DESIGN OPTIMIZATION OF HYBRID SOLAR-GRAVITY ENERGY STORAGE FOR ELEVATION SYSTEM

BY

MOHD RIDHUAN BIN ISMAIL

A dissertation submitted in fulfillment of the requirement for
the degree of Master of Science in Engineering.

Kulliyyah of Engineering
International Islamic University Malaysia

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ABSTRACT

Solar energy has become an increasingly important component in the global shift toward renewable energy. However, conventional solar energy systems that depend only on chemical batteries often face limitations such as high cost, energy degradation, and short operational lifespan, particularly in elevation-based applications. The objective was to design and optimize a hybrid energy storage system by integrating solar PV, battery, and gravity-based storage, and to evaluate its performance under real operating conditions. The goal was to optimize the design using a 50-Watt Solar PV, an 18Ah SLA Battery, and a Water Gravity Energy Storage Tank. The method included three steps and used five data loggers: a flow meter, a pyranometer, and three-watt meters. First, a fully charged SLA Battery was tested at various tank heights (from 1.5m to 3.5m) every 15 minutes. Then, the 50-Watt Solar PV was tested directly at a height of 3 meters. Lastly, the Solar Hybrid Gravity System with Battery Energy Storage was monitored over seven days at a 3-meter height. Energy use was measured through the SLA Battery, Solar PV, and a 22-Watt Water Pump at different tank heights to see improvements in efficiency and battery life. The results showed a 600% improvement in battery performance at 80% Depth of Discharge (DOD), proving the battery's potential as a reliable backup power source and extending its lifespan. The SLA Battery had a 22.1% energy loss during charging and discharging at 5% DOD, while the 22-Watt Water Pump achieved a flow rate of 11.0 L/min at peak solar irradiance of 900 W/m², with a maximum motor power of 24.32 Watts. A minimum of 300 W/m² solar irradiance was needed for the pump to run efficiently. In conclusion, the energy efficiency of the solar hybrid gravity system was optimized, reducing reliance on the battery and extending its lifespan, making it a sustainable solution for elevation applications. This system can be applied in water pumping, agricultural irrigation, and elevator systems in off-grid or rural areas, offering a cost-effective and environmentally friendly energy storage alternative.

ملخص البحث

أصبحت الطاقة الشمسية مكونًا متزايد الأهمية في التحول العالمي نحو الطاقة المتجددة. ومع ذلك، تواجه أنظمة الطاقة الشمسية التقليدية التي تعتمد فقط على البطاريات الكيميائية بعض القيود، مثل التكلفة العالية، وتدهور الطاقة، وقصر العمر التشغيلي، لا سيما في التطبيقات التي تعتمد على الارتفاع. كان الهدف من هذه الدراسة هو تصميم وتحسين نظام تخزين طاقة هجين من خلال دمج الطاقة الشمسية الكهروضوئية والبطارية والتخزين القائم على الجاذبية، وتقييم أدائه في ظروف التشغيل الفعلية. تم تطوير النظام باستخدام لوحة شمسية بقدرة 50 واط، وبطارية SLA بسعة 18 أمبير-ساعة، وخزان تخزين مياه يعمل بالجاذبية. شملت منهجية البحث ثلاث خطوات واستخدمت خمسة أجهزة لتسجيل البيانات: عداد تدفق، مقياس الإشعاع الشمسي، وثلاثة مقاييس طاقة. أولًا، تم اختبار البطارية المشحونة بالكامل على ارتفاعات مختلفة للخزان (من 1.5 متر إلى 3.5 متر (كل 15 دقيقة. بعد ذلك، تم اختبار لوحة الطاقة الشمسية على ارتفاع 3 أمتار. وأخيرًا، تم مراقبة، أداء النظام الهجين لمدة سبعة أيام متتالية على ارتفاع 3 أمتار. تم قياس استخدام الطاقة من خلال البطارية والطاقة الشمسية، ومضخة المياه بقدرة 22 واط، على ارتفاعات مختلفة للخزان بهدف تحسين الكفاءة وإطالة عمر البطارية. أظهرت النتائج تحسنًا بنسبة 600% في أداء البطارية عند عمق تفريغ 80% (DOD)، مما يثبت جدواها كمصدر احتياطي موثوق للطاقة ويساهم في إطالة عمرها. كما أظهرت فقدًا في الطاقة بنسبة 22.1% عند عمق تفريغ 5%، بينما حققت المضخة معدل تدفق 11.0 لتر/دقيقة عند أقصى إشعاع شمسي قدره 900 واط/م^2، وتطلبت حدًا أدنى من الإشعاع الشمسي قدره 300 واط/م^2 للتشغيل بكفاءة. ختامًا، أظهر النظام الهجين كفاءة محسّنة في استخدام الطاقة، وقلل الاعتماد على البطارية، وأثبت كفاءته في التطبيقات التي تعتمد على الارتفاع مثل أنظمة ضخ المياه، الري الزراعي، والمصاعد في المناطق النائية أو خارج الشبكة، مما يجعله خيارًا اقتصاديًا ومستدامًا لتخزين الطاقة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Engineering.

……………………………….
Zafri Azran Abdul Majid
Supervisor

Sany
……………………………….
Sany Izan Ihsan
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Engineering.

……………………………….
Prof. Ir. Dr. Siti Fauziah Bt. Toha @ Tohara
Examiner

……………………………….
Prof. Dato' Ts. Dr. Kamaruzzaman Sopian
External Examiner

This dissertation was submitted to the Department of Mechanical And Aerospace Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science in Engineering.

……………………………….
Hanan Mokhtar
Head, Department of Mechanical
Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a fulfillment of the requirement for the degree of Master of Science in Engineering

……………………………….
Khairul Azami Sidek
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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This thesis is dedicated to my mother, my wife and sons for laying the foundation of what I turned out to be in life.

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LIST OF SYMBOLS

E	Energy (Wh)
P	Power (W)
V	Voltage (V)
I	Current (A)
Q	Charge (Ah)
η	Efficiency (%)
t	Time (minutes or hours)
h	Elevation height (meters)
ΔE	Energy difference (Wh)
Ein	Energy input (Wh)
Eout	Energy output (Wh)
DoD	Depth of Discharge (%)
L	Water volume (liters)
FR	Flow Rate (L/min)
ρ	Density of water (kg/m³)
g	Acceleration due to gravity (m/s²)
m	Mass (kg)
kW	Kilowatt (1000 W)
Ah	Ampere-hour, a unit of electric charge
T	Temperature (°C)
SoC	State of Charge (%)
BMS	Battery Management System

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

Renewable energy has become more important in recent years to solve global energy problems. The main goal is to reduce carbon emissions and rely less on fossil fuels. For many years, fossil fuels like coal, oil, and natural gas were the main sources of energy, but their negative impact on the environment has led to a shift towards cleaner options. Among these options, solar energy is one of the most popular because it is clean, reliable, and easy to access.

Many countries now use different types of renewable energy, such as hydropower, wind, geothermal, biomass, and ocean energy, to help reduce environmental problems. These energy sources not only provide power but also help lower greenhouse gas emissions, which cause global warming (Oludaisi et al., 2017). For developing countries, solar power is especially useful because it can generate electricity without harming the environment, and it is becoming cheaper and more efficient (Bocklish et al., 2015).

Solar energy systems work by using photovoltaic (PV) panels to turn sunlight into electricity. These systems are considered "green" because they do not produce harmful emissions, making them a sustainable choice (Shahsavari et al., 2018). Solar energy is also very reliable because sunlight is available almost everywhere, and the sun's energy is practically endless.

