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Design and Implementation of Solar-Powered Pumping System in IKN Nusantara Area

Hebert Arthur Sigiro, Prabowo, Burhanuddin Halimi

Institut Teknologi Bandung, Jl. Ganesha 10, Bandung, 40123, Indonesia

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CORRESPONDENCE

Phone: +62 (0812) 13074284
E-mail: 18020010@std.stei.itb.ac.id

A B S T R A C T

Solar-powered pumping systems are an alternative to providing a sustainable and independent water source. This system declines the dependency on fossil fuels, which generate no greenhouse gas emissions while operating. This paper presents the design, implementation, and performance testing of a solar-powered submersible water pump in Bumi Harapan and Bukit Raya Village to provide a supplementary water source for residents. To meet the daily water supply requirement of 10 m^3 in two identical water towers, a 1.1 kW rated power water pump and a 2.2 kW photovoltaic system are chosen. A solar pump controller with the ability to switch power sources from photovoltaic to grid is used in the system to maintain a consistent water supply if needed. Based on performance simulations using PVSyst software, the designed systems cannot fulfill daily water requirements. However, they are expected to fill both water towers with a daily average supply of 5.78 m3 for the Bumi Harapan site and 9.23 m3 for the Bukit Raya site. These inabilities occurred because the pumps must operate with an elevation head that is more remarkable than the specifications. Performance tests using a solar power meter (SPM) and power quality analyzer (PQA) showed that the electric submersible pump (ESP) will supply water with a flow rate that depends on solar irradiance. Based on the data collection, the ESP successfully operates near its rated capacity during the peak sun hour.

INTRODUCTION

Indonesia officially announced the move of its capital city from Jakarta to East Kalimantan based on national regulation on January 18, 2022 [1]. The relocation of the capital city has several considerations, such as a strategic location with minimal disaster risk and relatively complete infrastructure. Additionally, East Kalimantan is seen as a region that can accommodate rapid urban development while mitigating some of the challenges faced by the overpopulated and sinking Jakarta. This relocation project holds immense potential in transforming IKN Nusantara into a model city that uses renewable energy to empower green technology and sustainable practices. The ambition is to provide better infrastructure and set a precedent for future sustainable urban developments.

Behind the capital city movement to IKN Nusantara, there is a significant clean water crisis, with a total of 2,146 families affected during the dry season, coming from 6 villages, namely Tengin Baru Village, Sukaraja, Bukit Raya, Bumi Harapan, and Sepaku Village [2]. This crisis underlines the importance of sustainable water management in the new capital, as water scarcity can pose severe challenges to the region's growth and sustainability. In 2021, clean water was made accessible again after the Sepaku water treatment plant was built and began operating. However, despite these efforts, clean water has not yet reached all villages, highlighting the need for further water distribution and infrastructure improvements.

Through the Ministry of Energy and Mineral Resources, the government has set a target of achieving a 23% contribution from renewable energy sources to the national energy mix by 2025, with a projected total investment cost of 13,197 million USD [3]—The objective drives renewable energy development in IKN Nusantara, a key for future sustainable projects. Solar energy, identified as a prime resource due to Indonesia's high sunlight intensity, is ideal for any scale of installations.

Solar-powered water pumping systems have become widely recognized for their sustainable and efficient energy use [4]. However, while there has been substantial research into their application in rural regions, studies focusing on newly developed urban areas, such as IKN Nusantara, are still limited. Existing studies often emphasize the need for more region-specific case studies, particularly in rapidly growing areas [5, 6]. Research on rural applications explores technical and economic challenges but provides limited insight into the unique requirements of urban environments [7, 8]. Technical challenges specific to urban expansion, such as grid integration and infrastructure adaptation, are also areas where further research is needed. This study aims to address these gaps by designing and implementing solar pumping systems adapted to the conditions of IKN Nusantara.

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In line with the sustainable objectives initiated by the country, this study will determine the technical specifications and design of the system to meet daily water supply requirements. The design will then be implemented, and the performance will be examined to ensure the system's continuous operation. The projects are conducted to provide clean water with solar energy in the IKN Nusantara area, particularly in Bumi Harapan and Bukit Raya Village. By leveraging solar power, the project addresses the immediate need for clean water and showcases the practical application of renewable energy in local challenges.

METHODS

The first step in this study is designing the solar pumping system. Different site characteristics will affect the system design, particularly regarding construction details. To be applicable, the system design will be carried out from architectural and electrical aspects. From an architectural perspective, this includes optimizing the placement of solar panels to maximize sunlight exposure and minimize roof area acquisition. Sketchup software will be used for 3D modeling of photovoltaic (PV) array installation. On the electrical side, the design will ensure that the PV system can efficiently convert solar energy into electricity. This involves selecting the appropriate components.

Once the system design is finalized, a performance simulation will be conducted using PVSyst 7.4.6 software. This simulation will evaluate the efficiency of the designed solar pumping system under a specific condition. The software will model the system’s energy generation and usage based on the local solar irradiance and other relevant data. The simulation will also provide data on system losses, performance ratio, and expected water supply.

Since the system design is constructed directly, the performance of the installed system can be examined to ensure its continuous operation. A solar power meter (SPM) will measure the solar irradiance during data collection. This data will be combined with the system’s electrical performance information to understand better how solar power impacts overall efficiency. Key electrical parameters like PV output voltage, current, and power will be measured using a power quality analyzer (PQA). These measurements will help ensure that the system works efficiently and identify any issues that might affect the stability of the water supply. Figure 1 and Figure 2 show two instruments used for performance testing.

