Techno-economic analysis and optimization of solar energy systems: a case study at Ar-Raniry State Islamic University

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ABSTRACT

This research examines the implementation of a solar power generation system at Ar-Raniry State Islamic University (UIN Ar-Raniry), specifically focusing on the Faculty of Tarbiyah and Keguruan building. The study aims to enhance energy efficiency, assess economic feasibility, and reduce environmental impacts by optimizing solar energy potential through variables such as local meteorological conditions, panel orientation, tilt angles, and system efficiencies. Utilizing PVSyst software for simulations, the research evaluates technical performance, life cycle costs, and carbon dioxide (CO_2) emission reductions. The results indicate that the solar Photovoltaic (PV) system can generate 251,214 kWh annually while reducing CO_2 emissions by 173,095 kg. Economically, the investment is deemed feasible, with a payback period of 7.8 years, a lower cost of energy (LCOE) compared to State Electricity Company (*PLN*) tariffs, a positive net present value (NPV), and a high internal rate of return (IRR). Although there are minor losses in thermal and module quality, the system remains effective. This study contributes significantly to sustainable energy policies in higher education and recommends further long-term performance monitoring and exploration of additional renewable energy technologies on campus.

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1. INTRODUCTION

In addressing global challenges related to climate change and dependence on fossil fuels, the use of renewable energy [1], particularly solar energy, has become a top priority [2]. Solar energy offers significant potential as a clean and sustainable energy solution, particularly for tropical regions like Indonesia [3], [4]. Advanced simulation tools such as PVSyst, widely adopted globally, are now increasingly applied to optimize the design of photovoltaic systems tailored to the country's tropical conditions [5]. Furthermore, internet of things (IoT) technologies is emerging as a critical component in smart energy management systems, enabling localized solutions for Indonesia's renewable energy sector.

Indonesia, located along the equator, benefits from optimal sunlight intensity year-round [6], [7]. Data from the National Energy Council shows that the potential for solar energy in Indonesia averages 4.8 kWh/m²/day, equivalent to 112,000 GWp [8], which is ten times the potential of developed countries like Germany and Europe [9]. This potential provides a strong foundation for developing national strategies in solar energy utilization. The Indonesian government has demonstrated its commitment to renewable energy through the National Energy Policy and the General National Energy Plan [10]. The National Energy Policy sets an ambitious target to increase the contribution of new and renewable energy to 23% of the national energy mix by 2025, with a specific goal of 6.5 GW for solar energy. However, by the end of 2020, the current installed capacity of solar power plants has only reached 181.2 MW, far from the set target [11].

University buildings are significant energy consumers [12], [13], with usage patterns that vary based on the institution's focus and specialization. Electricity, the primary energy source, powers heating, cooling, laboratories, lighting, elevators, and educational technologies [13]. Ar-Raniry State Islamic University (UIN Ar-Raniry)'s Faculty of Tarbiyah and Keguruan building is one relevant example as it supports three main specializations: multimedia, network computer technology, and software engineering. These three fields require high energy consumption to support the operation of computer labs, network hardware, and other electronic devices. The large energy demand makes the Faculty of Tarbiyah and Keguruan building an ideal candidate for a study on the application and optimization of solar energy. Several previous studies have used PVSyst for solar power design analysis, some of which were conducted in coastal areas [14], [15], and educational buildings [16], [17].

The application of solar energy in the Faculty of Tarbiyah and Keguruan building serves not only for energy efficiency but also as an educational tool, introducing renewable energy technologies to students and lecturers. With its high energy needs and focus on information and communication technology programs, the building is an ideal site for studying solar power implementation. However, despite Indonesia's vast solar energy potential, its application in educational buildings remains underutilized. The lack of optimization tailored to local conditions, such as panel orientation and economic feasibility, further hinders its adoption. The findings are expected to offer practical solutions for the building and contribute to the development of sustainable energy strategies in higher education, serving as a model for other institutions nationally and internationally. This research will employ an optimization approach to maximize the efficiency and economic feasibility of solar power plant implementation at UIN Ar-Raniry, specifically for the Faculty of Tarbiyah and Keguruan buildings. The theoretical framework includes technical, economic, and environmental analysis of the solar power plant system, taking into account variables such as solar panel orientation, tilt angle, system component efficiency, and local meteorological conditions. Simulations will be conducted using PVSyst software, a comprehensive simulation tool for designing and evaluating the performance of solar power plant systems.

Several studies have explored the optimization and design of solar power generation systems using software such as MATLAB and PVsyst. For example, Linelson *et al*. [18] developed an AI-based solar tracker system using MATLAB/Simulink to optimize photovoltaic panel orientation by implementing proportional-integral-derivative (PID) control for minimal error. They found that the system effectively tracks the sun from sunrise to sunset, maximizing solar energy utilization and resetting the panel position for the next day. Islam [19] designed and evaluated a 3kW grid-connected rooftop solar photovoltaic (PV) system for residential use in Tetulia, Panchagrah, and Bangladesh, using PVsyst software. They found that the system generates 4,172 kWh/year of AC energy, supplying 1,871 kWh/year of surplus energy to the grid and predicting power outages with backup energy storage. The research by Duhis *et al*. [20] investigated the impact of roof albedo on PV performance, using modeling and simulation to assess solar structures on horizontal concrete tiles with adjustable albedo levels. They found that increasing the surface albedo from 0.25 to 0.7 significantly enhances yearly solar PV power generation, as demonstrated in a case study at Al-Mussaib Technical College using PVsyst software. Similarly, Lorent *et al.* [21] evaluated the feasibility and economic sustainability of installing a solar power system in a university parking area with a PVsyst simulation. The study evaluates the feasibility of a solar power system in Universitas Multimedia Nusantara (UMN)'s back parking area, showing it can generate 224 MWh annually, meet 20% of energy needs, and reduce 2,775.513 tons of carbon dioxide (CO_2), with a net present value (NPV) of Rp. 4.38 billion and an internal rate of return (IRR) of 34.28%. Many researchers use PVSyst to do modeling and simulation. PVSyst has been utilized to assess PV potential in various regions [22], [23], in the design and performance analysis of both grid-connected and standalone PV power plants [24] as well as in the analysis of shading events on solar panels [25].

