaluation of the performance of implemented energy systems. The suggestions also lead to more research using better or more advanced MCDM methods like AHP or TOPSIS, along with advanced analytical techniques like fuzzy logic or grey system theory. There is also in-depth research on the social, economic, and political factors that affect how well HRES is put into place.

6. REFERENCES

[1] K. Almutairi, S. S. H. Dehshiri, S. J. H. Dehshiri, A. Mostafaeipour, A. Issakhov, K. Techato, "Use of a hybrid wind—solar—diesel—battery energy system to power buildings in remote areas: A case study", Sustainability, Vol. 13, No. 16, 2021, p. 8764.

[2] S. M. Mahmoudi, A. Maleki, D. Rezaei Ochbelagh, "Optimization of a hybrid energy system with/without considering back-up system by a new technique based on fuzzy logic controller", Energy Conversion and Management, Vol. 229, 2020, p. 113723.

[3] A. Baruah, M. Basu, D. Amuley, "Modeling of an autonomous hybrid renewable energy system for electrification of a township: A case study for Sikkim, India", Renewable and Sustainable Energy Reviews, Vol. 135, 2021, p. 110158.

[4] A. K. S. Maisanam, A. Biswas, K. K. Sharma, "Integrated socio-environmental and techno-economic factors for designing and sizing of a sustainable hybrid renewable energy system", Energy Conversion and Management, Vol. 247, 2021, p. 114709.

[5] A. Gonzalez, J. R. Riba, B. Esteban, A. Rius, "Environmental and cost optimal design of a biomass-Wind-PV electricity generation system", Renewable Energy, Vol. 126, 2018, pp. 420-430.

[6] H. El-houari, A. Allouhi, T. Salameh, T. Kousksou, A. Jamil, B. El Amrani, "Energy, Economic, Environment (3E) analysis of WT-PV-Battery autonomous hybrid power plants in climatically varying regions", Sustainable Energy Technologies and Assessments, Vol. 43, 2020, p. 100961.

[7] M. J. Mayer, A. Szilágyi, G. Gróf, "Environmental and economic multi-objective optimization of a

household level hybrid renewable energy system by genetic algorithm", Applied Energy, Vol. 269, 2020, pp. 2-16.

[8] M. S. Nazir, A. J. Mahdi, M. Bilal, H. M. Sohail, N. Ali, H. M. N. Iqbal, "Environmental impact and pollution-related challenges of renewable wind energy paradigm - A review", Science of The Total Environment, Vol. 683, 2019, pp. 436-444.

[9] M. Moazzami, D. Fadaei, H. Shahinzadeh, S. H. Fathi, "Optimal sizing and technical analysis of rural electrification alternatives in Kerman province", Proceedings of the Smart Grid Conference, Tehran, Iran, 20-21 December 2017, pp. 1-8.

[10] M. Mehrpooya, M. Mohammadi, E. Ahmadi, "Techno-economic-environmental study of hybrid power supply system: A case study in Iran", Sustainable Energy Technologies and Assessments, Vol. 25, 2016, pp. 1-10.

[11] W. Ma, X. Xue, G. Liu, R. Zhou, "Techno-economic evaluation of a community-based hybrid renewable energy system considering site-specific nature", Energy Conversion and Management, Vol. 171, 2018, pp. 1737-1748.

[12] A. O. Samson, O. M. Babatunde, I. H. Denwigwe, "Powering a Space Environment Research Laboratory (SERL): Hybrid Renewable Energy System or Diesel System?", Journal of the Association of Energy Engineers, Vol. 116, No. 2, 2019, pp. 41-64.

[13] K. Aghapouramin, "Technical, Economical, Environmental Feasibility of Hybrid Renewable Electrification Systems for off-Grid Remote Rural Electrification Areas for East Azerbaijan Province, Iran", Technology and Economics of Smart Grids and Sustainable Energy, Vol. 5, No. 1, 2020.