However, there is one main issue with solar energy systems: they need batteries to store extra energy. Since solar panels only produce electricity during the day when the sun is shining, batteries are needed to store this energy so it can be used at night or during cloudy weather. While batteries help provide steady power, they have some problems, including high costs and maintenance needs.

To address these issues, other energy storage methods are being explored to make solar systems more efficient and long-lasting. One promising solution is gravity-based energy storage. This method uses the potential energy of water stored at a high level to generate electricity when needed. It can reduce the need for batteries, making energy storage cheaper and less harmful to the environment (Blanco et al, 2018).

Gravity-based energy systems are simpler and usually have lower maintenance costs compared to batteries. They also last longer. By combining gravity storage with solar systems, overall efficiency can be improved, and costs can be reduced (Chen et al., 2022).

Elevators, which use a lot of energy to move people and goods, often waste the energy produced by their motors (Zhao et al., 2019). Recent studies have investigated using gravity energy storage (GES) for elevators. GES systems store energy by lifting heavy weights, making elevator systems more efficient. These systems can work many times without wearing out and can be combined with other methods, like compressed air storage (Morstyn et al., 2019; Annisa et al., 2022). Using GES in elevators can help buildings save energy.

1.2 PROBLEM STATEMENT

Solar energy systems face major challenges in energy storage, especially when using conventional chemical batteries. One significant issue is high cost, making solar setups less affordable (Meza et al., 2014). Batteries also suffer energy loss during charge and discharge cycles. Typically, 20 to 25% which reduces system efficiency (Doucette et al., 2011).

More critically, battery performance degrades over time. Waldmann et al. (2014) observed that battery capacity can drop by 15 to 20% after only 100 cycles. This leads to higher long-term costs and environmental concerns due to battery disposal. Regular maintenance is also required to avoid failures such as overheating (Reza et al., 2024; Lukic et al., 2006).

These issues point to the need for an alternative or supplementary energy storage method. One solution is to integrate gravity-based energy storage (GES) with battery systems in a hybrid setup. GES uses the potential energy of water stored at a height, which can be released to generate usable energy without chemical degradation.

However, limited studies have investigated the performance of such hybrid systems under real operating conditions for elevation tasks like water pumping or lifting systems. Therefore, this research focuses on designing and optimizing a hybrid energy storage system using solar PV, SLA battery, and gravity storage. The goal is to evaluate its efficiency, performance, and energy usage at different elevations under varying solar irradiance.

1.3 OBJECTIVES OF THE STUDY

The main goals of this research are:

i. To optimize the design of a solar hybrid system that combines gravity energy storage with battery storage.
ii. To test the performance and efficiency of this hybrid system using a 50-Watt solar panel, an 18Ah SLA battery, and a water gravity storage tank.
iii. To study how energy consumption and efficiency change when the water tank is placed at different heights.

1.4 RESEARCH SCOPE

This study focuses on the development and evaluation of a solar hybrid gravity energy storage system designed for elevation-based applications. The goal is to integrate solar photovoltaic (PV) power with sealed lead-acid (SLA) battery storage and gravity-based water storage to improve system efficiency and reduce battery dependency. The scope of this research covers system design, testing under real-world conditions, data analysis, and performance comparison against conventional setups. This research focuses on:

i. Designing and setting up a solar hybrid system that combines gravity-based energy storage with battery storage.
ii. Running experiments to measure how well the system performs under different

conditions.

iii. Analyzing the data to find the best setup for storing and using energy efficiently.

iv. Comparing the performance of the hybrid system with traditional solar systems to show the benefits of adding gravity-based energy storage.

To give a clearer understanding of the system's scope and structure, the following block diagram illustrates the major stages of the research project from system design to data analysis and comparison.

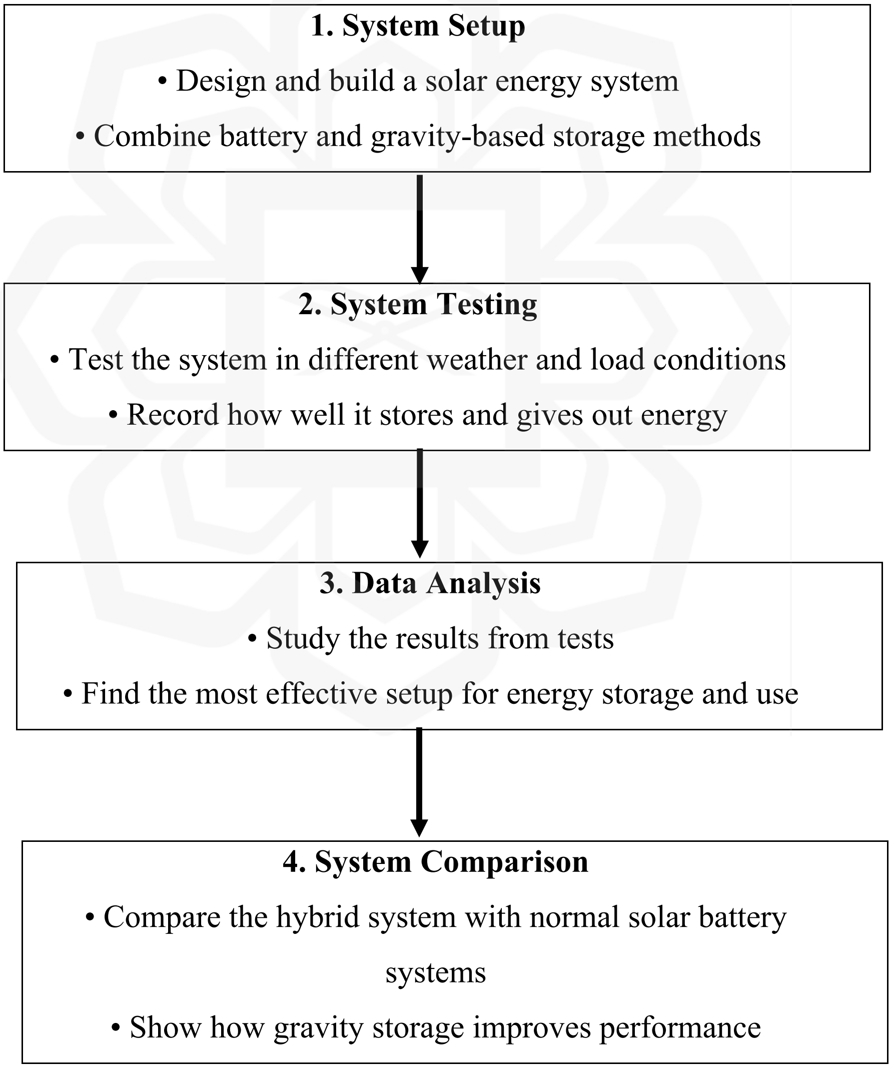

Figure 1.1: Block Diagram of Overall Research Scope and Project Workflow

1.5 SIGNIFICANCE OF THE RESEARCH

This study is significant because it provides a practical solution to the challenges of energy storage in solar-powered elevation systems. By combining solar photovoltaic (PV), sealed lead-acid (SLA) battery, and gravity-based water storage, the system reduces battery reliance and improves overall efficiency. The findings show that the hybrid system can reduce energy loss, extend battery lifespan, and support lifting operations with minimal power wastage.