Research on solar PV systems has utilized tools like PVSyst for assessing potential, designing systems, and analyzing shading effects. However, limited studies address tropical regions, particularly regarding local meteorological conditions and design parameters. This study bridges the gap by optimizing PV systems at UIN Ar-Raniry in Aceh, Indonesia, using technical simulations and economic feasibility analysis, and a model for energy efficiency in educational institutions.

2. RESEARCH METHOD

In this section, the methodology employed in this study is presented, detailing the research approach, tools and techniques, data collection methods, and data analysis procedures. The objective of this research is to evaluate and optimize the implementation of a solar power generation system at

UIN Ar-Raniry, focusing on the Faculty of Tarbiyah and Keguruan building. To achieve this, a quantitative method based on simulation is adopted, which facilitates a comprehensive assessment of energy efficiency, economic feasibility, and environmental impacts associated with the solar power system. The flow of the methodology is illustrated in flowchart Figure 1, which outlines the step-by-step process of the study.

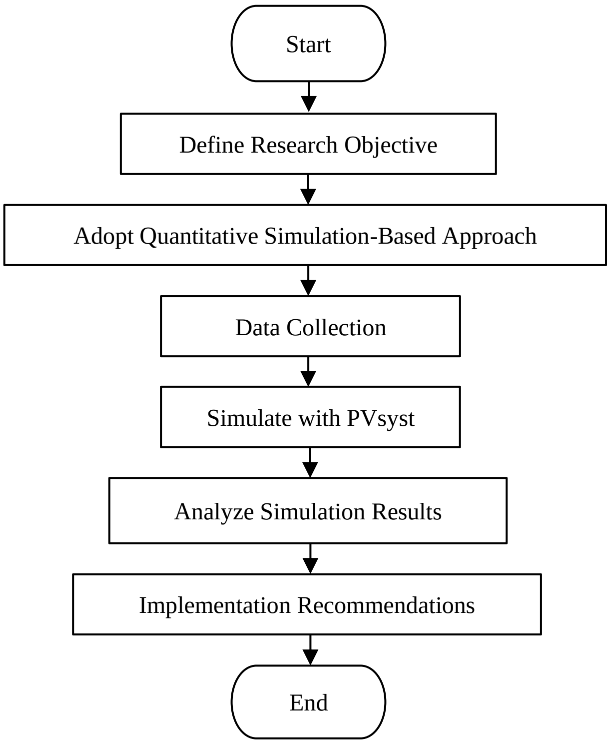

Figure 1. Flowchart of research

2.1. Research approach

This study employs a quantitative method based on simulation to evaluate and optimize the implementation of a solar power generation system. The object location is in the UIN Ar-Raniry, especially the Faculty of Tarbiyah and Keguruan building. This approach allows for an in-depth analysis of energy efficiency, economic feasibility, and the environmental impact of the solar system while providing practical recommendations for effective implementation.

2.2. Tools and techniques

This research utilizes the PVSyst software for simulation and analysis of the solar system. PVSyst is a software developed by the University of Geneva that provides comprehensive tools for designing and analyzing photovoltaic systems. The software supports simulations of grid-connected systems, standalone systems, pumping systems, and DC-grid systems for public transportation [26], [27]. PVSyst is also equipped with an extensive meteorological database and PV component data, including sources like MeteoNorm V7.1, NASA's surface meteorology and solar energy (NASA-SSE), and photovoltaic geographical information system (PVGIS).

2.3. Data collection

The initial stage of the study involved the collection of meteorological data and technical specifications. Global horizontal irradiance (GHI) data was obtained from the Global Solar Atlas website to determine the intensity of solar radiation at the study site. Information regarding latitude and longitude coordinates was also taken from the site. Furthermore, the closest location to the substation for solar system installation was ascertained using the Indonesian Geo-energy portal. Data on the location and construction area of solar panels were obtained through the Google Earth Pro application.

2.4. Simulate with PVSyst

Using the collected data, simulations were conducted in PVSyst to model the solar power system's performance. Parameters such as panel orientation, tilt angle, and system configuration were optimized to maximize energy production. The simulation process aimed to identify the most efficient configuration while minimizing costs and environmental impacts. Simulation using software is also important before the actual installation of the solar power generation system [2].

2.5. Analyze simulation results

The simulation outputs were analyzed to assess the system's performance, economic viability, and environmental contributions. Key metrics included energy production capacity, system performance ratio, life cycle costs, and the payback period of the investment. The environmental analysis focused on quantifying CO_2 emission reductions attributable to the solar system.

2.6. Implementation recommendations

Based on the simulation results and analysis, practical recommendations were developed to guide the effective implementation of the solar power system. These included optimizing the tilt angle, panel orientation, and energy management strategies. The study also highlighted policy implications to encourage broader adoption of renewable energy in educational institutions across Indonesia. These findings underline the potential of simulation-based approaches in designing efficient and sustainable solar energy systems.