Figure 1. Hioki PQA-HiVIEW PRO 9624-50 [9]

Figure 2. Lutron SPM-1116SD Solar Power Meter [10]

RESULTS AND DISCUSSION

System Design

The daily water supply requirement should be determined to determine the solar pumping system's technical specifications. Supplementary water sources from the solar pumping system should fill two water towers holding 10 m3 of water daily. A submersible water pump from Grundfos with 1.1 kW rated power is chosen to meet this requirement. It can supply 3 m^3 of water if operated with 80 m head and in nominal capacity. The image of the item and technical specifications of the submersible water pump can be seen in Figure 3 and Table 1, respectively.

Figure 3. Grundfos SP3A-18 [11]

Table 1. Technical Specification of Grundfos SP3A-18 [11]

Parameters	Value
Pump speed	2900 rpm
Rated flow	3m3/h
Rated head	80 m
Motor version	T40
Rated power	1,1 kW
Main frequency	50 Hz
Rated voltage	1 x 220-230-240 V
Rated current	8-8.40 A
Start method	DOL
Motor flange design	Grundfos

The Solartech PB2200S2-G4 solar pumping inverter is an excellent option for use with the selected pump, which has a power range between 1.1 kW and 3 kW. One of the key

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advantages of this inverter is its ability to switch between solar power and grid electricity. The inverter automatically allows the pump to draw electricity from the grid if the solar panels cannot generate enough energy due to low sunlight or weather conditions. This ensures that the pump continues to operate without interruptions, even when solar power alone isn't sufficient. As a result, the system can maintain a steady water supply while optimizing energy consumption by using solar power whenever possible and only relying on the grid when necessary. For further details, the technical specifications of the Solartech PB2200S2-G4 can be found in Table 2, and the image of the item is shown in Figure 4.

Figure 4. Solartech PB2200S2-G4 [12]

Table 2. Technical Specification of Solartech PB2200S2-G4 [12]

Parameters	Value
Power Range	1.1-3 kW
Adapting Pump Motor	1PH 220-240V 50Hz 0.37-2.2 kW
AC Input Voltage	1PH 220V(-10%)
Max. DC Input Voltage	430V
Ambient Temperature	-20-60°C
Startup Voltage	90V
Rated Conversion Efficiency	≥96%
MPPT Efficiency	99%
Display	LED
Protection Grade	IP65

The system's operating time and energy requirements are calculated to meet the new daily water requirement of 10 m³. The submersible pump, with a flow rate of 3 m³/h, would need to run for approximately 3.33 hours per day to supply the necessary volume of water. Given the pump's power rating of 1.1 kW, the daily energy requirement is 3.67 kWh/day to pump 10 m³ of water. Based on this requirement, a capacity of 2.2 kWp is chosen for the photovoltaic (PV) system. This site can generate 9.9 kWh/day, assuming 4.5 peak sun hours per day [13].

Since the PV system can produce more energy than the pump's daily requirement (9.9 kWh/day compared to 3.67 kWh/day), it can provide sufficient power to operate and meet the daily water requirement of 10 m³. The excess electricity productions from the photovoltaic system are used for unexpected situations, such as higher energy demands due to water contamination, which increases its density, or sudden drops in solar irradiation that automatically stop the system operation. This extra energy ensures the pump can still operate efficiently, preventing automatic shutdowns by the inverter and maintaining a reliable water supply of 10 m³ per day [14].

The Solartech PB2200S2-G4 inverter is compatible with an array of 11 Solana Mono-24V-200 solar panels connected in series. Based on the technical specifications of both the inverter and the solar panel, the Solana Mono-24V-200 panels are well-suited for the inverter's input requirements. Each panel has a maximum power output of 200W, a voltage at maximum power (Vmp) 35.6V, and an open-circuit voltage (Voc) of 42V. With 11 panels connected in series, the total Voc would be approximately 462V, within the inverter's maximum DC input voltage of 430V when considering the temperature coefficient adjustments. Further details regarding the panel's technical specifications are shown in Table 3, and the module's image can be seen in the attached Figure 5.

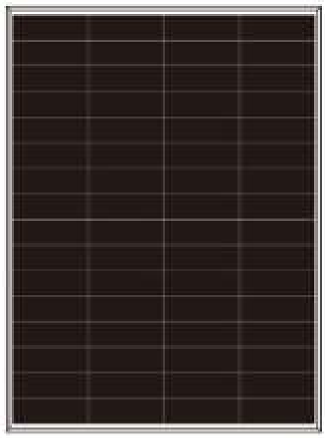

Figure 5. Solana Mono-24V-200 [15]

Table 3. Technical Specification of Solana Mono-24V-200 [15]

Parameters	Value
Maximum Power (Pmax)	200W
Voltage at Pmax (Vmp)	35.6V
Current at Pmax (Imp)	5.62A
Open-circuit voltage (Voc)	42
Short-circuit current (Isc)	5.95A
Module Efficiency	19%
NOCT	47 ±2°C
Maximum System Voltage	1000V DC
Temperature coefficient of Voc	-(0.40 ± 0.05)%/°C
Temperature coefficient of Isc	(0.065 ± 0.01)%/°C
Temperature coefficient of power	-(0.5 ± 0.05)%/°C
Power Tolerance	± 3%
Module Dimension	1188mm x 880mm x 35mm
Weight	10.7 kg

After discussing the main components, such as the inverter and solar panels, the working principle of the overall system operation will be explained. As shown in the schematic diagram from Figure 6, the system is designed to pump water using solar energy while ensuring a reliable water supply through sensors and future upgrades.