Through experimental testing at different tank heights and under real solar irradiance, this project provides new data on how a hybrid storage setup performs in off-grid or rural conditions. It offers a cost-effective alternative for applications such as water pumping, agricultural irrigation, and small-scale elevation systems where reliable and sustainable energy is crucial.

This system also supports the global shift toward cleaner energy by using gravity as a natural energy buffer, reducing chemical battery use and its environmental impact. The outcomes of this research can guide future designs of solar-powered systems that are more affordable, sustainable, and reliable in remote areas.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Photovoltaic (PV) systems and other solar energy technologies convert sunlight directly into electricity. This technology is becoming more popular because it generates power without producing greenhouse gases, making it an environmentally friendly option (Shahsavari et al., 2018). Solar energy is a reliable and renewable resource since it is widely available in most parts of the world.

However, one main challenge with solar energy systems is the need for batteries to store extra energy produced during sunny periods. This stored energy can be used later, like at night or on cloudy days, to provide a steady power supply. While batteries ensure reliable power, they also come with problems such as high costs, energy loss, and limited lifespan (Meza et al., 2014).

To overcome these challenges, researchers are exploring alternative energy storage methods to improve the efficiency and sustainability of solar systems. One promising method is gravity-based energy storage. These systems store energy by using the potential energy of water or heavy objects lifted to a higher height. When needed, this stored energy is released to generate electricity. This approach can help reduce the reliance on batteries, lower costs, and minimize the environmental impact of energy storage (Blanco et al., 2018).

Gravity-based energy storage systems are generally simpler and more cost-effective than batteries. They avoid issues related to battery wear and have a longer lifespan with minimal maintenance. By combining gravity-based storage with solar energy systems, renewable energy can become more reliable and efficient, while also reducing costs (Chen et al., 2022).

Additionally, gravity-based storage can be used in systems like elevators, making them more energy-efficient. Elevators use a lot of energy, and much of it is often wasted (Zhao et al., 2019). By adding gravity-based storage, buildings can use energy more efficiently and sustainably (Annisa et al., 2022).

This literature review will explore different aspects of solar energy systems, battery storage, hybrid systems, and gravity-based energy storage. It will discuss the limitations of traditional storage methods and the benefits of combining solar energy with gravity-based storage. By examining existing research, case studies, and future trends, this review will provide a detailed understanding of the current state and future potential of hybrid and gravity-based energy storage systems.

2.2 SOLAR ENERGY AS RENEWABLE ENERGY

One of the most common ways to convert sunlight into electricity is through photovoltaic (PV) systems. These systems use the "photovoltaic effect," where special materials (usually silicon) turn sunlight into electrical power. When sunlight hits the PV cells, it makes electrons move, creating an electric current. PV systems are versatile and can range from small setups on rooftops to large solar farms. Over time, PV technology has become more efficient, with many systems now reaching over 20% efficiency. Advances in manufacturing have also brought down costs, making solar power more competitive with other energy sources.

To provide consistent and reliable power, PV systems are often paired with battery storage solutions. This combination ensures that energy is available even when sunlight is low, like during nighttime or cloudy weather. New developments, such as bifacial panels and tandem cells, have further improved the efficiency and cost-effectiveness of solar energy, making it a strong choice for widespread use (Shahsavari et al., 2018).

Another technology used to harness solar energy is Concentrated Solar Power (CSP). Unlike PV systems, CSP uses mirrors or lenses to focus sunlight onto a small area, producing high temperatures. This heat is then used to create steam that powers a turbine, generating electricity. CSP can also store thermal energy, like molten salt, which allows it to keep producing power even when the sun is not shining. This makes CSP a more stable and reliable source of energy than traditional PV systems (Lovegrove et al., 2012).

CSP systems are best suited for large-scale power generation and are often built in sunny regions like deserts, where they can maximize energy production. Recent improvements, such as better heat transfer fluids and materials, have made CSP more efficient and cost-effective. Some researchers are also exploring hybrid CSP systems that combine solar thermal power with other renewable or traditional energy sources, boosting reliability and lowering costs (Zhang et al., 2016).

2.2.1 Solar Energy Systems

Solar energy systems capture power from the sun, mainly using photovoltaic (PV) technology. As shown in **Figure 2.1**, these systems consist of panels made up of many PV cells that convert sunlight directly into electricity. Solar energy is widely recognized as a clean, renewable, and sustainable energy source. It is abundant and helps reduce our dependence on fossil fuels, which are limited and contribute to climate change and greenhouse gas emissions.

According to Shahsavari et al (2018), solar energy is an effective way to cut down on carbon emissions and fight climate change. By lowering the need for fossil fuels, solar power helps decrease the overall carbon footprint, which is crucial as the world shifts towards greener energy sources.

However, the performance of solar PV systems depends greatly on the availability of sunlight. Factors such as location, time of day, and weather conditions can affect how much energy is produced. PV systems work best in places with lots of sunlight, like deserts and warmer climates. In contrast, their efficiency may drop in regions with less sunlight or unpredictable weather, like northern areas or places that often have cloudy skies (Jain et al., 2018).

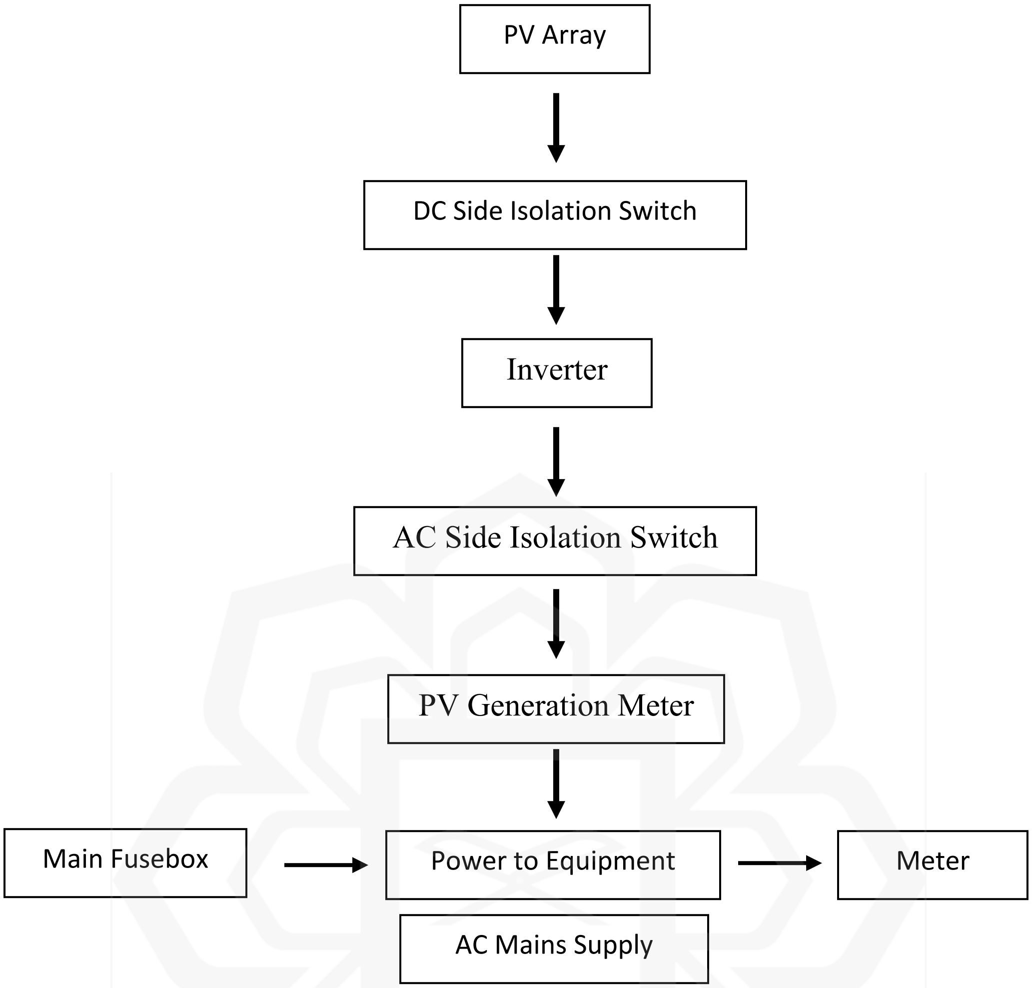

Figure 2.1 shows the basic components of a solar PV system.