3. RESULTS AND DISCUSSION

In this section, we present the findings from the simulation and analysis of the solar power generation system designed for the Faculty of Tarbiyah and Keguruan at UIN Ar-Raniry. The results highlight the effectiveness of the implemented solar photovoltaic system, detailing its geographical positioning, grid configuration, energy losses, overall performance, and economic viability. Each section will delve into important aspects of the system, including the optimization of the PV panel tilt and azimuth, the selection of components, and the assessment of energy production efficiency. Additionally, we will discuss the financial implications, including the initial investment and payback period, while also addressing the environmental benefits derived from the reduction of CO_2 emissions.

3.1. Geographical position adjustment of PV tilt and azimuth

The geographical position of an area greatly affects the optimization of the azimuth direction and tilt angle of photovoltaic panels, so the setting of these two parameters must be adjusted specifically for each location. Based on the geographical analysis of the UIN Ar-Raniry, especially the Faculty of Tarbiyah and Keguruan building, which is located in Kopelma Darussalam, Syiah Kuala Subdistrict, Banda Aceh City as a simulation object in the solar power plant design research.

The building is located in Indonesia, within the Asian region at geographical coordinates 5.5798° N and 95.3680° E, with an altitude of 12 meters above sea level as shown in the interactive map Figure 2. The site is in the Indonesian standard time zone (UTC+7), with a time difference of 0 hour 39 minutes between local time and solar time. The meteorological data used in the simulation of the solar PV design on this building was imported from the Meteo source, which allowed for an in-depth analysis of the solar energy potential of the site. The geographical coordinates and altitude of the Faculty of Tarbiyah and Keguruan building provide an accurate basis for the optimization of the solar PV system, ensuring that parameters such as the tilt and orientation of the photovoltaic panels can be adjusted to maximize the absorption of solar radiation, taking into account the specific conditions of solar time and position at this location.

Through simulation and evaluation using PVSyst software, this research reveals that the solar PV system designed with a fixed tilted plane configuration, a tilt of 30°, and an azimuth of 0° (facing south), produces global radiation at the collector plane of 1737 kWh/m² per year. The solar panel orientation with a tilt of 30° and an azimuth of 0° was chosen because it is a common configuration in tropical regions such as Indonesia to maximize the absorption of solar radiation.

Based on Figure 3, the transposition factor value of 0.95 indicates that about 95% of the solar radiation reaching the earth's surface is successfully captured by the solar panel. However, there is a power loss of 5.3% compared to the optimal conditions, which can be caused by various factors such as temperature, shading, or module degradation. Nonetheless, the global radiation received by the solar panels reached 1737 kWh/m² per year, which is quite a high value and indicates the great energy potential of the site.