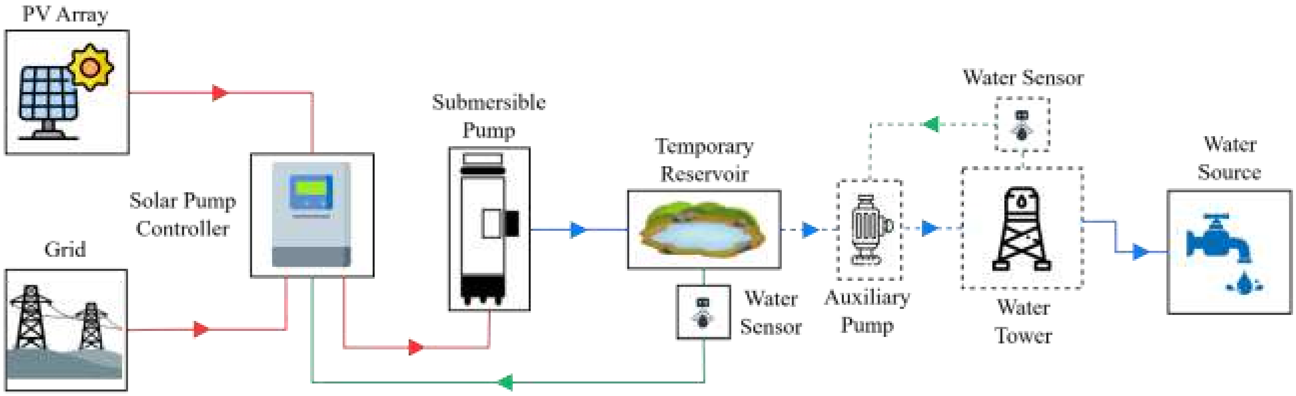

Figure 6. Schematic Diagram of Solar Pumping System

The diagram's red lines represent the power supply from the PV array and the utility grid to the solar pump controller. The green lines show the control signal to the submersible pump and auxiliary pump, commanding them to operate and stop. The blue lines indicate the water movement from the reservoir to the water source. The dashed lines in the diagram indicate that the components or systems they represent have not yet been installed. These lines show the planned future connections, which will be integrated into the system later.

The system includes two necessary water sensors—one in the temporary water reservoir and another in the water tower. The sensor in the reservoir monitors the water level to ensure the submersible pump stops working when it is complete. On the other hand, the sensor in the water tower checks the water level to determine when the auxiliary pump needs to be activated. When the water level in the tower drops below a certain point, the system turns on the pump to transfer water from the reservoir to the tower.

The diagram shown in Figure 7 is an electrical block diagram of the solar pumping system. In the diagram, the blue line represents the DC power flow from the PV array to the DC combiner box, which is then fed into the solar pump controller. The red lines indicate the AC power connection, where the grid supplies power through the AC protection box to the solar pump controller, and finally, the green line shows the AC power output from the solar pump controller to the motor pump.

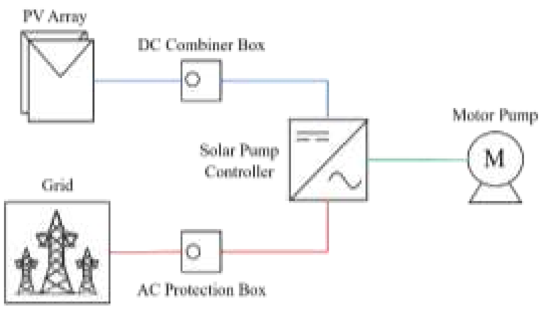

Figure 7. Electrical Block Diagram of Solar Pumping System

In this system, the inverter functions as a solar pump controller because it can switch between power sources—either from the photovoltaic (PV) array or the grid—depending on the availability of solar energy. When the PV array generates sufficient power, the inverter uses it to drive the motor pump. However, if the solar energy is insufficient, the inverter automatically switches to grid power to ensure continuous operation of the pump.

The two sub-chapters below describe the site characteristics and illustrate the construction design. The villages of Bukit Raya and Bumi Harapan have different site characteristics that impact the design and implementation of the photovoltaic system. Bukit Raya may have environmental conditions other than those in Bumi Harapan, affecting how and where the PV array will be installed. Additionally, the characteristics of the water wells in each village are unique. These characteristics include the depth of the wells and the distance between the wells and the solar power system.

Bumi Harapan Site

From Figure 8, a satellite view of a construction site in Bumi Harapan Village can be seen. The photovoltaic will be installed on the rooftop of the water treatment plant. This existing infrastructure can be utilized to purify the water pumped from underground. The pumping well is also located near the water treatment plant. Hence, an underground electrical connection is used. The submersible pump is 140 meters above sea level at the Bumi Harapan site. This site profile negatively affects the system because the pump is designed by default to operate with a head of 80 meters. This elevation factor has been anticipated when determining the specifications of the system components. The expected performance will be evaluated through simulations to ensure the system operates efficiently.

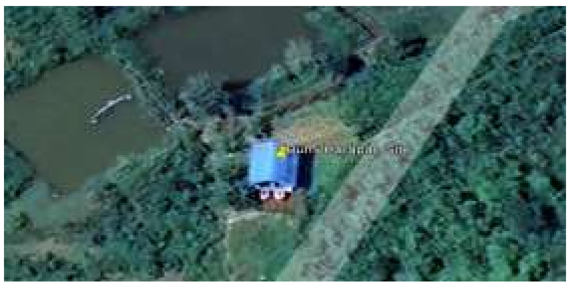

Figure 8. Satellite View of Bumi Harapan Site

However, the Bumi Harapan site is quite open, with fewer obstacles blocking sunlight, allowing the system to produce more consistent energy. This low shading profile is an essential factor that positively impacts system performance.

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Figure 9 shows a 3D model of the roof structure where the solar panels will be mounted. The model differs from the Bukit Raya site, adapting to roof area availability and condition. The photovoltaic array is placed with double rows on the roof. Due to this layout, the total roof area used for the solar panels is 12 m². This is larger than the roof area at the Bukit Raya site.