Solar energy systems are commonly categorized into three main types based on their application scale and purpose: residential, commercial, and utility scale. Residential solar PV systems are typically installed on the rooftops of individual homes to fulfill household electricity needs. These systems allow homeowners to reduce dependence on the conventional electricity grid, potentially lowering monthly utility costs. Additionally, in many regions, surplus energy generated can be exported back to the grid under net metering schemes, offering further financial incentives (Ghosh et al., 2020). Commercial solar PV systems, on the other hand, are larger installations designed for use on business properties such as factories, shopping complexes, and office buildings. These systems provide a cost-saving advantage for businesses and contribute to reducing their overall carbon footprint. Owing to their larger scale, commercial PV setups typically have a lower cost per watt of electricity produced compared to smaller systems (Blanco et al., 2018). The third category, utility-scale solar PV systems often referred to as solar farms, involves large-scale installations that feed electricity directly into the public grid. These systems are composed of thousands of panels distributed across expansive land areas and can generate electricity on a regional or national scale. Due to their high-volume energy output and the benefits of economies of scale, utility-scale PV systems tend to offer the lowest cost per watt of energy produced (Ghasempour et al., 2021).

While solar PV systems provide clean and renewable energy, they have some limitations, especially in terms of consistency. Since solar power depends on sunlight, which isn't always available (at night or during cloudy weather), it can be challenging to maintain a steady energy supply. To address this, PV systems are often combined with energy storage solutions like batteries. Batteries store the extra energy produced during sunny periods and release it when sunlight is not available, ensuring a reliable power supply (Amini et al., 2017).

Ongoing advancements aim to make solar PV systems more efficient and affordable as shown in Table 2.1. Researchers are developing new materials and better manufacturing methods to improve PV cell performance. For example, multi-junction PV cells capture more of the sunlight spectrum, boosting efficiency. Thin-film solar technology and organic PV cells are also being explored to reduce costs and increase the adaptability of solar systems (Chen et al., 2022).

Moreover, integrating solar PV systems with smart grid technology can enhance the overall efficiency and reliability of power distribution. Smart grids use advanced control systems to optimize how electricity is generated and consumed. By connecting solar PV systems to smart grids, energy supply and demand can be balanced more effectively, ensuring a stable and efficient power grid (Johnson et al., 2015).

Table 2.1: Factors Influencing Solar PV System Efficiency

Factor	**Impact on Efficiency**
Geographic Location	Higher efficiency is achieved in sunnier regions.
Time of Day	Peak efficiency is reached during midday.
Weather Conditions	Efficiency is reduced on cloudy or rainy days.
Solar Panel Orientation	Proper orientation ensures maximum sunlight exposure.
Temperature	Efficiency can be lowered by extreme temperatures.

2.3 BATTERY STORAGE IN SOLAR ENERGY SYSTEMS

Batteries play a key role in solar energy systems. They store extra energy produced when there is plenty of sunlight so that it can be used later when sunlight is low, such as at night or on cloudy days. Since solar energy depends on weather conditions, batteries are essential for providing a steady power supply. They help balance supply and demand, making the energy system more reliable and less dependent on direct sunlight.

2.3.1 High Costs

One of the biggest challenges of using batteries for solar energy storage is the high cost. A significant part of the expense of a solar energy system comes from batteries. According to Meza et al. (2014), the initial investment in battery storage can be very expensive, which prevents many people from adopting solar energy. Beyond the cost of the batteries, there are also expenses related to equipment needed to store and maintain them. This high upfront cost can discourage homeowners and businesses, even though solar systems can save money in the long run.

Several factors drive the high cost of batteries. First, the materials used to make batteries, like lithium, cobalt, and nickel, are expensive and sometimes hard to get. These materials are important for high energy storage and long battery life, but they also raise costs (Dehghani-Sanij et al., 2019). The mining and extraction of these materials can also have negative environmental and ethical impacts, further increasing the cost of obtaining sustainable and responsibly sourced materials (Shahsavari et al., 2018).

Second, manufacturing batteries is a complex process that requires advanced technology and expertise. Building battery cells that are safe, reliable, and efficient needs specialized equipment and skilled workers, which adds to production costs. This, in turn, makes the batteries more expensive for consumers (Blanco et al., 2018).

Additionally, the infrastructure needed to store and maintain batteries increases the overall investment. Batteries need to be kept in the right condition to protect them from factors like temperature changes, humidity, and physical damage, all of which can shorten their lifespan. This may require climate-controlled spaces, protective enclosures, and monitoring systems, which add to the cost (Garcia et al., 2021).

The costs don’t stop after installation. Batteries need ongoing maintenance to work effectively over their lifetime. Regular maintenance, such as monitoring charge levels, managing temperature, and checking for damage, require specialized skills and equipment, increasing the long-term costs of running a solar energy system with battery storage (Amini et al., 2017).

2.3.2 Energy Losses

Another problem with battery storage in solar systems is the loss of energy during charging and discharging. According to Doucette et al. (2011), energy losses can range from 20% to 25%, reducing the overall efficiency of solar systems. These losses occur because of internal resistance in the batteries, which generates heat and wastes energy. As a result, some of the energy generated by solar panels is lost, making the system less efficient. This issue is especially serious during times of high energy demand, when maximizing stored energy is critical.

Energy loss happens mainly due to the battery's internal resistance. When a battery charges, electrical energy is stored as chemical energy, but some of this energy is lost as heat due to resistance. When discharging, the stored energy converts back to electricity, but more energy is lost again. This process reduces the total energy that can be used and can lead to higher temperatures, which can further affect the battery's efficiency and lifespan (Garcia et al, 2021).

To manage this heat and prevent damage, additional cooling systems are sometimes needed, but they use energy themselves, which lowers overall system efficiency. During periods of rapid charging and discharging, these energy losses can become more significant, making it essential to have efficient energy management (Amini et al., 2017).

2.3.3 Degradation And Maintenance

Over time, batteries wear out, reducing their ability to store and deliver energy. Repeated cycles of charging and discharging cause the materials inside the battery to break down, leading to a gradual decline in performance. According to Reza et al. (2024), batteries lose capacity over time, and this wear and tear means they need to be replaced more frequently, adding to the long-term costs and environmental impacts of solar systems.

There are several reasons why batteries degrade. One major factor is the number of charge and discharge cycles they go through. Every cycle slightly damages the battery materials, reducing the battery's capacity over time. For example, lithium-ion batteries, which are common in solar energy systems, can lose a large part of their capacity after a few hundred cycles (Waldmann et al., 2014).

