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Multi-Criteria Decision-Making on The Selection of IoT-Based Inverter Smart Grid System and Smart Meter for Solar Photovoltaic and Wind Turbine Installations in Pelabuhan Ratu CFPP using AHP & TOPSIS Method*

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Abstrak

Pemilihan inverter yang tepat sangat penting untuk memaksimalkan efisiensi dan kinerja sistem tenaga surya fotovoltaik (PV) dan turbin angin, karena inverter memiliki dampak langsung pada efisiensi konversi energi secara keseluruhan dan output sistem dengan mempengaruhi efisiensi dan keandalan. Pemilihan inverter juga mencakup kriteria penting seperti biaya, kompatibilitas dengan sumber energi terbarukan, dan pertimbangan lingkungan. Oleh karena itu, pendekatan yang menyeluruh dan sistematis diperlukan untuk mengevaluasi dan membandingkan berbagai opsi inverter secara efektif. Penelitian ini menggunakan pengambilan keputusan multi-kriteria untuk mengatasi tantangan ini, dengan mengevaluasi kriteria yang diidentifikasi menggunakan Proses Hirarki Analitik (AHP) dan merankingnya untuk menentukan solusi optimal melalui Teknik Pemesanan Preferensi berdasarkan Kemiripan dengan Solusi Ideal (TOPSIS). Akibatnya, investigasi ini mengidentifikasi inverter smart grid dan smart meter sebagai solusi ideal, berhasil mengatasi masalah stabilitas daya, komunikasi dan konektivitas, keamanan, manajemen data, dan biaya. Metodologi yang diusulkan menghasilkan total ekuitas substansial sebesar USD 9.325,71, disertai dengan pendapatan sebelum bunga, pajak, depresiasi, dan amortisasi (EBITDA) sebesar USD 1.734,09 per tahun. Periode pengembalian investasi yang diperkirakan adalah 6,85 tahun, dan tingkat pengembalian investasi (ROI) mencapai 338,07%. Selain itu, pendapatan bersih secara signifikan mengurangi biaya produksi, dengan USD 40.853,34 dalam satu periode.

Kata kunci : Pemilihan inverter, fotovoltaik surya, turbin angin, pengambilan keputusan multi-kriteria, efisiensi, keandalan, smart grid, smart meter, stabilitas daya, biaya, AHP, TOPSIS.

Abstract

The selection of appropriate inverters is pivotal in maximizing the efficiency and performance of solar photovoltaic (PV) and wind turbine systems, as they directly impact the overall energy conversion efficiency and system output by influencing efficiency and reliability. Inverter selection also encompasses critical criteria like cost, compatibility with renewable energy sources, and environmental considerations. Thus, an exhaustive and systematic approach is essential to effectively evaluate and compare different inverter options. This study employs multi- criteria decision-making to address these challenges, evaluating the identified criteria using the Analytical Hierarchy Process (AHP) and ranking them to determine the optimal solution via Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS). Consequently, the investigation identifies smart grid and smart meter inverters as the ideal solutions, successfully addressing concerns regarding power stability, communication and connectivity, security, data management, and cost. The proposed methodology yields a substantial total equity portion of USD 9,325.71, accompanied by impressive earnings before interest, taxes, depreciation, and amortization (EBITDA) of USD 1,734.09 per year. The estimated payback period is 6.85 years, and the return on investment (ROI) reaches a remarkable 338.07%. Additionally, the net income significantly reduces the production cost, with USD 40,853.34 in a single period.

Keywords: Inverter selection, solar photovoltaic, wind turbine, multi-criteria decision-making, efficiency, reliability, smart grid, smart meter, power stability, cost, AHP, TOPSIS.

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1. INTRODUCTION

Electricity consumption in Indonesia impacts national development and increases economic growth. According to the Electricity Supply Business Plan (RUPTL) for 2021–2030, the average projected electricity demand growth is 4.9%, with 40,575 MW in planned power plant development. Renewable energy power plants account for 20,923 MW, or 51.6%, of total power-producing capacity (PLN, 2021). However, as of 2022, renewable energy power plants account for just 11.3% of total current power output (NZE, 2023).