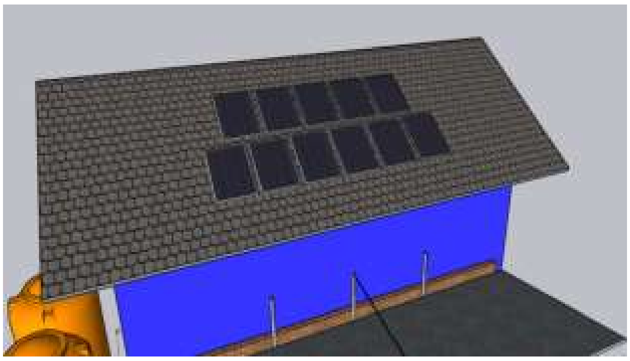

Figure 9. 3D Model of Photovoltaic Array in Bumi Harapan Site

Bukit Raya Site

From Figure 10, a satellite view of a construction site in Bukit Raya Village can be seen. The photovoltaic will be installed on the rooftop of the waste management building. In the future, this existing infrastructure can use excess electricity from photovoltaic systems to increase the use of renewable electricity. The pumping well is located near the waste management building. Hence, an underground electrical connection is also used. In Bukit Raya Village, the submersible pump is 90 meters above sea level.

Figure 10. Satellite View of Bukit Raya Site

Figure 11 shows a 3D model of the roof structure where the solar panels will be mounted. The model illustrates how the panels will be positioned on the roof to maximize sunlight exposure, ensuring optimal energy production for the system. The photovoltaic array is placed in a single row along the roof. Due to this layout, the total roof area used for the solar panels is only 9.23 m². This is much smaller than the roof area utilized in the Bumi Harapan site, where a larger space was needed to accommodate a different panel configuration.

Bukit Raya site has more shading than Bumi Harapan because tall palm oil trees surround it. These trees block sunlight at different times of the day, reducing the solar energy the panels can produce. This shading will affect the overall performance of the water pump at Bukit Raya. Bumi Harapan is more open, with fewer obstacles blocking sunlight, allowing the system to produce more consistent energy. This difference in shading is an essential factor that impacts how well each solar pumping system works.

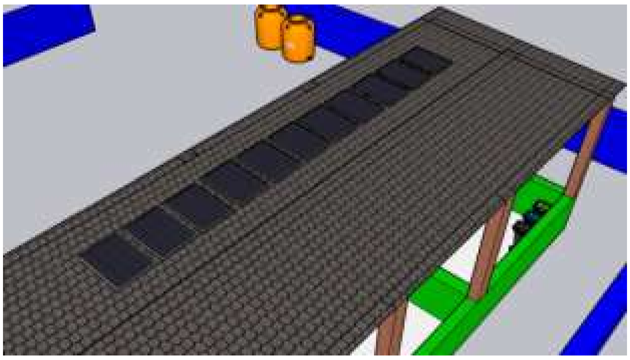

Figure 11. 3D Model of Photovoltaic Array in Bukit Raya Site

PVSyst Simulation

The performance simulation of the pump in the existing system uses the PVSyst software to analyze the system. The simulation components are defined according to the site condition, with a summary of the data presented in Table 4 and Table 5.

Table 4. Simulation Site Specifications for Bumi Harapan Site

Parameters	Value
PV Field Orientation	Tilt Angle: 30° Azimuth: 89.2°
Near Shading	Linear Shading: Fast
Geographical Data	Latitude: -0.97 °S Longitude: 116.74 °E Altitude: 12 m

Table 5. Simulation Site Specifications for Bukit Raya Site

Parameters	Value
PV Field Orientation	Fixed Plane: 5° Azimuth: -89.9°
Near Shading	Linear Shading: Fast
Geographical Data	Latitude: -0.91 °S Longitude: 116.75 °E Altitude: 19 m

From those data, a simulation is carried out with the pumping feature option in the PVsyst application. In PVsyst, solar pumping simulation models the performance of a photovoltaic system used to power a water pump, analyzing energy production and water flow based on solar irradiance, system configuration, and pump characteristics. The software considers vital parameters such as panel tilt, azimuth, and solar radiation to predict daily and annual water output. The summary results are obtained as explained in Table 6 and Table 7.

Table 6. Simulation Result Summary for Bumi Harapan Site

Parameters	Value
Water Pumped	2108 m^3 (104 m^3/kWp/bar)
Pumping Energy	1601 kWh (0.76 kWh/m^3)
Unused PV Energy	0 kWh
Unused Fraction	0 %
System Efficiency	52 %
Pump Efficiency	34 %

Table 7. Simulation Result Summary for Bumi Harapan Site

Parameters	Value
Water Pumped	3368 m^3 (238 m^3/kWp/bar)
Pumping Energy	1656 kWh (0.49 kWh/m^3)
Unused PV Energy	58 kWh
Unused Fraction	1.9 %
System Efficiency	53.7 %
Pump Efficiency	37 %

Based on the simulation results, the solar pumping system cannot supply 10 m^3 of supplementary water per day for both villages. This happened due to the higher elevation head compared to the nominal value given in pump specifications. On the other hand, it can be seen that the current system design has a pretty good system efficiency of 52%, with the pump operating at an efficiency of 34%. In the Bukit Raya location, the system has a slightly higher efficiency of 53.7%, with the pump working at 37% efficiency based on the characteristics of the well.

This situation can be analyzed in detail by examining the existing losses, allowing for future improvements to increase the amount of water supplied by the solar pumping system, as shown in Figure 12 and Figure 13, according to the defined installation locations. The loss diagram shows how energy is gradually lost in a solar pumping system, from when sunlight hits the solar panels to the amount of water pumped. It starts with sunlight hitting the panels, which reduces the energy by factors like shading, the angle of the sunlight, and temperature.