Temperature also affects how fast batteries degrade. They work best within a certain temperature range, and extreme temperatures (too hot or too cold) can speed up the wear and tear. High temperatures can even lead to overheating, which can cause safety issues. Cold temperatures, on the other hand, slow down the chemical reactions inside the battery, making it less efficient (Dehghani-Sanij et al., 2019).

Proper maintenance is essential to extend battery life and keep them working well. This includes regular checks for physical damage or leaks, monitoring charge levels, and controlling temperature. Without regular care, batteries can degrade faster, leading to more costs. For instance, constantly overcharging or draining a battery too much can shorten its life significantly (Garcia et al., 2021).

To extend battery life, regular maintenance and proper usage are necessary. This means keeping the charge levels within safe limits, avoiding deep discharges, and storing the batteries in a temperature-controlled environment. A well-designed battery management system (BMS) can help monitor these factors and keep the batteries in good condition (Amini et al., 2017).

2.3.4 Type Of Batteries

Different types of batteries are used in hybrid energy systems, each offering unique advantages, trade-offs, and suitable applications. Lithium-ion batteries are widely used across various industries due to their high energy density, allowing them to store large amounts of energy in compact sizes. They are known for their efficiency and long lifespan, making them a preferred choice for mobile devices, electric vehicles, and solar energy systems. However, lithium-ion batteries are relatively expensive and pose safety concerns such as the risk of overheating and fire hazards. Efforts are ongoing to enhance their safety and reduce production costs (Shahsavari et al., 2018; Mosely et al., 2014). In contrast, lead-acid batteries represent a more traditional technology that is both cost-effective and reliable. Commonly used in backup power systems, uninterruptible power supplies (UPS), and automotive applications, lead-acid batteries are attractive due to their low upfront cost. However, they suffer from lower energy density, shorter lifespan, and require frequent maintenance, which can lead to increased long-term costs (Shen et al., 2011). Solid-state batteries, a newer innovation, replace the liquid electrolytes found in conventional batteries with solid materials. This design greatly improves safety by minimizing the risk of overheating and fire, while also offering higher energy storage capacity and durability. Despite these advantages, solid-state batteries are still expensive to produce and are not yet fully scalable for commercial or industrial applications. Researchers continue to explore methods to reduce manufacturing costs and improve their long-term reliability (CT, 2017). Overall, each battery type presents distinct benefits and limitations, and continued research is essential to optimize their use in hybrid energy systems for greater safety, performance, and cost efficiency.

2.3.5 Performance Metrics

The performance of battery storage systems is evaluated through several key indicators that determine their suitability and efficiency in energy applications. One of the primary metrics is capacity and Depth of Discharge (DoD). Capacity indicates the total amount of energy a battery can store, while DoD refers to the proportion of that energy which can be used without adversely affecting the battery's lifespan. Managing DoD is crucial because a lower DoD extends battery life but limits available energy, whereas a higher DoD offers more usable energy at the cost of faster degradation. Melikoglu (2017) emphasizes that understanding these parameters is essential for optimizing energy usage, particularly in systems that prioritize both efficiency and durability. Another vital indicator is efficiency, which measures effectively battery stores and returns energy. It is typically expressed as the ratio of energy output to energy input during the charging process. Higher efficiency reduces energy losses and improves system performance. According to Bocklisch et al. (2015), increasing battery efficiency is critical for reducing energy waste and ensuring the sustainability of energy storage solutions. Lastly, lifespan and durability are key considerations, defined by the number of charge-discharge cycles a battery can endure before its performance deteriorates. Durable batteries are capable of withstanding repeated usage without significant loss in capacity or function. As noted by Smith et al. (2021), advancements in battery materials and design are necessary to enhance both lifespan and durability, which are essential for reducing replacement frequency, lowering costs, and minimizing environmental impact over the system's operational life.

2.4 HYBRID ENERGY

Hybrid energy systems combine different methods to produce and store energy, creating a more reliable, efficient, and durable power solution. By using multiple technologies together, these systems take advantage of the strengths of each component and minimize their weaknesses. This results in a balanced energy supply that can adjust to changing conditions and demand patterns.

2.4.1 Concept And Advantages of Hybrid Energy Systems

The main objective of hybrid energy systems is to enhance overall performance, reliability, and sustainability by integrating multiple energy sources with various storage technologies. These systems typically combine renewable energy sources such as solar, wind, and hydropower with conventional energy inputs and advanced storage solutions, including batteries, flywheels, and gravity-based energy storage. One of the most significant advantages of hybrid systems is their ability to provide reliability and stability. They ensure a consistent energy supply by compensating for the intermittent nature of renewables—when solar power is unavailable at night, for instance, stored or alternative energy sources can maintain the load. In terms of efficiency, hybrid systems enable smart energy management by storing surplus energy during periods of low demand and discharging it during peak usage, thereby minimizing waste and optimizing overall system performance. From an environmental perspective, these systems help reduce carbon emissions by emphasizing renewable sources and reducing dependence on fossil fuels, contributing to cleaner and more sustainable energy production. Although the initial setup of hybrid systems may be more expensive, they offer cost savings in the long run by decreasing energy bills and reducing operational and maintenance costs. The combined benefits of improved efficiency, reliability, and environmental impact make hybrid systems an increasingly attractive and economically viable solution for modern energy infrastructure.

2.4.2 Integration Of Multiple Energy Storage Technologies

Combining different energy storage methods within hybrid systems allows for more effective balancing of energy supply and demand across various time scales and usage scenarios. Each storage type contributes distinct advantages that complement one another, enhancing the system’s overall efficiency and resilience. Battery storage, particularly lithium-ion technology, is highly efficient for short-term applications. Batteries offer fast response times and can deliver immediate backup power when there are fluctuations in demand or generation. Their high energy density and reliability make them ideal for rapid energy management and short-duration grid support (Chen et al., 2009). In contrast, gravity-based storage systems such as those using pumped hydro or heavy mass elevation are better suited for long-duration energy storage. These systems can store vast quantities of energy and discharge it over extended periods, which is particularly valuable in renewable-heavy grids where generation may not always align with demand. Gravity storage helps smooth out fluctuations and enhances grid stability (Blanco et al., 2018). Thermal storage systems offer yet another dimension of energy management by storing energy in the form of heat. This stored heat can be used directly in heating processes or reconverted into electricity as needed. Thermal storage is especially beneficial in industrial environments where both thermal energy and electricity are required, providing added efficiency and reducing reliance on conventional fossil fuels (Nisshanthan et al., 2023). By integrating these storage technologies, hybrid energy systems can better respond to variable renewable inputs while maintaining reliability, cost-effectiveness, and sustainability.

2.4.3 Examples Of Hybrid Systems

Hybrid energy systems have been successfully implemented in various real-world scenarios, showcasing their versatility and efficiency in different environments. One notable example is the Solar-Wind-Battery System deployed in a remote town, where solar panels and wind turbines were combined to ensure a continuous energy supply. Solar energy provided power during daylight hours, while wind turbines operated at night or during cloudy conditions. Excess energy generated from both sources was stored in batteries, offering reliable and uninterrupted electricity for the isolated community (Jones et al, 2020). Another case involved an industrial building that integrated solar thermal collectors with battery storage to optimize overall energy use. The solar thermal system captured heat for immediate operational use or for storage, while the battery system managed electrical energy demands. This dual approach enhanced energy efficiency and significantly reduced the facility's dependence on external power and non-renewable sources (Sharma et al., 2015). These case studies demonstrate the practical benefits of hybrid systems in improving energy reliability, efficiency, and sustainability across different sectors.