[14] F. M. Kouhestani et al. "Multi-criteria PSO-based optimal design of grid-connected hybrid renewable energy systems", International Journal of Green Energy, Vol. 17, No. 11, 2020, pp. 617-631.

[15] D. Roy, R. Hassan, B. K. Das, "A hybrid renewable-based solution to electricity and freshwater problems in the off-grid Sundarbans region of India: Optimum sizing and socio-enviro-economic evaluation", Journal of Cleaner Production, Vol. 372, 2022, p. 133761.

[16] B. K. Das, R. Hassan, M. S. H. K. Tushar, F. Zaman, M. Hasan, P. Das, "Techno-economic and environmental assessment of a hybrid renewable energy system using multi-objective genetic algorithm: A case study for remote Island in Bangladesh", Energy Conversion and Management, Vol. 230, 2021, p. 113823.

[17] M. R. Elkadeem, A. Younes, S. W. Sharshir, P. E. Campana, S. Wang, "Sustainable siting and design optimization of hybrid renewable energy system: A geospatial multi-criteria analysis", Applied Energy, Vol. 295, 2021, p. 117071.

[18] Q. Jia, H. Q. Hu, J. L. Yu, "The model construction in airport renewable energy system scale planning based in Multi-Criteria Decision Making", Energy Reports, Vol. 7, 2021, pp. 92-98.

[19] D. T. Hermann, N. Donatien, T. K. Armel, T. René, "A Feasibility Study of an on-Grid PV/Wind/Battery/Diesel for Residential Buildings Under Various Climates in Cameroon", Energy Technology, Vol. 9, No. 12, 2021.

[20] D. Bishnoi, H. Chaturvedi, "Optimised Site Selection of Hybrid Renewable Installations for Flare Gas Reduction using Multi-Criteria Decision Making", Energy Conversion and Management X, Vol. 10, 2022, p. 100181.

[21] H. M. Ridha et al. "Multi-objective optimization and multi-criteria decision making aided by numerical method: Framework and a case study of Malaysia and South Africa", Energy Conversion and Management, Vol. 274, 2022, p. 116468.

[22] S. Peirow, F. Razi Astaraei, A. Saifoddin Asl, "Techno-Economic and Environmental Assessment of a Hybrid Renewable Energy System for a Hospital Using Multi-Criteria Decision-Making Method", Energies, Vol. 16, No. 4, 2023, p. 1916.

[23] R. Tarife, Y. Nakanishi, Y. Zhou, N. Estoperez, A. Tahud, "Integrated GIS and Fuzzy-AHP Framework for Suitability Analysis of Hybrid Renewable Energy Systems: A Case in Southern Philippines", Sustainability, Vol. 15, No. 3, 2023, p. 2372.

[24] P. Bakhshaei, A. Askarzadeh, R. Arababadi, "Demand response-based operation of a hybrid renewable energy system with energy storage by multi-objective optimization and multi-criteria

decision making", Environmental Progress & Sustainable Energy, Vol. 42, No. 2, 2023, p. e13992

[25] H. Yazdani, M. Baneshi, M. Yaghoubi, "Techno-economic and environmental design of hybrid energy systems using multi-objective optimization and multi-criteria decision making methods", Energy Conversion and Management, Vol. 282, 2023, p. 116873.

[26] S. Das, S. Pradhan, S. De, "Multi criteria decision making for the most suitable combination of energy resources for a decentralized hybrid energy solution with green hydrogen as the storage option", Energy Conversion and Management, Vol. 285, 2023, p. 117028.

[27] H. M. Ridha, H. Hizam, S. Mirjalili, M. L. Othman, M. E. Ya'acob, M. Ahmadipour, "Innovative hybridization of the two-archive and PROMETHEE-II triple-objective and multi-criterion decision making for optimum configuration of the hybrid renewable energy system", Applied Energy, Vol. 341, 2023.