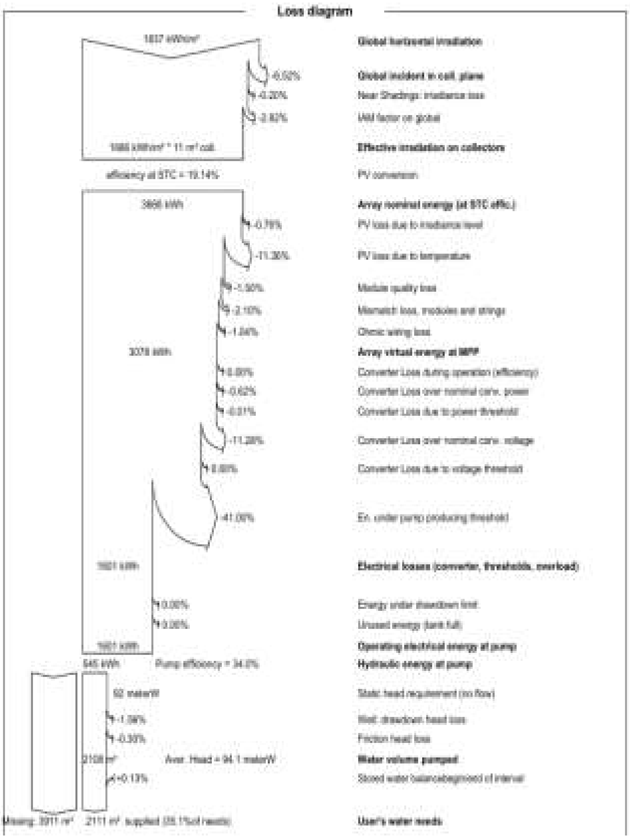

Figure 12. Losses Diagram of Solar Pumping System in Bumi Harapan Site

Next, inefficiencies within the solar modules and wiring cause further energy loss before reaching the inverter. At the inverter, mismatches in power and voltage cause more energy to be wasted. When the energy finally gets to the pump, additional losses happen due to hydraulic issues like the pump's head, friction, and drawdown. Ultimately, the amount of water pumped is much less than the system's theoretical capacity, showing how these losses stack up throughout the process.

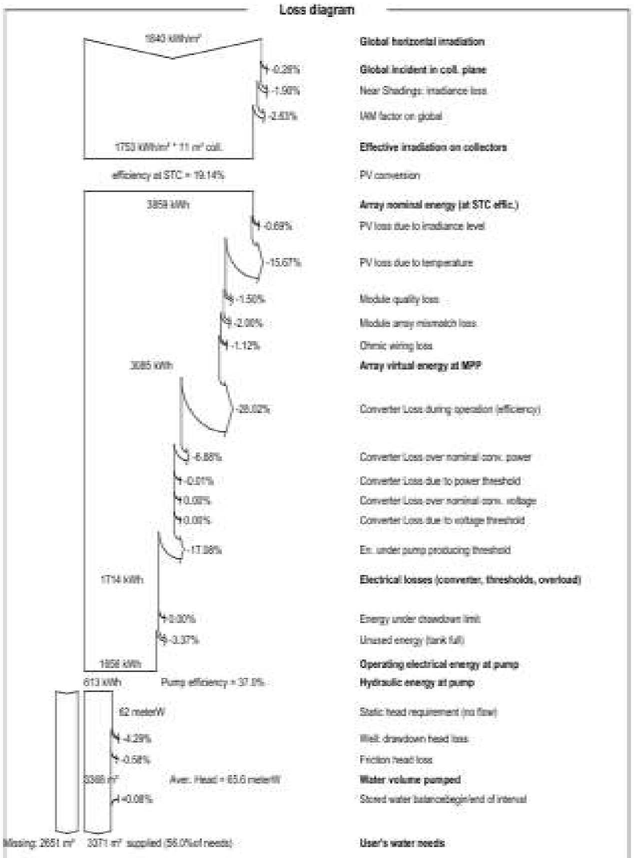

Figure 13. Losses Diagram of Solar Pumping System in Bukit Raya Site

By taking the losses diagram from the Bumi Harapan site shown in Figure 12, it is observed that the PV system has the potential to receive an annual GHI average of 1,837 kWh/m². Under STC conditions, the solar panels used have an efficiency of 19.14% when converting sunlight into electrical power, which aligns with the specifications of the solar panels. The following explains the details of the other losses:

Photovoltaic (PV) loss analysis reveals several key factors affecting energy production. Firstly, the losses due to irradiance are minimal, with recorded values of -0.76% and -0.69%. These minor reductions stem from fluctuations in sunlight intensity, often caused by shadows in the surrounding area or decreased solar radiation at certain times throughout the day.

In contrast, the losses attributable to temperature are significantly more pronounced, with figures of -11.36% and -15.67%. Solar panels operate most efficiently at lower temperatures, and their performance declines as temperatures rise. The panels under investigation possess a Pmax temperature coefficient of 0.5%/°C, indicating a high sensitivity to temperature increases.

Additionally, mismatch losses have been quantified at -2.10% and -2%. These losses occur due to the requirement for different modules within a single string to function at the same operational point, dictated by the module exhibiting the lowest performance. The simulation models, such as PVsyst, evaluate mismatch losses by considering the specific system data, module characteristics, and operational conditions.

Lastly, the energy under the pump-producing threshold is notable, with the simulation indicating values of -41% at the Bumi Harapan site and -6.88% at the Bukit Raya site. This measurement reflects energy that cannot be utilized because the pump system is inoperative when the available energy falls below its minimum operational threshold. Consequently, there are specific periods when the energy generated by the solar power system is insufficient to power the pump, rendering that energy unusable..