2.4.4 Challenges And Potential Solutions

Despite their many advantages, hybrid energy systems also face several challenges that must be addressed to ensure successful implementation and long-term sustainability. One major issue is the high start-up cost associated with integrating multiple technologies. The initial investment can be substantial due to the need for various components and advanced infrastructure. However, these costs can be mitigated through financial incentives, government grants, and strategic long-term planning (Aliyu et al., 2021). Another challenge lies in the complexity of technology. Coordinating different energy sources requires sophisticated control systems and skilled technical expertise. This complexity can be managed by standardizing operational procedures and investing in training programs for engineers and technicians to enhance integration and system reliability (Denholm et al, 2011). Environmental concerns also arise during the production, operation, and disposal of system components, which may contribute to pollution or resource depletion. Implementing life cycle assessments (LCA) and encouraging the use of recyclable and sustainable materials can help reduce these impacts (Zakeri et al., 2015). Lastly, grid integration remains a technical hurdle, particularly when connecting hybrid systems to conventional power grids. Compatibility issues may affect efficiency and stability. The development of smart grids that utilize real-time data and automated control can help facilitate smoother integration and improve overall grid resilience (Lukic et al., 2006). Addressing these challenges is essential for maximizing the potential of hybrid systems in advancing global energy sustainability.

2.5 GRAVITY-BASED ENERGY STORAGE (GES)

2.5.1 Gravity-Based Energy Storage (GES)

Gravity-Based Energy Storage (GES) is a mechanical energy storage method that utilizes gravitational potential energy by lifting and lowering a mass. It is increasingly being recognized as a sustainable alternative to battery-based systems due to its minimal self-discharge, long operational life, and compatibility with renewable energy systems.

Unlike chemical batteries, GES does not suffer from electrochemical degradation. This makes it ideal for long-duration energy storage applications, especially in rural or off-grid environments where battery maintenance and replacement are costly. According to Tong et al. (2022), solid gravity energy storage systems exhibit high round-trip efficiencies, ranging from 70% to 90%, depending on the configuration and mechanical conversion losses. Their ability to retain energy without active management makes them particularly suitable for elevation-based applications such as water pumping and lifting mechanisms.

Pimm et al. (2023) introduced the concept of Underground Gravity Energy Storage (UGES), which utilizes decommissioned mine shafts to store energy by lowering and raising solid masses. Their study demonstrated that UGES can retain energy over extended periods in weeks or even months with negligible storage losses, since energy is only lost during mechanical conversions.

Further supporting these findings, Lv et al. (2025) developed a capacity optimization strategy for GES in power systems. Their simulation showed that integrating GES can reduce peak-to-valley load differences by 36.1% and renewable curtailment rates by 42.3% (wind) and 18.7% (PV). Moreover, the study reported a lower levelized cost of storage compared to Compressed Air Energy Storage (CAES), highlighting GES's economic feasibility for grid and remote applications.

In conclusion, GES offers a robust and low-maintenance solution for long-duration energy storage. It reduces dependency on conventional batteries and provides high-efficiency performance with minimal energy degradation, aligning well with the objectives of this research.

2.5.2 Conditions, Location Requirements, and Design Architecture for Gravity-Based Energy Storage (GES)

The effectiveness of Gravity-Based Energy Storage (GES) depends significantly on the vertical height available, and the mass used for storage. Recent studies, such as those by Tong et al. (2022) and Elsayed et al. (2022), indicate that typical GES systems achieve optimal performance at height differences ranging between 10 and 30 meters. However, smaller-scale systems utilizing lower elevations (1.5 to 5 meters) have also proven feasible, particularly when combined with optimized mass management or advanced mechanical systems to minimize losses. Emrani et al. (2021) further validate the practicality of lower-height systems through controlled experiments demonstrating viable energy retrieval even at minimal heights.

Suitable GES locations should inherently possess adequate vertical height differences or permit easy structural modifications. Commonly identified locations in recent literature include hilly terrains or mountainous regions, naturally providing substantial elevation differences essential for energy storage (Tong et al., 2022). Other innovative implementations explored by researchers like Pimm et al. (2023) include abandoned mine shafts and underground storage facilities, where significant vertical depth facilitates substantial potential energy storage. Urban and rural built environments also present viable options; rooftop tanks or multi-storey structures can be effectively leveraged for smaller-scale systems. Emrani et al. (2021) emphasize the adaptability of GES to existing infrastructure, highlighting practicality in diverse settings ranging from urban high-rises to rural water towers.

The design architecture selected for this research integrates three core components: solar photovoltaic (PV) panels, battery storage, and gravity storage. This hybrid arrangement leverages renewable solar energy and gravitational potential energy while reducing the battery storage burden. The proposed system specifically includes a 50-Watt Solar PV panel, an 18Ah Sealed Lead-Acid (SLA) battery, and a 22-Watt DC water pump. The gravity storage component is represented by a water tank, positioned at heights varying between 1.5m, 2.5m, and 3.5m. Solar energy is first captured by the PV panel, stored temporarily in the SLA battery, and then used to operate the DC pump. The pump elevates water into the storage tank, converting electrical energy into gravitational potential energy. This stored energy is later retrieved as needed by allowing water to flow downward, driving a hydroelectric or mechanical retrieval system.

To optimize this design architecture, a structured methodology aligned with recent research recommendations was employed. Elsayed et al. (2022) utilized parametric optimization, applying the Taguchi method and Analysis of Variance (ANOVA) to identify influential parameters for GES systems, such as height, mass, and mechanical efficiencies. Drawing on similar methods, this study performs systematic variations of tank height and monitors the corresponding energy efficiency. Experimental validations are conducted in three distinct operational modes—battery-only, solar-only, and hybrid mode (solar, battery, and gravity storage combined) to quantify the effectiveness and efficiency gains of each configuration. Data collection incorporates precise instrumentation, including pyranometers for measuring solar irradiance, flow meters for quantifying water movement, and watt meters for electrical energy monitoring, a methodology aligned with procedures described by Emrani et al. (2021) and Pimm et al. (2023).

The anticipated outcomes from this methodological approach, based on recent research, include a significant reduction in battery load, thus extending battery life expectancy and efficiency. As reported by Lv et al. (2025), hybrid systems effectively minimize battery depth of discharge (DoD), potentially extending battery lifespan by approximately 15 to 30%. Furthermore, this research expects that even low-height (1.5 to 3.5 meters) systems will demonstrate notable viability and efficiency improvements if properly optimized, a prediction supported by Tong et al. (2022). Ultimately, the comprehensive design and optimization approach taken in this study aim to provide empirical evidence supporting the practical implementation of small-scale hybrid solar–battery–GES systems, particularly in rural and off-grid environments, addressing identified research gaps in current literature.

2.5.3 Challenges

While GES systems have many benefits, they also face some challenges. One significant issue is the high upfront cost of building large-scale GES facilities. GES systems often need specific locations, such as areas with natural elevation changes, to be effective. Building structures like towers or reservoirs can also be expensive and require careful planning and engineering to handle the physical stress of storing and releasing energy (Dehghani-Sanij et al., 2019). There are also challenges with space. GES systems require a lot of room, which can limit their use in densely populated or urban areas. The large structures needed for GES can be difficult to fit into locations where space is limited (Blakers et al., 2017). Lastly, building and operating GES systems can impact the environment and local communities. For example, digging deep shafts or creating large reservoirs might disrupt local ecosystems and could lead to changes in land use that affect nearby residents. Addressing these concerns is important for the long-term success of GES projects (Schmidt et al., 2017).