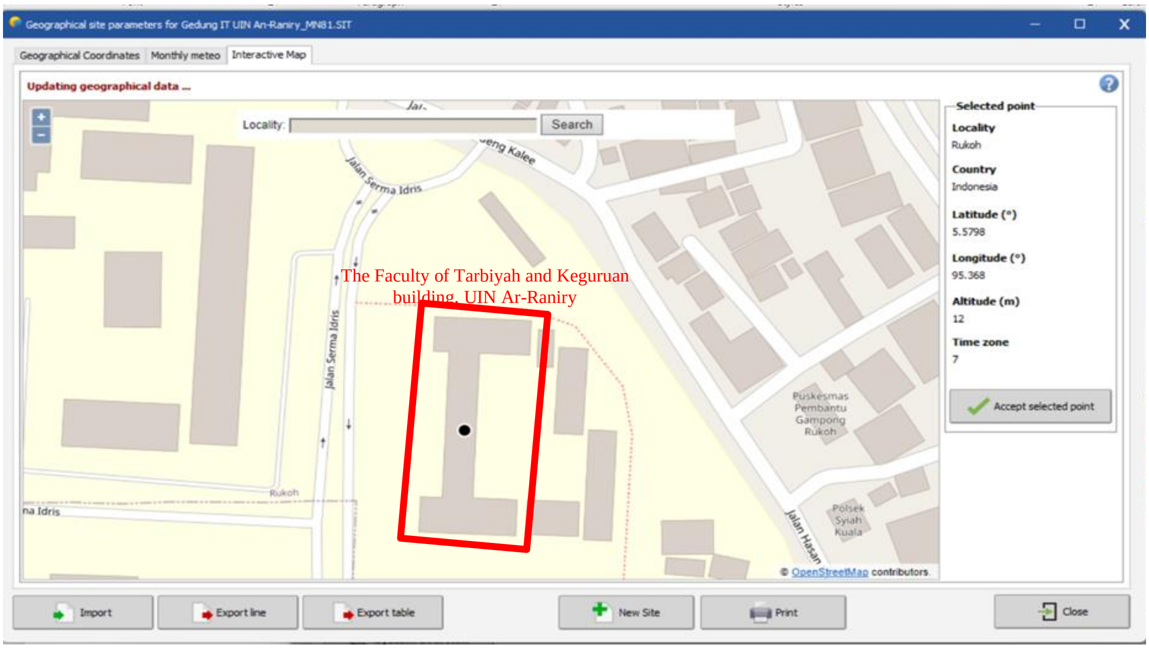

Figure 2. Interactive map view PVSyst

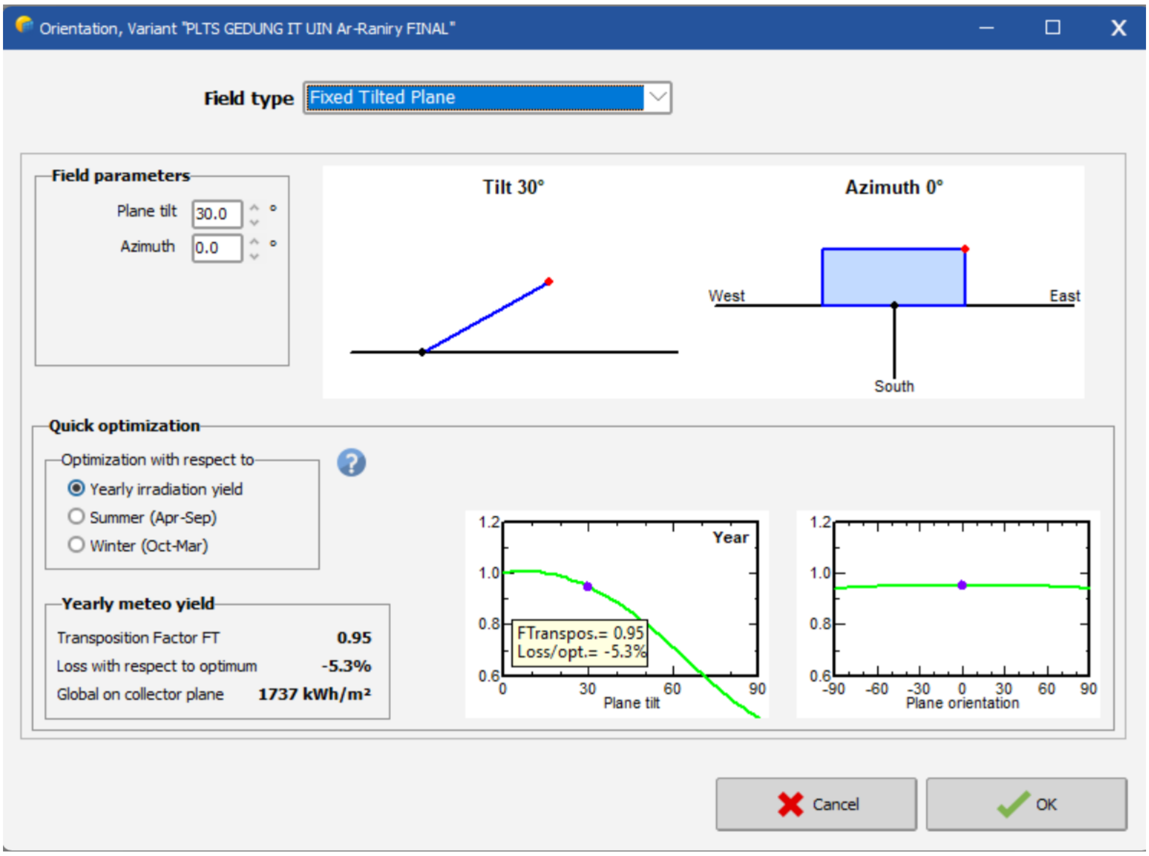

Figure 3. Field PV orientation parameter

3.2. Grid system

The solar power generation system at the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building is designed with careful and strategic selection of components where the system overview can be seen in Figure 4. The solar panel used is the Longi Solar LR5-66HIH-500M G2 type, which is a monocrystalline module with a high reputation for energy conversion efficiency. The use of 340 of these modules represents an attempt to achieve significant system capacity, with each module's peak power of 500 Wp under standard test conditions (STC), resulting in a total system peak power of 170 kWp. This large capacity is designed to meet the substantial energy needs of the Faculty of Tarbiyah and Keguruan building UIN Ar-Raniry.

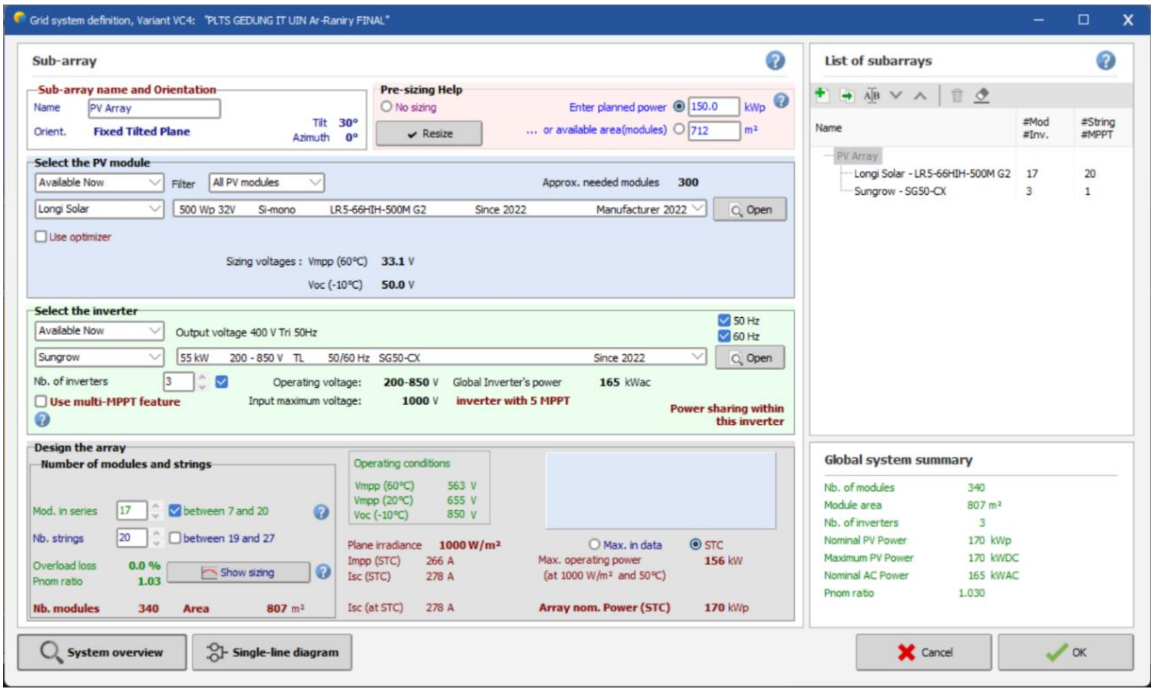

Figure 4. System overview

The system configuration shown in Figure 5 consists of 20 strings, with each string consisting of 17 modules connected in series. This configuration was chosen to ensure compatibility with the voltage and current characteristics of the inverter used as well as to maintain overall system efficiency. This arrangement aims to optimize energy output while maintaining system stability and reliability under various operational conditions.