[28] M. M. Tehrani, M. Akhtari, A. Kasaeian, M. A. V. Rad, A. Toopshekan, M. S. Motlagh, "Techno-economic investigation of a hybrid biomass renewable energy system to achieve the goals of SDG-17 in deprived areas of Iran", Energy Conversion and Management, Vol. 291, 2023.

[29] D. Roy, M. Bhowmik, A. P. Roskilly, "Technoeconomic, environmental and multi criteria decision making investigations for optimisation of off-grid hybrid renewable energy system with green hydrogen production", Journal of Cleaner Production, Vol. 443, 2024.

[30] Z. Li, Y. Wang, J. Xie, Y. Cheng, L. Shi, "Hybrid multi-criteria decision-making evaluation of multiple renewable energy systems considering the hysteresis band principle", International Journal of Hydrogen Energy, Vol. 49, 2024, pp. 450-462.

[31] S. Pranomo, "Kementerian Komunikasi dan Informatika", https://www.kominfo.go.id/content/detail/40069/undang-undang-ibu-kota-negara-menandai-dimulainya-pembangunan-ikn/0/artikel_gpr (accessed: 2023)

[32] T. Tukimun, "Konsep perencanaan infrastruktur transportasi smart, integrated sustainable & environment friendly di kawasan Ibu Kota Negara (IKN) Nusantara", Kurva S: Jurnal Keilmuan dan Aplikasi Teknik Sipil, Vol. 1, No. 1, 2022.

[33] M. Fajri, "Menggagas Ide Miniatur Hutan Dipterokarpa Ibu Kota Negara Nusantara", STANDAR: Better Standar Better Living, Vol. 1, No. 2, 2022, pp. 5-15.

[34] A. C. A. P. Tampubolon, "Laporan Status Energi Bersih Indonesia", IESR, 2019, pp. 1-23.

[35] S. Zafar, Z. Alamgir, M. H. Rehman, "An effective blockchain evaluation system based on entropy-CRITIC weight method and MCDM techniques", Peer-to-Peer Networking and Applications, Vol. 14, No. 5, 2021, pp. 3110-3123.

[36] M. Madic, M. Radovanovic, "Ranking of some most commonly used nontraditional machining processes using rov and critic methods", UPB Scientific Bulletin, Series D: Mechanical Engineering, Vol. 77, No. 2, 2015, pp. 193-204.

[37] T. Salameh, E. T. Sayed, M. A. Abdelkareem, A. G. Olabi, H. Rezk, "Optimal selection and management of hybrid renewable energy System: Neom city as a case study", Energy Conversion and Management, Vol. 244, 2021, p. 114434.

[38] J. Papathanasiou, N. Ploskas, "Topsis", Optimization and Its Applications, Vol. 136, 2018, Springer, pp. 1-30.

[39] P. Hasanah, S. A. Wiradinata, M. Azka, "Forecasting approach for solar power based on weather parameters (Case study: East Kalimantan)", Journal of Physics: Conference Series, Vol. 2106, No. 1, 2021, pp. 1-10.

[40] M. R. Kresnawan, I. A. Safitri, I. Darmawan, "Long term projection of electricity generation sector in east kalimantan province: LEAP model application", Proceedings of the 12th South East Asian Technical University Consortium, Yogyakarta, Indonesia, 12-13 March 2018, pp. 1-5.

[41] J. Windarta et al. "Planning for the utilization of hydro power in the Belayan river, East Kalimantan", Journal of Physics: Conference Series, Vol. 1524, No. 1, 2020, pp. 1-7.

[42] L. M. H. Zakir, J. Windarta, S. Saptadi, D. Rinaldo, "Analysis of planning for utilization of East Borneo hydro power with techno economy principle", AIP Conference Proceedings, Vol. 2202, 2019, pp. 1-7.

[43] F. Nashrulloh, M. Sulaiman, R. Budiarto, "Analysis of Potential and Feasibility of Hydropower Energy from Sepaku Semoi Dam in Penajam Paser Utara Regency", IOP Conference Series: Earth and Environmental Science, Vol. 927, No. 1, 2021, pp.1-8.