One of the natural resources that can be utilized in tropical regions to close the gap between the goal and its realization is solar energy production. Solar cell modules can be used to generate electricity from sunlight. The average solar radiation intensity in Indonesia is approximately 4.8 kilowatt-hours per square meter per day (International Energy Agency, 2021). This is a significant figure, high solar radiation intensity directly translates to a higher potential for solar energy production.

Solar energy is an energy source that has the potential to be developed in Indonesia, considering that Indonesia is a country located on the equator. The solar energy that can be generated for Indonesia, which has an area of ±2 million km2 with an irradiation distribution of 4.8 kWh/m2/day, is equivalent to 112.000GWp (International Energy Agency, 2021). Therefore, solar energy has advantages compared to fossil energy. Solar energy is a low-cost, environmentally friendly energy source that is adaptable to a variety of geographical circumstances and relatively simple to install, use, and maintain (Zhong, 2023).

Furthermore, Indonesia has enormous potential for wind energy, particularly in its hilly and coastal regions. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), the average wind speed in Indonesia is 4-5 meters per second (PLTB, 2023). To meet its electricity needs, Indonesia has a tremendous chance to use wind energy as a sustainable energy source. Wind energy only contribute around 0.3% of Indonesia's total power-producing capacity by 2022 (PLTB, 2023). The Indonesian government has set a target of raising the percentage of renewable energy to 23% by 2025, and wind turbines are one of the renewable energy sources projected to contribute to this goal's attainment (PLN, 2021). Therefore, to help the government achieve the energy mix target in 2025, Pelabuhan Ratu Coal Fired Power Plant (CFPP) also wants to contribute green power by utilizing solar energy and wind energy.

However, an electricity-efficient and cost-effective configuration system is required due to the utilization of multiple generating sources (CFPP grid, solar photovoltaic, and wind turbine). In addition, to optimize the distribution system and use of electrical energy in the digital age, the following system is required:

1. Increase efficiency in the use of electrical energy by monitoring and managing energy use more effectively.
2. Improving the safety of using electrical energy by detecting and preventing disturbances in the electrical network system.
3. A real-time system that can monitor electricity consumption is required to reduce the likelihood of electrical energy theft or loss.
4. A more consistent supply of electrical energy necessitates a system of distribution that can more effectively regulate electric current.

This scientific paper focuses on the selection process of the most suitable Internet of Things (IoT)-based inverter, smart grid system, and smart meter for Pelabuhan Ratu CFPP, utilizing the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods. By employing these multi-criteria decision-making techniques, it aims to evaluate and rank potential systems based on various criteria such as reliability, interoperability, scalability, cost- effectiveness, and environmental impact.

A thorough assessment of the literature and data collection will result in the development of a set of evaluation criteria as well as a decision matrix for the selection process. Using AHP and incorporating expert viewpoints will identify the relative weights of criteria and sub-criteria, ensuring a well-balanced evaluation. Furthermore, the TOPSIS method will calculate the closeness coefficients and rank the candidate systems, considering both positive and negative ideal solutions.

2. METHODOLOGY

A. Identification of Problems

Several problems that can be identified with the addition of renewable sources of electrical energy to the existing power system can be identified using the root cause analysis method described below in Fig. 1.