The energy production results of Bumi Harapan over the annual period and the system performance ratio for the current installation can be seen in Figure 14 and Figure 15.

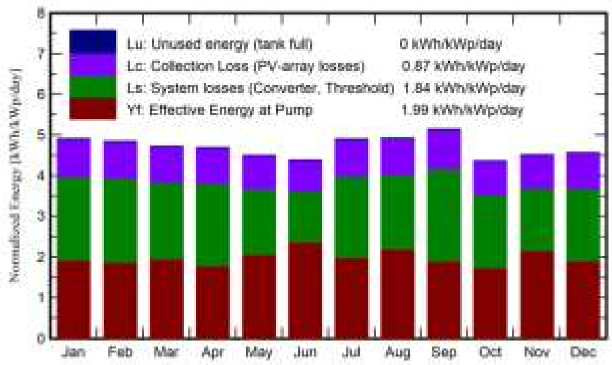

Figure 14. Normalized Production for Bumi Harapan Site

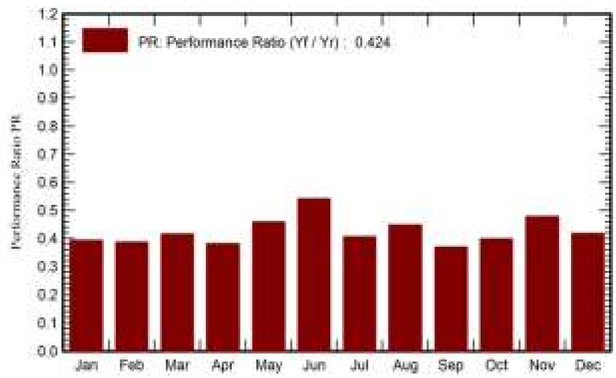

Figure 15. System Performance Ratio for Bumi Harapan Site

The performance ratio results of the submersible pump system at the Bumi Harapan location, as shown in Figure 15, only reached 42.4%, which is still below the main target of achieving a performance ratio value of around 75% to 85%. Figure 15 also shows that the red color, representing the energy used by the pump, remains small and is dominantly reduced by the system losses, indicated by the green graph, due to the pump not reaching the minimum energy required for operation. Meanwhile, the purple graph shows the losses from the solar panels used.

The same situation also occurs at the installation location in Bukit Raya, with the exact details presented in Figure 16 and Figure 17.

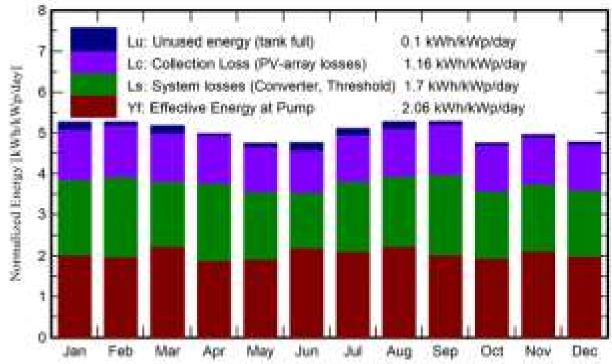

Figure 16. Normalized Production for Bukit Raya Site

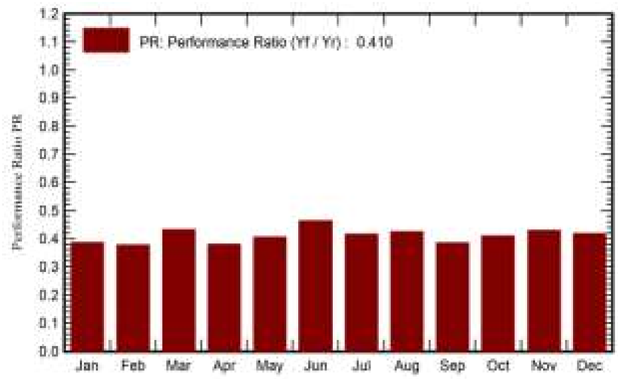

Figure 17. System Performance Ratio for Bukit Raya Site

The simulation results at Bukit Raya are similar to those at Bumi Harapan, with an average performance ratio of 41%. It also shows that the energy used by the pump (represented by the red color) is still small, and most of the energy is lost, indicated by the green graph, because the pump does not receive enough energy to operate.

This research focuses on the reliability of the pump in extracting water from the ground, so the main parameters considered are the energy required to run the pump and the amount of water pumped from the ground. These parameters are presented in Tables 8 and 9, which contain data from both pump system installation locations based on the PVsyst analysis.

Table 8. Monthly Pump Energy and Water Supply (Bumi Harapan)

Month	Pump Energy (kWh)	Water Pumped (m^3)
January	131.4	172.8
February	115.4	152.3
March	134	176.4
April	118.2	154.2
May	141.1	185.8
June	157.2	207.5
July	135.8	179.9
August	150.5	199.9
September	125.7	165.1
October	118.8	155.1
November	142.7	189.2
December	130.3	170.1
Total	**1601.1**	**2108.5**

Table 9. Monthly Pump Energy and Water Supply (Bukit Raya)

Month	Pump Energy (kWh)	Water Pumped (m^3)
January	138.5	282.1
February	122.3	249.3
March	152.7	311.8
April	124.8	252.7
May	131.3	265.7
June	145.7	296.9
July	144.7	294.6
August	152.8	312
September	134.1	272.1
October	132.8	268.9
November	140.4	285.4
December	136.4	276.8
Total	**1656.4**	**3368.4**

Based on the data on energy used by the pump and the water supplied each month, as shown in Table 8, it can be seen that only a small amount of the energy generated by the solar panels over the year can be utilized to power the pump. The amount of water produced is insufficient to fulfill two identical water towers. Still, it is expected to fill more than one because the daily water supply for Bumi Harapan and Bukit Raya sites are 5.78 m^3 and 9.23 m^3. The lower water supply in the Bumi Harapan site from the PVSyst simulation occurred because the submersible pump was forced to operate well beyond its capability [16].