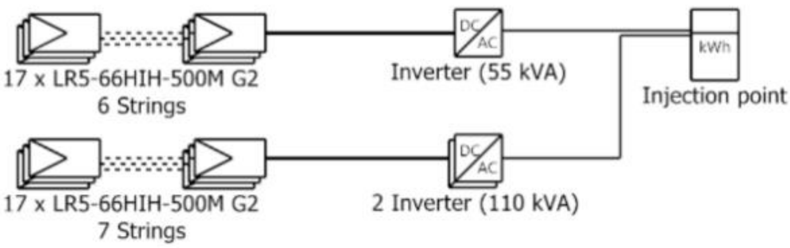

Figure 5. Single line diagram

The system is equipped with three Sungrow SG50-CX model inverter units, each with an output power of 50 kWac, bringing the total output capacity to 165 kWac. Sungrow inverters are known for their high efficiency and reliability, making them the right choice for this system. The combination of Longi Solar modules and Sungrow inverters is a choice that has proven effective in large-scale photovoltaic applications, combining cutting-edge technology and reliability. The use of monocrystalline modules provides significant advantages in terms of energy conversion efficiency, although there is a drop in performance at higher operating temperatures, such as 50 °C, which are common in Indonesia's tropical climate. Consideration of these thermal factors is important in system performance evaluation, as they can affect efficiency and output.

3.3. Losses

In analyzing the losses of the solar power generation system at the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building, various loss factors need to be taken into account to get an accurate picture of the overall efficiency of the system. Thermal loss is one of the significant factors, which is caused by the increase in module temperature due to solar radiation. Based on Figure 6, this thermal loss factor involves a radiation-related temperature coefficient (Uc) of 29.0 W/m²K, while the wind-related temperature coefficient (Uv) is 0.0 W/m²K/m/s. These coefficients are used to calculate the power drop due to increased temperature, which can reduce the overall efficiency of the solar panel.

The losses in the DC cables are caused by the electrical resistance in the cables connecting the solar modules. With a total array resistance of 36 mΩ, the power loss that occurs under STC is 1.5%. The longer and smaller the cross-section of the cable, the greater the resistance and power losses that occur. Module quality losses are the result of imperfections in the modules, such as manufacturing defects or variations in characteristics between modules, with losses reaching -0.8%. These losses are difficult to avoid completely as they are related to the production quality of the modules.

Module mismatch losses occur when there are differences in electrical characteristics between modules in a string, with losses reaching 2.0% at the maximum power point (MPP). This difference can affect the total output power of the system. String mismatch losses, caused by current differences between different strings, result in a power loss of 0.1%. The current imbalance on each string can affect the overall system efficiency. The incidence angle modifier (IAM) loss factor refers to the influence of the incident angle of solar radiation that is not perpendicular to the module surface. The IAM profile used shows that at 0° and 25° incident angles, the IAM value is 1.000, while at 45° incident angle, the IAM value drops to 0.995, and at 90° incident angle, the IAM value reaches 0.000. This shows that the larger the angle of incidence, the smaller the proportion of light absorbed by the solar cell, so the power generated is also reduced.

The loss analysis of the designed solar system is shown in Figure 7. The loss diagram provides a comprehensive guide to the factors that affect the conversion efficiency and energy output of the system. The total global horizontal radiation received is 1834 kWh/m², while the radiation received by the solar panel collectors on an area of 807 m² is 1681 kWh/m². With a conversion efficiency at STC of 21.10%, the nominal energy that the system can produce under ideal conditions is 286,262 kWh.

However, a number of losses affected the final energy yield. Losses due to non-optimal solar radiation levels contributed 6.22% of the total energy produced. Thermal losses due to solar panel temperature accounted for 2.31%, while losses caused by module quality amounted to 0.58%. The losses due to the mismatch between the module and the string, which includes the mismatch of electrical characteristics, contributed 6.97%. After accounting for these losses, the available energy is reduced to 258,621 kWh. Furthermore, losses in the inverter, including inverter efficiency which is affected by nominal power, maximum input current, and nominal power voltage and threshold, increase the losses to 2.02%. These losses also include the energy loss due to ohmic resistance in the cables, which causes the available energy at the inverter output to be 251,214 kWh. This energy is then transmitted to the grid.