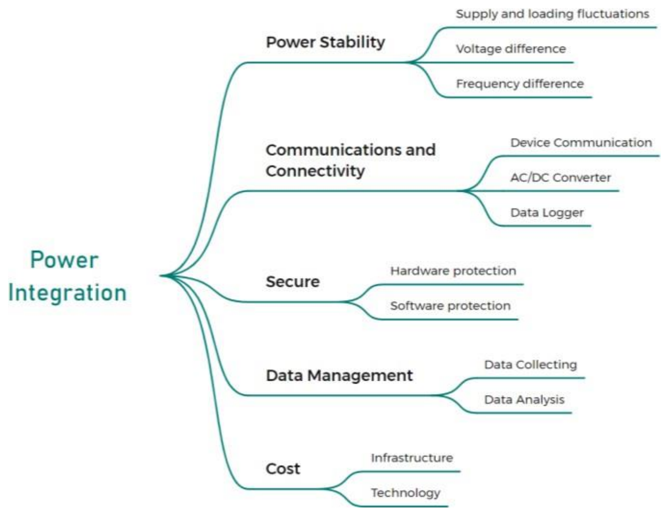

Fig. 1. Root cause analysis.

1. Power Stability: Installing solar panels and wind turbines can lead to oscillations in the grid's power supply, compromising its stability. Consequently, a power supply regulation system that can account for fluctuations is required.
2. Communication and connectivity: IoT-based smart grid systems and smart meters need robust and dependable communication to gather and process data from solar photovoltaic (PV) and wind turbine installations.
3. Secure: Sensitive data, including details on electricity consumption and the setup of solar PV and wind turbines, is collected and processed by the IoT-based smart grid system and smart meters. A robust security system is required and hardware protection connected to tampering.
4. Data management: Smart meters and IoT-based smart grid systems gather and analyse massive amounts of complex data. Therefore, processing and creating helpful information requires an efficient and effective data management system.
5. Cost: The infrastructure and technology required to deploy IoT-based intelligent grid systems and smart meters in solar PV and wind turbine installations are expensive. Therefore a barrier to the widespread use of this method.

B. Problem Solving

The Multi-criteria Decision-Making (MCDM) approach is used to conduct problem-solving analysis to find the best decision from several criteria based on previously identified problems, as described below in Fig. 2.

This study combines two MCDM techniques: the Analytical Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS). Based on the concerns mentioned, this study's preference is for a solar PV and wind turbine inverter system.

Fig. 2. Criteria based on the problems that have been identified.

Based on the availability of inverters in the market, here are some inverters that we use as alternative solutions.

1. On-Grid Inverter (On-Grid): Inverters directly connected to the network or grid won't work if they don't recognize a network supply. A unique circuit in an on-grid inverter allows it to sync the grid voltage, frequency, and phase of the PV network with the grid.
2. Off-Grid Inverter (Off-grid): Inverters not connected to the grid have their system (stand-alone) from generation to load, are separated from the network, and require a battery for energy storage.
3. Microinverter (Micro-Inv): A small inverter is installed on each solar panel. This type of solar panel inverter can be directly installed under the solar panel. A microinverter is more expensive overall than other inverters.

4. Smart Grid Smart Meter Inverter (SGSM-Inv): Inverters that can synchronize with the network and support the load according to the output produced based on IoT, where operating, production, and disturbance parameters can be displayed visually and monitored online and in real-time.

C. Integrated AHP-TOPSIS Method

The Analytic Hierarchy Process (AHP) represents a methodology within the realm of Multi-Criteria Decision-Making (MCDM) that facilitates decision-makers in selecting the optimal alternative from a multitude of choices, while concurrently taking into account diverse criteria or factors. In support of the analysis conducted in this research, Microsoft Excel is employed.

The AHP technique provides decision-makers with more specific information regarding the relative priority or weight assigned to each criterion connected with the option. AHP divides decision-making into three steps: first, the decision maker lists the alternatives and criteria to be evaluated; second, the decision maker uses a relative scale to perform a pair-wise comparison analysis between each criterion and alternative; and third, AHP calculates the alternative priority score against the criteria and the alternative overall score against all criteria.

The following mathematical formulas are utilised to analyse the AHP analysis in this work, as well as the AHP method steps.