The insufficient water supply from solar pumping systems can be mitigated by integrating a battery energy storage system (BESS) or utilizing other renewable energy sources. By storing excess solar energy during peak sunlight hours, a BESS ensures a continuous and reliable power supply, even during cloudy periods or at night. Additionally, incorporating bio-diesel derived from palm oil as a supplementary energy source can provide a clean and renewable alternative. These hybrid approaches help stabilize water availability while adhering to sustainable practices.

Implementation and Performance Testing

The construction results of implementing the designs that have been made can be seen in Figure 18 for the Bumi Harapan site and Figure 19 for the Bukit Raya site.

Figure 18. Bumi Harapan Site Rooftop View after Construction

Figure 19. Bukit Raya Site Rooftop View after Construction

To ensure the system works well, performance testing was carried out using a power quality analyzer (PQA) and solar power meter (SPM) at the Bukit Raya site. The test was conducted in the Bukit Raya site, representing both systems from two villages. The water output discharge from the submersible pump was considered to determine whether the electrical energy produced by the solar pumping system has been successfully converted into mechanical energy through the pump motor. The details of measurement instrument placement for performance monitoring can be seen in Figure 20.

Figure 20. PQA and SPM Placement

The PQA was placed near the inverter panel box while the SPM was put on a surface with a low shading rate. Solar irradiance measured by the solar power meter, therefore, represents the solar irradiance that is radiated to solar cells. The period of performance monitoring is 11:40:00 until 15:00:00 WITA. Both instruments capture data every 5 minutes. The PQA will capture various electrical performance data such as voltage, current, and photovoltaic output power in this measurement. The measurement results from PQA and SPM can be seen in Table 10.

Table 10. Performance Monitoring Results

Time (WITA)	Irradiance (W/m^2)	Voltage (V)	Current (A)	Power (Watt)
11:40:00	1214	217	4.3	933.1
11:45:00	1135	217	4.4	954.8
11:50:00	1118	217	4.4	954.8
11:55:00	1085	217	4.4	954.8
12:00:00	1078	217	4.3	933.1
12:05:00	1110	217	4.3	933.1
12:10:00	1180	217	4.3	933.1
12:15:00	1229	217	4.3	933.1
12:20:00	273.1	184	4.5	828.0
12:25:00	358.9	102.7	4.3	441.6
12:30:00	330.6	119	4.6	547.4
12:35:00	234.7	118.6	4.5	533.7
12:40:00	902.5	115.8	4.7	544.3
12:45:00	1109	215.5	4.8	1034.4
12:50:00	1154	217	4.3	933.1
13:25:00	127.9	28	1.3	36.4
13:30:00	83.2	19	1	19.0
13:35:00	70.9	13.8	0.8	11.0
13:40:00	51.4	13	0.7	9.1
13:45:00	63.3	11.2	0.6	6.7

Table 10 (cont). Performance Monitoring Results

Time (WITA)	Irradiance (W/m²)	Voltage (V)	Current (A)	Power (Watt)
13:50:00	67	12.9	0.7	9.0
13:55:00	51.1	14	0.8	11.2
14:00:00	41.2	12.2	0.7	8.5
14:05:00	34.5	11	0.6	6.6
14:10:00	22.3	6	0.4	2.4
14:15:00	28.9	1.3	0.1	0.1
14:20:00	32.4	1.4	0.1	0.1
14:25:00	38.2	5.8	0.3	1.7
14:30:00	42.1	13	0.7	9.1
14:35:00	43.1	13.5	0.7	9.5
14:40:00	49.5	13.2	0.7	9.2
14:45:00	52.8	12.6	0.7	8.8
14:50:00	45.8	12.3	0.7	8.6
14:55:00	66.3	12.1	0.7	8.5
15:00:00	76.4	15	0.8	12.0

During peak sun hours, the system performed exceptionally well, generating near-maximum power output with consistent voltage and current. This high performance corresponds to elevated solar irradiance levels (above 1000 W/m²), allowing the pump to operate efficiently. However, as solar irradiance decreased due to cloud cover or changes in the solar angle, the power output dropped significantly. The fluctuations in solar irradiance throughout the day directly impacted the performance of the solar pumping system, demonstrating its strong dependence on consistent sunlight for optimal operation.

As indicated in Table 10, there was a rapid decline in solar irradiance due to heavy rain recorded at 12:55:00 WITA. Consequently, the performance of the solar pumping system was adversely affected. When the rain started, the water flow ceased because the pump could no longer elevate water from the well.

Curves have been created to show the relationship between solar irradiance and the output voltage, current, and power of the photovoltaic array to illustrate how weather conditions or sunlight intensity influence the performance of the solar pumping system. These illustrations can be found in Figures 21, 22, and 23, respectively.