2.5.4 Advantages

Gravity-based energy storage (GES) systems offer a range of compelling advantages, making them an increasingly attractive option in the realm of sustainable energy storage. One key benefit is their scalability—GES systems can be designed to store varying amounts of energy, making them adaptable for both small-scale urban applications and large-scale grid infrastructure projects (Blakers, 2018). From a financial standpoint, GES systems are highly cost-effective over the long term. Unlike chemical batteries, which degrade over time and require regular replacement, GES systems involve fewer maintenance demands and lower operational costs once installed (Heindl, 2014). They are also notable for their durability and longevity, with some systems capable of functioning for over 50 years with minimal performance loss. This contrasts sharply with the limited lifecycle of traditional battery technologies, which suffer capacity degradation after repeated charging and discharging cycles (Barnhart & Benson, 2013). In terms of environmental impact, GES is particularly advantageous because it avoids the use of toxic chemicals or rare earth materials. Utilizing basic and abundant materials such as water or solid masses, these systems provide an environmentally friendly alternative to conventional storage methods (Blakers et al., 2017). Additionally, GES can be effectively integrated with other storage technologies, such as compressed air systems, to form hybrid storage solutions. This integration improves overall system reliability and energy supply stability, particularly in renewable-heavy grids (Morstyn et al., 2019). Together, these benefits highlight the potential of gravity-based storage as a robust, long-term, and sustainable energy storage solution. Here is the comparison of energy storage systems as shown in **Table 2.2**.

Table 2.2: Comparison of Energy Storage Systems

Feature	Battery Storage	Gravity-Based Energy Storage GES)
Cost	High initial and maintenance costs are incurred.	Lower costs, particularly for maintenance, are seen.
Lifespan	A limited lifespan is experienced, degrading over time.	A long lifespan with minimal degradation is provided.
Environmental Impact	A high impact is caused by materials and disposal.	A lower impact, mainly due to mechanical components, is noted.
Efficiency	Efficiency is around 75-80% due to energy losses.	Typically, high efficiency is achieved, with minimal energy loss.
Maintenance Requirements	Regular maintenance is required.	Minimal maintenance is required.
Integration with Other Systems	Moderate integration is possible.	High integration with other storage methods is possible.

2.5.5 Limitations

Despite the advantages, GES has some limitations. One of the biggest challenges is the need for specific geographical features, such as elevation differences, which restricts where GES systems can be installed. Creating artificial elevation changes or digging deep shafts may not always be practical, especially in flat or crowded areas (Heindl, 2014). Building GES systems can be expensive because of the infrastructure required. Structures like towers and reservoirs must be strong enough to handle the repeated stress of storing and releasing energy, which increases the cost (Barnhart et al, 2013). Finally, there can be environmental and social concerns. Construction may disrupt local ecosystems and cause changes in land use. The visual impact of large GES structures can also lead to opposition from communities. Addressing these issues is essential to the future success of GES projects (Schmidt et al., 2017).

2.6 EXISTING RESEARCH AND CASE STUDIES

Recent research has focused on improving how gravity-based energy storage (GES) systems manage the storage and release of energy. These systems use real-time data and smart technologies to make energy use more efficient, ensuring that energy is stored and released at the best times. For example, algorithms can predict when energy demand will be high or when renewable energy production will be low and adjust storage operations accordingly to keep the grid stable (Schmidt et al., 2017). These improvements help make GES systems more reliable and cost-effective, making them a competitive option for energy storage.

Another growing trend is combining battery storage with GES to create hybrid systems that use the strengths of both technologies. In these systems, batteries handle short-term changes in energy demand, like sudden surges or power outages, while GES provides long-term storage, releasing energy over extended periods. This approach reduces stress on each part of the system, making the whole setup more reliable and efficient. For example, when there is a lot of solar energy, the extra energy can be used to power GES by pumping water uphill, which can later be released to supplement the battery output when needed (Heindl, 2014).

2.6.1 Case Studies of Gravity-Based Energy Storage Systems

Several real-world projects have demonstrated the practical application and benefits of gravity-based energy storage (GES) systems, especially when integrated with renewable energy sources. The Linthal Project in Switzerland is a pumped hydro storage system that employs advanced technologies and smart control mechanisms to efficiently manage energy storage and release. It highlights how GES can effectively stabilize the electrical grid while complementing variable sources like solar and wind energy. Similarly, the Snowy 2.0 Project in Australia represents one of the world’s largest pumped hydro initiatives, with a storage capacity of up to 2,000 MW. This project supports national renewable energy integration by utilizing innovative materials and intelligent energy management systems to enhance storage efficiency and grid responsiveness. Another notable example is Energy Vault, a Swiss-based project that uses cranes to lift and stack heavy blocks, storing energy as gravitational potential. Unlike traditional hydro systems, Energy Vault combines solid mass-based GES with battery storage to provide a hybrid solution capable of addressing both short-term and long-term energy needs. These case studies illustrate the scalability, reliability, and technological adaptability of modern GES systems, reinforcing their critical role in advancing clean energy infrastructure.

2.6.2 Review Of Existing Research on Hybrid Energy Storage Systems

Hybrid energy systems have demonstrated high efficiency due to their ability to adapt dynamically to fluctuations in energy production and consumption. Their effectiveness lies in storing surplus energy during periods of excess generation and utilizing it when supply is low. For example, solar panels may produce more energy than needed during peak sunlight hours, and this excess can be stored in batteries or gravity-based energy storage (GES) systems for use during nighttime or cloudy conditions (Luo et al., 2015). Urban renewable energy systems are one area where hybrid configurations have proven beneficial. Research has examined the integration of thermal storage, batteries, and GES within city buildings to balance heating and cooling demands efficiently while minimizing dependence on non-renewable energy sources (Schoenung et al, 2003). Similarly, in utility-scale applications, hybrid energy systems have played a key role in stabilizing large power grids. By combining lithium-ion batteries with gravity storage, these systems are capable of handling peak energy loads and providing essential grid services, including frequency regulation and voltage stability (Sterling et al., 2015). These examples reinforce the importance of hybrid systems as versatile, scalable, and reliable solutions in the transition toward sustainable energy infrastructure.

2.6.3 Successful Case Studies of Hybrid Energy Storage Systems

Hybrid energy systems have been successfully implemented in real-world applications, demonstrating their capacity to enhance energy efficiency, reliability, and cost-effectiveness. In a remote village, a hybrid setup that integrated solar panels, wind turbines, and batteries significantly improved energy reliability while reducing operational costs. Solar panels provided power during daylight hours, while wind turbines generated electricity at night or under cloudy conditions. Excess energy was stored in batteries, ensuring uninterrupted power supply and minimizing dependence on diesel generators. Another example is an industrial facility that adopted a hybrid system using solar thermal collectors and battery storage. The system allowed the collection and storage of thermal energy for direct use, while batteries handled the electrical demand. This approach ensured steady energy availability and reduced reliance on external power sources, enhancing the overall efficiency of energy use. These case studies highlight the practical benefits of hybrid systems, particularly in optimizing energy flow and adapting to varying load demands by leveraging the complementary strengths of different energy technologies.