Table 1. Numeral representation of importance level

Importance Numerical Intensity	Interest Level
1	Equivalent Importance
3	Moderate Positioning
5	Strong Positioning
7	Very Strong Importance
9	Extreme Positioning
2,4,6, and 8	Intermediate Values

Step-1: Making a pair-wise comparison matrix While weighing the importance of one criterion over another, a conclusion was reached (Saaty, 1987).

$$A = \begin{vmatrix} a_{11} & a_{12} & .. & a_{1m} \\ a_{21} & a_{22} & .. & a_{2m} \\ .. & .. & .. & .. \\ a_{m1} & a_{m2} & .. & a_{mm} \end{vmatrix}, where \;\; a_{ji} = \frac{1}{a_{ij}} \qquad (1)$$

Step-2: The normalizing approach with Equation (2) was utilized in matrix calculations to estimate significant amounts of factors in the decision matrix (Saaty, 1987). As demonstrated below, a normalized matrix B is formed.

$$b_{ij} - \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \qquad (2)$$

$$B = \begin{vmatrix} b_{11} & b_{12} & .. & b_{1m} \\ b_{21} & b_{22} & .. & b_{2m} \\ .. & .. & .. & .. \\ b_{m1} & b_{m2} & .. & b_{mm} \end{vmatrix}, where \;\; a_{ji} = \frac{1}{a_{ij}} \qquad (3)$$

Step-3: Calculation of the criterion weight. The criteria weights generated in this phase are represented by the column vector W. The priority vector, often known as a measure of importance, is generated from Equation (4) and is the arithmetic average of matrix B's row components (Saaty, 1987).

$$W = \begin{vmatrix} w_1 \\ w_2 \\ .. \\ w_m \end{vmatrix}, w_i = \frac{\sum_{j=1}^{m} b_{ij}}{m} \qquad (4)$$

Step-4: The determination of eigenvalues is carried out through the utilization of Equations (5), (6), and (7). As described subsequently, matrix D is generated.

$$D = [A][W] \qquad (5)$$

The Eigenvalue (λ) is obtained by taking the arithmetic mean value of E values, which is calculated as shown below.

$$E = \frac{a_i}{w_i}(i = 1,2,3, \ldots m) \tag{6}$$

$$\lambda = \frac{\sum_{i=1}^{m} E_i}{m} \tag{7}$$

Step-5: Check for consistency. Equations (8) and (9) are used to check for data consistency. After calculating (λ), Equation (8) can calculate the consistency indicator (CI). Table II and Equation (9) can also be used to determine the consistency ratio (CR).

$$CI = \frac{\lambda - m}{m - 1} \tag{8}$$

$$CR = \frac{CI}{RI} \tag{9}$$

Table 2. Random consistency index (RI)

N	RI
1	0
2	0
3	0,58
4	0,9
5	1,12
6	1,24
7	1,32
8	1,41
9	1,46
10	1,49

The consistency test is completed when CR is determined numerically. If the CR is less than 10%, the obtained data is consistent. If the CR is greater than or equal to 10%, the results are inconclusive. As a result, the comparison matrix must be modified (Mehra, 2023).

The distances from positive and negative ideal solutions are chosen using this procedure. The TOPSIS technique prioritizes options based on predefined criteria. As the first stage in this process, a choice matrix is constructed. In the following phase, the choice matrix was normalized. In the third stage, the choice matrix is weighted. Calculating ideal-solving and negative ideal-solving solutions is the fourth level. The fifth stage involves calculating both positive and negative ideal distances. The relative scores of each option are determined in the sixth phase (Wang, 2013).

Step-6: Making an experimental data matrix. The initial stage is to create an experimental emission data matrix for various criteria (columns) and alternatives (rows) as shown in Equation (10).

The hierarchy modelling of the AHP and TOPSIS methods is used to determine the selection of an inverter system for solar PV and wind turbines based on criteria determined by the results of problem identification shown as Fig.3.