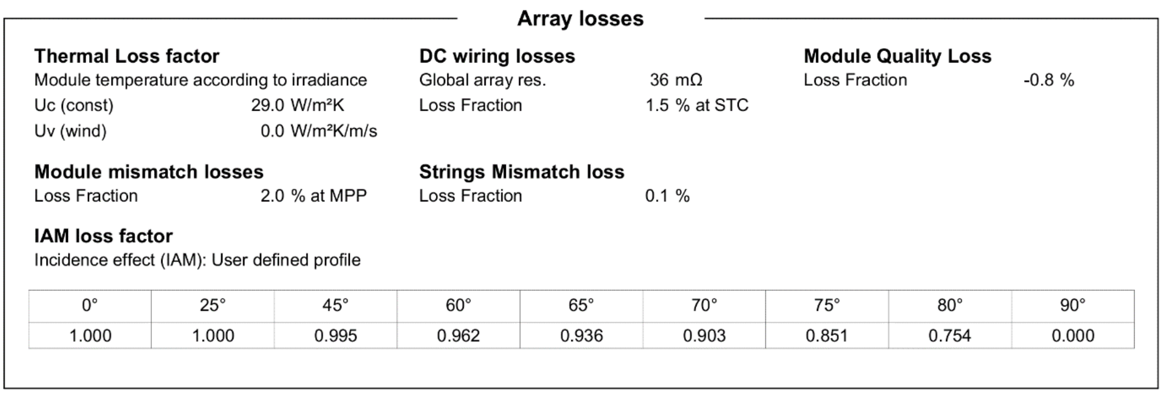

Figure 6. Array losses

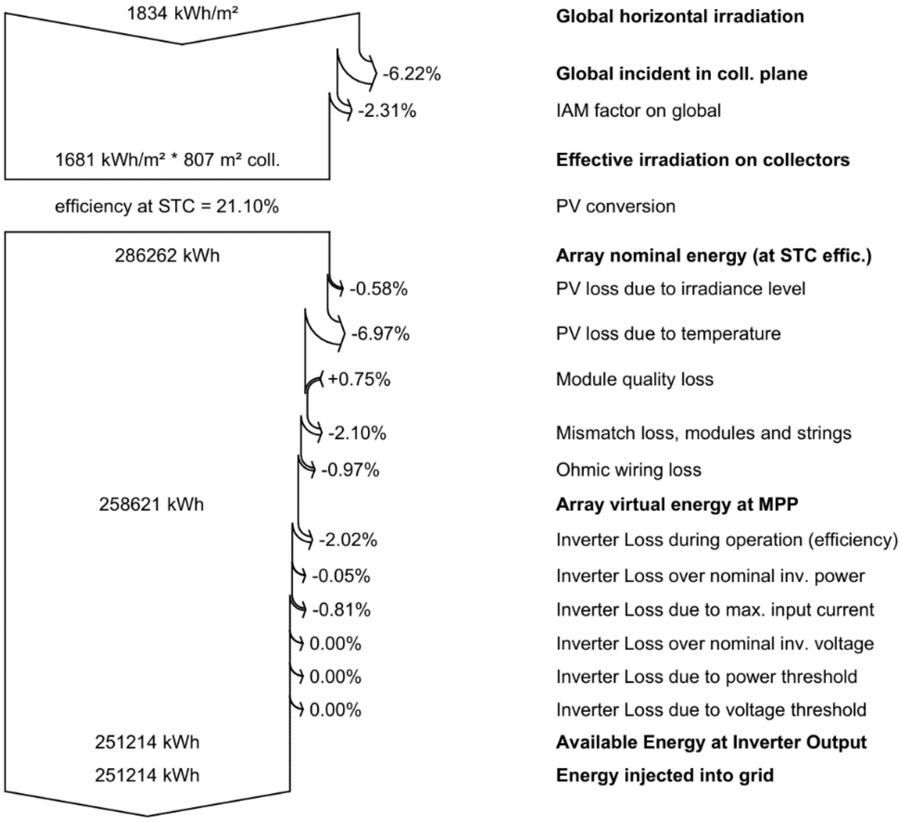

Figure 7. Loss diagram

3.4. Main results

The solar power plant system at the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building shows significant performance with annual energy production reaching 251,214 kWh. The specific production was recorded at 1,478 kWh/kWp per year, while the performance ratio (PR) of the system reached 85.89%. This high PR reflects the system's optimal efficiency in converting solar energy into electricity that is transmitted to the grid.

The initial investment required for the construction of this solar power system amounted to IDR 977,280,700, with a specific cost of IDR 5,749/Wp. Despite requiring a significant initial investment, the low annual operating costs of IDR 184,266,807, and an estimated payback period of 7.8 years, indicate that the system has a good potential return on investment. The cost of energy generated from this solar power plant is calculated at IDR 725/kWh, which is economically competitive compared to conventional electricity tariffs from the State Electricity Company (*PLN*).

Monthly operational data showed that the annual global horizontal irradiation reached 1,834.4 kWh/m², with a diffuse horizontal irradiation of 881.21 kWh/m². The average ambient temperature was recorded at 27.50 °C. The global irradiation at the collector plane reached 1,720.4 kWh/m², while the effective irradiation after correction for the angle of arrival and shading factor was 1,680.7 kWh/m². The effective energy generated at the output of the array was recorded at 256,444 kWh, and the energy delivered to the grid reached 251,214 kWh, indicating that the system is operating at a high efficiency, as indicated by the consistent monthly PR between 85 and 87%.

3.5. Cost of system

In an economic evaluation of the solar power generation system at the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building, the total installation cost of the system reached IDR 977,280,700 based on Figure 8. This cost includes various components, with Longi Solar LR5-66HIH-500M G2 solar panels as the main component, with 340 units requiring a total cost of IDR 161,811,200. In addition, the cost for the module support structure, Sungrow SG50-CX inverters of which 3 units amounted to IDR 52,423,500, and various additional components including cables, combiner boxes, as well as monitoring systems, added to the total installation cost.