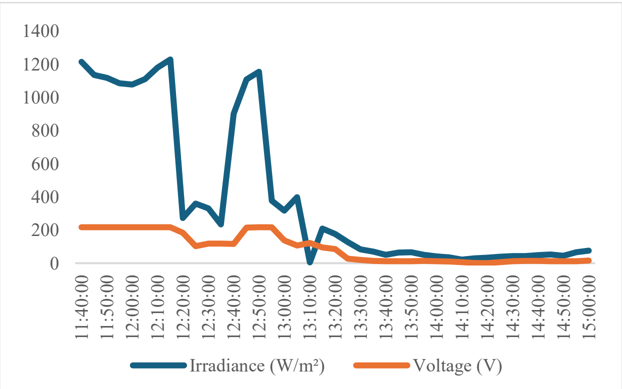

Figure 21. Solar Irradiance and PV Array Voltage Curve

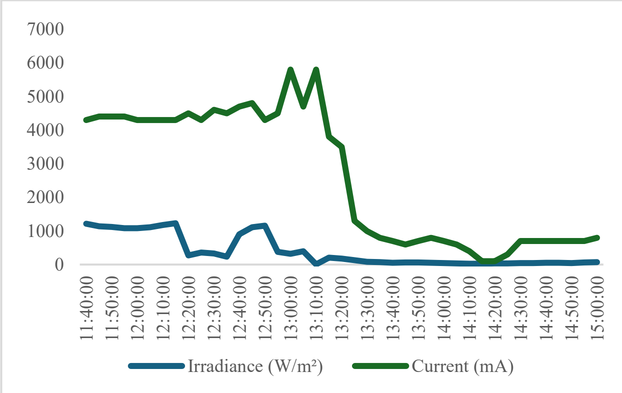

Figure 22. Solar Irradiance and PV Array Output Current Curve

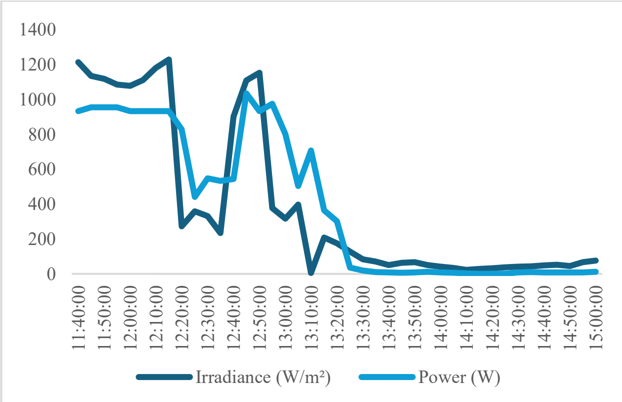

Figure 23. Solar Irradiance and PV Array Output Power Curve

The output power of a photovoltaic system is the product of voltage and current. Therefore, an increase in solar irradiance leads to higher power output from the system. The relationship between power and irradiance is not linear but follows a more complex curve due to factors like the efficiency characteristics of the solar cells [17]. Photovoltaic systems are desired to operate at their maximum power point (MPP), where the product of voltage and current is maximized. Solar irradiance changes can affect the MPP's position on the voltage-current curve [18]. It's also important to note that solar cell temperature also affects the performance of a PV system. As the temperature increases, the efficiency of solar cells typically decreases [19].

Besides, the curve inequality trend between electrical performance and solar irradiance can happen because of the shading of palm oil tree leaves. Shading significantly reduces the output power of the photovoltaic system by limiting the amount of sunlight reaching shaded areas. This reduction leads to energy loss and potential hotspot formation [20].

Figure 24 serves as documentation showing the successful implementation of the system. The water was effectively streamed to the land surface with a consistent flow during the peak sun hours. This visual representation underscores the system's ability to maintain constant water discharge throughout the specified period, indicating its reliability.

 https://doi.org/10.25077/ajeeet.v4i2.139

Figure 24. Solar Pumping System Water Outflow

CONCLUSIONS

In conclusion, the water pumping system, featuring a 1.1 kW submersible pump and a 2.2 kW photovoltaic array, was designed to meet a daily demand of 10 m³ for two water towers. A solar pump controller allows the pump to draw grid electricity when solar energy is insufficient.

Simulations indicated that relying solely on solar power failed to meet demand, with Bumi Harapan supplying 5.78 m³ and Bukit Raya 9.23 m³ due to higher elevation heads and system losses. A battery energy storage system or bio-diesel backup can address water shortages if necessary.

Performance tests showed the pump operates near capacity during peak sun hours but shuts off at minimum power levels. Despite not fully meeting the expected supply, the system remains a beneficial supplementary water source, enhancing resilience in the water supply rather than replacing the primary source.

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AUTHORS BIOGRAPHY

Hebert Arthur Sigiro

Hebert Arthur Sigiro is a master student majoring in Electrical Power Engineering at Bandung Institute of Technology. He is passionate in power generation and energy technology. Until now, he had active involvements in sustainable energy related projects, professional experiences, researches, organizations, courses, and national competitions. He is skilled in renewable energy system modeling, optimization, and techno-economic assessment. He is very enthusiast to contribute on Indonesia energy transition, towards a more sustainable future.

Prabowo

Prabowo, known as Bowo, is a graduate with a Bachelor's degree in Electrical Power Engineering of Bandung Institute of Technology, specializing in power generation systems. He has extensive experience in electrical installation projects, including solar power plants and coal-fired power plants. Outside of his engineering career, he is also an education influencer, leveraging his strong personal branding and communication skills. He plans to pursue a Master's degree in the next five years to deepen his knowledge in power engineering.

Burhanuddin Halimi

Burhanuddin Halimi is with School of Electrical Engineering and Informatics, Institut Teknonologi Bandung. He received the B.S. degree and M.S. degree in electrical engineering from Institut Teknologi Bandung, Indonesia in 2000 and 2002, respectively; his Ph.D. degree in energy systems Engineering from Seoul National University, Republic of Korea in 2013. Since 2014 he is working as one of faculty members in School of Electrical Engineering and Informatics, Institut Teknonologi Bandung. His current research interests include electric power generation, energy conversion, renewable energy application, electric propulsion and thermal energy management.