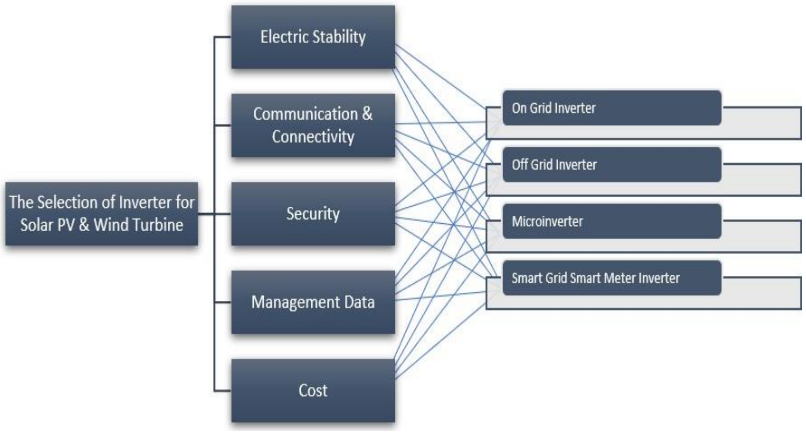

Fig. 3. Diagram Hierarchy AHP-TOPSIS.

3. RESULT & DISCUSSION

A. Analytical Hierarchy Process (AHP Solution)

After identifying the criteria like cost, safety and secure (S&S), management data (Man-Data), communication and connectivity (C&C), and power stability (PS) for the assessment to be carried out and determining the preferred candidate, the first step is to do the weighting, as shown in Table 3.

Table 3. Pair-wise comparison matrix using ahp method.

Criteria	Cost	S&S	Man-Data	C&C	PS
Cost	1,00	0,20	1,00	3,00	3,00
S&S	5,00	1,00	3,00	5,00	3,00
Man-Data	1,00	0,33	1,00	3,00	1,00
C&C	0,33	0,20	0,33	1,00	0,33
PS	0,33	0,33	1,00	3,00	1,00
Total	7,67	2,07	6,33	15,00	8,33

Criteria weighting is done by comparing it with other criteria. This treatment is called pair-wise comparison. The evaluation guidelines are based on Table I and then normalization of the matrix on Table IV.

Table 5. Eigen matrix value

Eigenvalue	5,42	5,59	5,28	5,21	5,03	
Weight Criteria	0,95	2,30	0,77	0,30	0,68	
Criteria	Cost	S&S	*Man-Data*	C&C	*PS*	Weight Value
Cost	0,95	0,46	0,77	0,90	2,05	5,12
S&S	4,73	2,30	2,31	1,50	2,05	12,88
Man-Data	0,95	0,77	0,77	0,90	0,68	4,06
C&C	0,32	0,46	0,26	0,30	0,23	1,56
PS	0,32	0,77	0,77	0,90	0,68	3,43

Perform normalization by dividing the results of pair-wise comparisons by the total value of each criterion. Then calculate each criterion's weight by adding up the results of the normalization of each criterion on Table 5.

Multiply pair-wise comparisons with the weight criterion to check for consistency. Then, to decide each criterion's weight, summarize the findings from assessing its consistency.

Table 6. shows a CR value of 0.068, where 0<CR<0.1. This proves that the data has met consistency requirements so that the weighting criteria can be used in further analysis.

Table 6. Final value

Parameter	Value
Eigenvalue Max	5,306
N	5,000
CI	0,076
RI	1,120
CR	0,068

B. TOPSIS Solution

After the weighting value on the criteria is proven consistent, we can use it to evaluate alternative solutions and rank the best solution.

Table 7. The matrix value and the total number of columns

Criteria	Cost	S&S	Man-Data	C&C	PS
On-Grid	4	4	2	2	4
Off-Grid	3	1	4	4	3
Micro-Inv	2	3	4	3	2
SGSM-Inv	3	4	3	4	4
Total	12	12	13	13	13
Attribute	benefit	benefit	benefit	benefit	benefit

Table 7 gives the weighting value of each solution based on the problem identification criteria formulated in Table VIII to evaluate alternative solutions and rank the best solution.