Cost of the system

Installation costs

Item	Quantity units	Cost IDR	Total IDR
PV modules			
LR5-66HIH-500M G2	340	1618112.00	550158080.00
Supports for modules	340	50000.00	17000000.00
Inverters			
SG50-CX	3	52423500.00	157270500.00
Other components			
Wiring	111	2107890.00	233975790.00
Combiner box	3	1298220.00	3894660.00
Monitoring system, display screen	3	4993890.00	14981670.00
		Total	977280700.00
		Depreciable asset	724428580.00

Operating costs

Item	Total IDR/year
Maintenance	
Provision for inverter replacement	31454100.00
Repairs	50000000.00
Cleaning	20000000.00
Security fund	10000000.00
Total (OPEX)	111454100.00
Including inflation (5.00%)	184266807.76

System summary

Total installation cost	977280700.00 IDR
Operating costs (incl. inflation 5.00%/year)	184266807.76 IDR/year
Produced Energy	251 MWh/year
Cost of produced energy (LCOE)	725.002 IDR/kWh

Figure 8. Cost of the system

The annual operating cost of the system, which includes maintenance, inverter replacement, repair, cleaning, and security funds, amounts to IDR 111,454,100. Considering an annual inflation of 5%, the annual operational cost is calculated to be IDR 184,266,807.76. The system is projected to produce 251,214 kWh of energy per year. Based on the total installation cost and annual operational cost, the levelized cost of energy (LCOE) of this system is IDR 725.00 per kWh.

3.6. Financial analysis

The financial analysis such as in Figure 9 stated that the solar system in the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building was conducted with a simulation period of 20 years starting in 2025. The economic parameters used include inflation rate, production variation caused by system aging, and discount rate, each at 5% per year. The analysis also considered an annual income tax of 10%, an additional income tax of 5%, as well as dividends of 50% of the income generated.

Depreciable assets, including Longi Solar LR5-66HIH-500M G2 solar panels, support structures, and Sungrow SG50-CX inverters, are calculated using the straight-line depreciation method over 20 years, with an estimated salvage value of zero. The total depreciable asset value reached IDR 724,428,580. Project financing involves own funds of IDR 100,000,000 and subsidies of IDR 300,000,000. Revenue from electricity sales is set based on a feed-in tariff of IDR 1,000.00 per kWh, with a 20-year tariff guarantee and an annual tariff variation of 5%. After the guarantee period, the feed-in tariff is expected to decrease by 10% per year.

The analysis shows that the payback period for this system is 7.8 years. The NPV of the project reached IDR 3,828,343,114.54, with an IRR of 69.03% and a return on investment (ROI) of 565.3%. Total dividends paid are estimated at IDR 3,929,432,216.11. These findings show that investment in a solar PV system not only provides technical benefits but also offers substantial economic returns in the long term, confirming the financial viability of this project.

The detailed financial analysis of the solar system at the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building is shown in Figure 10. The economic results show that in the first year, despite no revenue from electricity sales and an initial investment cost of IDR 100,000,000, there was a significant net loss. However, over time, revenue from electricity sales increased consistently, with annual net profit also seeing a substantial increase. By year 20, annual revenue reached IDR 1,504,121,493 with a net profit of IDR 1,044,543,368.

Total cumulative net profit over the 20-year period reached IDR 7,858,864,432, and total dividends paid were IDR 3,929,432,216, representing an accumulated net profit of 580.0% of the initial investment cost. Cumulative operating costs and depreciation reached IDR 3,685,336,155, with taxes paid reaching IDR 1,259,018,092. This analysis reflects the economic success of investing in a solar system designed to provide a sustainable source of renewable energy, delivering positive results in terms of both net profit and return on investment.

Financial analysis

Simulation period

Project lifetime	20 years	Start year	2025

Income variation over time

Inflation	5.00 %/year
Production variation (aging)	5.00 %/year
Discount rate	5.00 %/year

Income dependent expenses

Income tax rate	10.00 %/year
Other income tax	5.00 %/year
Dividends	50.00 %/year

Depreciable assets

Asset	Depreciation method	Depreciation period (years)	Salvage value (IDR)	Depreciable (IDR)
PV modules				
LR5-66HIH-500M G2	Straight-line	20	0.00	550158080.00
Supports for modules	Straight-line	20	0.00	17000000.00
Inverters				
SG50-CX	Straight-line	20	0.00	157270500.00
		Total	0.00	724428580.00

Financing

Own funds	100000000.00 IDR
Subsidies	300000000.00 IDR

Electricity sale

Feed-in tariff	1000.0000 IDR/kWh
Duration of tariff warranty	20 years
Annual connection tax	100000000.00 IDR/kWh
Annual tariff variation	+5.0 %/year
Feed-in tariff decrease after warranty	10.00 %

Return on investment

Payback period	7.8 years
Net present value (NPV)	3828343114.54 IDR
Internal rate of return (IRR)	69.03 %
Return on investment (ROI)	565.3 %
Paid dividends	3929432216.11 IDR

Figure 9. Financial analysis

Financial analysis

Detailed economic results (kIDR)

Year	Electricity sale	Own funds	Run. costs	Deprec. allow.	Taxable income	Taxes	After-tax profit	Divid. 50.00%	Cumul. profit	% amorti.
0	0	100000000	0	0	0	0	0	0	-100000000	0.0%
1	151214032	0	111454100	36221429	3538503	530775	39229156	19614578	-62638899	5.5%
2	176963470	0	117026805	36221429	23715236	3557285	56379379	28189690	-11501140	13.1%
3	205352225	0	122878145	36221429	46252651	6937898	75536182	37768091	53749855	22.7%
4	236650828	0	129022053	36221429	71407347	10711102	96917674	48458837	133484265	34.5%
5	271157538	0	135473155	36221429	99462954	14919443	120764940	60382470	228106755	48.4%
6	309201186	0	142246813	36221429	130732944	19609942	147344432	73672216	338057439	64.7%
7	351144308	0	149359154	36221429	165563725	24834559	176950595	88475298	463812923	83.2%
8	397386599	0	156827111	36221429	204338059	30650709	209908779	104954390	605887447	104.2%
9	448368726	0	164668467	36221429	247478830	37121824	246578434	123289217	764834105	127.7%
10	504576520	0	172901890	36221429	295453201	44317980	287356650	143678325	941246161	153.7%
11	566545613	0	181546985	36221429	348777200	52316580	332682049	166341024	1135758464	182.5%
12	634866539	0	190624334	36221429	408020776	61203116	383039088	191519544	1349048961	214.0%
13	710190359	0	200155551	36221429	473813379	71072007	438962801	219481401	1581840307	248.3%
14	793234871	0	210163328	36221429	546850114	82027517	501044026	250522013	1834901587	285.7%
15	884791445	0	220671494	36221429	627898521	94184778	569935172	284967586	2109050150	326.2%
16	985732568	0	231705069	36221429	717806070	107670910	646356588	323178294	2405153550	369.9%
17	1097020156	0	243290323	36221429	817508405	122626261	731103573	365551786	2724131618	417.0%
18	1219714722	0	255454839	36221429	928038454	139205768	825054115	412527058	3066958644	467.6%
19	1354985481	0	268227581	36221429	1050536471	157580471	929177430	464588715	3434665705	521.9%
20	1504121493	0	281638960	36221429	1186261104	177939166	1044543368	522271684	3828343115	580.0%
Total	**12803218679**	**100000000**	**3685336155**	**724428580**	**8393453944**	**1259018092**	**7858864432**	**3929432216**	**3828343115**	**580.0%**