[44] K. Esdm, "Kementerian ESDM RI - Media Center - Arsip Berita - Limbah Sawit Di Indonesia Berpotensi Hasilkan Listrik 12.654 MW", https://www.esdm.go.id/id/media-center/news-archives/limbah-sawit-di-indonesia-berpotensi-hasilkan-listrik-12654-mw (accessed: 2023)

[45] K. Kelapa et al. "Biogas And Bioenergy Potential From Solid Wastes (Empty Fruit Bunch, Mesocarp Fiber, and Decanter Cake) of Palm Oil Industries in East Kalimantan", Kemenperin, Vol. 15, No. 2, 2021, pp. 487-497.

[46] I. K. Hendy Wijaya, I. N. Satya Kumara, W. G. Ariastina, "Analisis PLTSAtap 25 KWp on Grid Kantor DPRD Provinsi Bali", Jurnal SPEKTRUM, Vol. 9, No. 2, 2022, pp. 128-137.

[47] E. T. Abit Duka, I. N. Setiawan, A. Ibi Weking, "Perencanaan Pembangkit Listrik Tenaga Surya Hybrid Pada Area Parkir Gedung Dinas Cipta Karya, Dinas Bina Marga Dan Pengairan Kabupaten Badung", Jurnal SPEKTRUM, Vol. 5, No. 2, 2018, pp. 67-73.

[48] S. Pramonos, "Survey of Operation and Maintenance Costs of PV Plants in Switzerland", EKP, Vol. 13, 2015, pp. 3-6.

[49] E. Oud, "The evolving context for hydropower development", Energy Policy, Vol. 30, 2002, pp. 1215-1223.

[50] T. S. Kishore, E. R. Patro, V. S. K. V. Harish, A. T. Haghighi, "A comprehensive study on the recent progress and trends in development of small hydropower projects", Energies, Vol. 14, No. 10, 2021, p. 2882.

[51] J. Li, P. Liu, Z. Li, "Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China", Energy, Vol. 208, 2020, p. 118387.

[52] C. Rangkuti, J. Teknik Mesin, "Perencanaan Pembangkit Listrik Tenaga Surya Di Atap Gedung Harry Hartanto Universitas Trisakti", Prosiding Seminar Nasional Cendekiawan, August 2016, pp. 1-22.

[53] C. Rolos et al. "Analisis Penentuan Harga Jual Listrik Pada PT PLN (Persero) Unit Induk Wilayah Sulawesi Utara, Sulawesi Tengah dan Gorontalo Analysis of Electricity Price Determination At PT PLN (Persero) Main Units for North Sulawesi, Central Sulawesi and Gorontalo Regi", Jurnal Riset Ekonomi, Manajemen, Bisnis dan Akuntansi, Vol. 9, No. 3, 2021, pp. 1703-1710.

[54] S. Abdelhady, "Techno-economic study and the optimal hybrid renewable energy system design for a hotel building with net zero energy and net zero carbon emissions", Energy Conversion and Management, Vol. 289, 2023, p. 117195.

[55] M. Thirunavukkarasu, Y. Sawle, H. Lala, "A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques", Renewable and Sustainable Energy Reviews, Vol. 176, 2023, p. 113192.

[56] R. Kumar, H. K. Channi, "A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: Design, optimization and techno-economic-environmental analysis", Journal of Cleaner Production, Vol. 349, 2022, p. 131347.

[57] Y. Sawle, S. C. Gupta, A. K. Bohre, "Review of hybrid renewable energy systems with comparative analysis of off-grid hybrid system", Renewable and Sustainable Energy Reviews, Vol. 81, 2018, pp. 2217-2235.

[58] S. Kaniapan, S. Hassan, H. Ya, K. P. Nesan, M. Azeem, "The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: A review", Sustainability, Vol. 13, No. 6, 2021, p. 3110.