Table 8. Index weighted score based on effect

Score	Description
Score 1	very low positive impact
Score 2	low positive impact
Score 3	high positive impact
Score 4	very high positive impact

Squaring each score, then calculating the sum of the squares (TSS), is followed by rooting to get a weighting value representing each criterion for normalizing show as Table 9. Then calculate the total square root (TSR) for each criterion

Table 9. Calculating the total sum of square roots

Criteria	Cost	S&S	Man-Data	C&C	PS
On-Grid	16	16	4	4	16
Off-Grid	9	1	16	16	9
Micro-Inv	4	9	16	9	4
SGSM-Inv	9	16	9	16	16
TSS	38	42	45	45	45
TSR	6,16	6,48	6,71	6,71	6,71

Table 10. Normalizing the decision matrix

Criteria	Cost	S&S	Man-Data	C&C	PS
On-Grid	0,65	0,62	0,30	0,30	0,60
Off-Grid	0,49	0,15	0,60	0,60	0,45
Micro-Inv	0,32	0,46	0,60	0,45	0,30
SGSM-Inv	0,49	0,62	0,45	0,60	0,60

Table 10 shows normalize the results of the decision matrix by dividing the values obtained for each criterion by the total number of square roots. Give weight to the decision matrix by multiplying the results of the decision matrix with the weight criteria based on Table IV as shown on Table 11.

Table 11. Giving weight to normalized decision

Criteria	Cost	S&S	Man-Data	C&C	PS
Weighted	0,95	2,30	0,77	0,30	0,68
On-Grid	0,61	1,42	0,23	0,09	0,41
Off-Grid	0,46	0,36	0,46	0,18	0,31
Micro-Inv	0,31	1,07	0,46	0,13	0,20
SGSM-Inv	0,46	1,42	0,34	0,18	0,41

To determine the data distribution range, look for the maximum and minimum values for each criterion to find out the data distribution limit range as shown on Table 12.

Table 12. Best and worse ideal value

	Cost	S&S	Man-Data	C&C	PS
Attribute	benefit	benefit	benefit	benefit	benefit
V+ (ideal+)	0,61	1,42	0,46	0,18	0,41
V- (ideal-)	0,31	0,36	0,23	0,09	0,20

Table 13. Positive ideal solution distance (D+)

Criteria	Cost	S&S	Man-Data	C&C	PS	*Total*	*D+*
On-Grid	0,00	0,00	0,05	0,01	0,00	0,06	0,25
Off-Grid	0,02	1,14	0,00	0,00	0,01	1,17	1,08
Micro-Inv	0,09	0,13	0,00	0,00	0,04	0,26	0,51
SGSM-Inv	0,02	0,00	0,01	0,00	0,00	0,04	0,19

Table XIII shows calculation of the distance of the decision matrix with the maximum data by squaring the decision matrix, summing, and doing a root square to obtain information on the ideal solution distance with the maximum value of each criterion.

Table 14. Negative ideal solution distance (D-)

Criteria	Cost	S&S	Man-Data	C&C	PS	*Total*	*D-*
On-Grid	0,09	1,14	0,00	0,00	0,04	1,27	1,13
Off-Grid	0,02	0,00	0,05	0,01	0,01	0,09	0,31
Micro-Inv	0,00	0,51	0,05	0,00	0,00	0,56	0,75
SGSM-Inv	0,02	1,14	0,01	0,01	0,04	1,22	1,11

Tabel XIV shows calculation of the distance of decision matrix with the minimum data by squaring the decision matrix, adding, and doing a root square to get the ideal solution distance with the minimum value of each criterion.

Calculate performance (V) by dividing the ideal worst by the ideal value (best + worst) to get the performance value as a reference for ranking as shown on Table 15.