Figure 10. Financial analysis detailed economic result (kIDR)

3.7. Carbon dioxide emission

The results of the environmental impact modeling of the solar system applied to the Faculty of Tarbiyah and Keguruan UIN Ar-Raniry building are shown in Figure 11. It is noted that the total CO_2 emissions generated by the system throughout its operating life, which is for 30 years, is 4,799.7 tons of CO_2. This evaluation shows that the solar PV system substantially reduces carbon emissions compared to fossil-based power generation. In comparison, emissions from a conventional grid system over the same life cycle amounted to 5,531.7 tons of CO_2, with an emissions ratio of 251.21 gCO_2/kWh. Thus, the solar system reduces annual emissions by 734 tons of CO_2. A 1% annual decrease in system efficiency indicates performance degradation over time. This data confirms the significant contribution of the solar system in reducing dependence on fossil energy sources and supporting climate change mitigation efforts, in accordance with the guidelines set by the International Energy Agency (IEA) for Indonesia.

To give a more understandable picture of the emission savings, let's look at some illustrations. The 4,490,440 tons of CO_2 emission savings are equivalent to the annual emissions from about 976 gasoline cars, each of which produces an average of 4.6 tons of CO_2 per year. In addition, these savings are equivalent to the annual emissions from around 4,490 motorcycles, each of which produces an average of 1 ton of CO_2 per year. Finally, these savings are also equivalent to the annual emissions from around 225 diesel trucks, each of which produces an average of 20 tons of CO_2 per year. This illustration gives a concrete idea of how large these savings are in the context of the number of vehicles on the road, confirming the significant impact of solar PV systems in reducing CO_2 emissions.

The analysis of the solar PV system implemented at the Faculty of Tarbiyah and Keguruan building UIN Ar-Raniry reveals an annual energy generation of 251,214 kWh, correlating with a reduction in CO_2 emissions by 173,095 kg, demonstrating its significant environmental impact. Economically, the system's payback period of 7.8 years and lower LCOE compared to *PLN* electricity tariffs confirm its financial viability, aligning with Islam's study [19] on the effectiveness of solar PV systems in tropical regions for reducing carbon footprints. The system's energy yield, despite minor thermal losses and module quality issues, remains competitive, as supported by Duhis *et al.* [20], highlighting the adaptability of PV systems under varying environmental conditions. However, limitations such as thermal losses and module degradation impact overall performance, which could be addressed through advanced module technologies and cooling mechanisms, as suggested by Linelson and Saputri [18]. Future research should explore long-term performance metrics, innovative cooling solutions, and scalability to diverse institutional settings, providing a foundation for promoting solar energy as a scalable and sustainable solution to reduce energy dependence and improve carbon management in higher education.

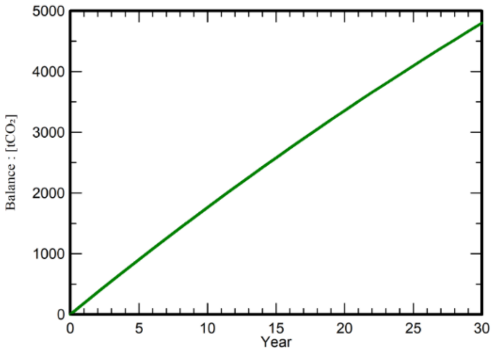

Figure 11. Saved CO_2 emission vs. time

4. CONCLUSION

Recent observations indicate that the implementation of solar power generation systems significantly reduces energy dependence on conventional sources while offering substantial environmental and economic benefits. Our findings offer definitive proof that the solar PV system at the Faculty of Tarbiyah and Keguruan building UIN Ar-Raniry generates 251,214 kWh annually, resulting in a CO_2 emissions reduction of 173,095 kg per year, directly linked to optimized energy utilization rather than increased system capacity. The economic analysis reveals the feasibility of this investment, with a 7.8-year payback period, lower LCOE than *PLN* tariffs, and positive financial metrics such as NPV and IRR. Despite minor technical limitations, the system's high energy yield and efficiency confirm its scalability and potential as a model for other educational institutions in Indonesia. Future advancements should explore the long-term performance of solar PV systems, focusing on mitigating thermal losses and enhancing module technology. Comparative analyses of solar technologies and energy storage integrations will further improve system reliability. By addressing policy impacts and conducting broader cost-benefit studies, solar PV implementation can be strategically expanded to foster sustainable energy practices in higher education and beyond.

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

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable.

ETHICAL APPROVAL

Not applicable.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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