Table 15. Euclidian distance and performance score

Criteria	D(+)	D(-)	V	Rank
On-Grid	0,25	1,13	0,82	2
Off-Grid	1,08	0,31	0,22	4
Micro-Inv	0,51	0,75	0,59	3
SGSM-Inv	0,19	1,11	0,85	1

Table 16. Alternative solution ranking

Criteria	Rank
SGSM-Inv	1
On-Grid	2
Micro-Inv	3
Off-Grid	4

Based on the results of the multi-criteria decision-making ranking of the four popular inverter options proposed as alternative solutions using the AHP and TOPSIS methods on Table XVI, it is determined that the Smart Grid Smart Meter Inverter is the most optimal and has a positive impact on solving problems of electricity network stability, communication and connectivity, security, data management, and costs.

C. Financial Benefit

Financial analysis is conducted using the kWh rate, as stipulated in Board of Directors Regulations 0283.P/DIR/2016, which pertains to the utilization of electricity by non-PT PLN power providers. These regulations specify service tariffs, particularly for payments related to imported kWh, which are set at 17.62 cents per kWh (PLN, 2016). The annual total power generation comprises 8255 kWh/year for solar PV and 1843.2 kWh for the wind turbine.

Table 17. Financial projections

PT PLN Indonesia Power PLTU Jawa Barat 2 Pelabuhan Ratu - Power Generation Unit			
No	**Description**	**Recapitulation**	
A	**Renewable energy projection on kwh**		
1.0	Solar PV Capacity	6.000,0	Wp
1.1	Wind Turbine Capacity	4.800,0	Watt
1.2	Production	10.098,20	Kwh/years
B	**Operating expenses**		
2.1	Project Value (CAPEX)	$ 9.325,71	USD
2.2	Depreciation Period	25	Year
2.3	Depreciation Value	$ 373,03	$/years
C	**Rates of power purchase**		
3.0	Rates kwh (0283.P/DIR/2016)	0,1762	$/kwh
D	**Income statement**		
4.1	Revenue Solar PV	$ 1.779,30	$/years
4.2	Maintenance Cost	$ 177,93	$/years
4.3	EBITDA	$ 1.601,37	$/years
E	**Return on equity**		
5.1	Net profit	$ 1.228,34	$/years
5.2	Total Profit	**$ 30.708,60**	$/Pd
5.3	Pay Back Period	**7,59**	Year
5.4	Discount Rate = Cost of Equity	**17,41**	Year
5.5	Return on Investment	**329,29%**	/Pd

EBITDA is derived through the subtraction of total revenue from maintenance costs, resulting in a figure of USD 1,601.37. Following the consideration of interest, taxes, depreciation, and amortization, the EBITDA value is adjusted to yield a net profit of USD $1,228.34, the same as the annual profit. Over the course of 25 years, the cumulative profit totals USD 30,708.60, and the investment will reach its payback period (PBP) in 7.59 years. The return on investment (ROI) for this venture stands at an impressive 329.29% within a single period.

4. CONCLUSION

The utilization of inverters in power generation holds promise as a viable alternative to mitigate carbon emissions associated with thermal power generation, thanks to the integration of renewable energy sources. In this study, we employ the AHP-TOPSIS method, integrated with the Multi- Criteria Decision-Making (MCDM) approach, to discern the optimal inverter selection based on experimental findings. The following results were obtained:

1. Safety and security were found to be the top-weighted criteria among all criteria by AHP. According to the comparison of AHP-TOPSIS analysis results, the smart grid and smart meter inverter was the best choice, followed by the on-grid Inverter, microinverter, and off- grid inverter.
2. Therefore, the Smart Grid Smart Meter Inverter is the most optimal and has a positive impact on solving problems of power grid stability, communication & connectivity, security, data management, and costs.
3. The total equity portion for this renewable energy project is worth USD 9,325.71 with an EBITDA of USD 1601.37/year, Pay Back Period is 7.59 years, ROI is 329.29%, and net income as a decrease in production cost of USD 30,708,6 in one period.

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