2.6.4 Case Studies and Real-World Applications

Installing solar hybrid systems in residential and commercial buildings has proven to be an effective way to cut energy costs and ensure reliable power. These systems, which mix solar panels with other energy generation or storage methods, help maintain a steady flow of energy. According to Jones et al (2020), buildings with hybrid systems have achieved significant energy savings and reduced their carbon footprint.

Combining battery storage with solar panels addresses the issue of inconsistent solar energy while providing a buffer to ensure a continuous supply throughout the day. This is especially useful for businesses that experience peak energy demands at different times. When solar energy production is low, stored energy from batteries can be used, and during high production, extra energy is stored for later use. This smart management cuts down on grid reliance, reducing energy bills and environmental impact (Jones et al, 2020).

Industrial sites are also adopting hybrid systems that combine battery storage with GES to handle peak energy loads and improve efficiency. This approach allows businesses to store energy during off-peak hours and use it when demand is high, saving costs by avoiding expensive energy grid during peak times. A study by MS Reza et al. (2024) found that facilities using these systems saw improved efficiency and significant cost savings.

The use of large-scale battery systems is becoming essential for grid stability and supporting the growth of renewable energy sources. As the use of variable renewable energy like wind and solar continues to grow, batteries are crucial for balancing grid supply and demand. According to Aliyu et al. (2021), integrating battery storage greatly improves grid stability and helps support the integration of renewables.

These battery systems can store extra energy produced during high production times and release it when demand is high, or production is low. This helps smooth out the variability of renewable sources and supports the grid during peak demand, reducing the need for fossil fuel-based power plants and encouraging a cleaner energy mix (Aliyu et al., 2021).

2.7 RESEARCH GAP

Previous studies have extensively investigated energy storage solutions utilizing either solar photovoltaic (PV) systems combined with chemical batteries or stand-alone gravity-based energy storage (GES). However, a comprehensive review of existing literature reveals that these studies typically treat these technologies separately, rather than exploring their integration into a cohesive hybrid system. Most gravity-based energy storage research, such as those conducted by Tong et al. (2022) and Pimm et al. (2023), focus predominantly on large-scale applications involving significant elevation differences, usually exceeding 10 meters. Consequently, there is limited exploration of GES at low elevation (below 5 meters) in small-scale hybrid applications that integrate solar PV and battery storage, despite the significant practical relevance to rural or off-grid regions where space and elevation might be limited.

This identified gap highlights a notable absence of research specifically targeting the optimization of small-scale, hybrid solar battery GES systems. The significance of optimizing GES in such hybrid setups lies in the potential benefits of significantly reducing battery reliance, enhancing battery lifespan through reduced depth of discharge (DoD), and improving overall energy efficiency of the system. Furthermore, optimizing GES parameters such as tank elevation, pump sizing, energy conversion efficiency, and control mechanisms is essential to realizing the full potential of these hybrid systems. Recent works by Lv et al. (2025) and Elsayed et al. (2022) underline the importance of optimizing system parameters through experimental validation and parametric analysis, reinforcing the need for such research in hybrid configurations.

Given this gap, the primary aim of this research is to address the need for integrating and optimizing solar PV, battery storage, and gravity-based energy storage into a single, optimized hybrid energy system suitable for practical implementation at lower elevations.

Firstly, this study aims to design and optimize a hybrid energy storage system that integrates solar photovoltaic (PV), sealed lead-acid (SLA) battery storage, and gravity-based energy storage (GES), evaluating overall system performance and energy efficiency under real-world operating conditions. This involves developing an integrated experimental setup, testing different operational configurations (battery-only, solar-only, hybrid mode), and systematically varying critical parameters such as tank elevation and flow rate.

Secondly, it seeks to experimentally determine the optimal operational parameters required for maximizing system efficiency and minimizing energy losses in small-scale hybrid systems. Specifically, this includes identifying optimal elevation heights within the tested range (1.5m–3.5m), appropriate pump power, battery operating conditions, and ideal flow rate for the gravitational storage element. These parameters are determined through structured experimental validation using instruments such as pyranometers, watt meters, and flow meters, following methodologies recommended by recent research (Emrani et al., 2021; Elsayed et al., 2022).

Finally, this research aims to analyze and validate the long-term performance, improved battery lifespan, and operational reliability of the optimized hybrid solar–battery–GES system. By evaluating key performance metrics over extended experimental periods, this study will provide practical insights and empirical evidence to support the real-world application of such hybrid systems, particularly in rural and off-grid scenarios. Ultimately, this objective aligns with the global shift toward sustainable, renewable energy solutions and addresses critical energy storage challenges identified in recent literature.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter explains the research methods used to test and improve a solar hybrid gravity system that includes battery storage. The goal is to find the best way to use solar energy for lifting water or other materials, which can be useful in agriculture, household water supply, and industry. The methodology covers how the experiments were designed, how data was collected, and how the results were analyzed to make the system more efficient.

The main aim is to check the reliability, efficiency, and durability of combining solar power, battery storage, and gravity-based energy storage into one system. By using this combination, the study hopes to create a setup that is both effective and long-lasting. The system is tested for different purposes, like pumping water for irrigation or supplying water to homes.

To meet these goals, the study uses a small-scale prototype that relect to real-life conditions. The experiments are done in a controlled setting where key factors can be adjusted to see how they affect the system's performance. Different setups of solar panels, batteries, and gravity-based storage are tested under various conditions to find the best combination.

The setup includes a sealed lead-acid (SLA) battery, a solar photovoltaic (PV) system, and a water pump connected to a gravity storage tank. The system collects energy from the sun, stores it in the battery, and uses it to pump water to different heights. By changing the height of the water tank and the way the system parts are arranged, the study aims to find the most efficient and affordable way to use solar energy for elevation tasks.

Collecting data is a key part of research. Sensors and data loggers are used to monitor solar energy, battery voltage and current, water flow rate, and energy usage. These readings are taken regularly to ensure the data is accurate and reliable. The data is then analyzed using computer models and statistical tools to understand how well the system works and to identify trends or patterns.

The analysis includes calculating efficiency, checking the balance of power and energy, and using advanced modeling to improve the system's performance. These methods help to see how different setups and operating conditions affect the system's reliability and efficiency. The results will guide future improvements.

The study also looks at external factors that might affect system performance, like weather, changing energy demands, and seasonal variations. By simulating these conditions in the experiments, the research aims to give a full understanding of how the system performs in different situations.

Beyond the technical aspects, the study also considers the environmental and economic benefits of using hybrid energy systems. A cost-benefit analysis is done to compare the initial investment and running costs of the hybrid system with other energy options. Additionally, the study looks at the environmental impact by measuring how much carbon emissions and other pollutants are reduced by using renewable energy.

3.2 RESEARCH DESIGN

The research uses an experimental testing method, which is ideal for studying how technological systems perform and finding ways to improve them. This approach is useful because it allows researchers to carefully control different factors and collect data in a systematic way. By doing this, it is possible to test ideas and draw clear, well-supported conclusions.

Experimental research is especially effective in engineering because it helps assess how different setups and operating conditions impact system performance. By adjusting specific variables, this method provides important insights into the efficiency, reliability, and optimization of the systems being studied. This makes it easier to see which configurations work best and how to improve the overall system.

3.2.1 Types Of Experiments Conducted

3.2.1.1 Efficiency Testing

The efficiency test is designed to evaluate how effectively the solar hybrid gravity system transforms solar energy into mechanical work, specifically in the form of pumped water. The primary metric used is the ratio of the volume of water pumped (in liters) to the energy consumed (in watt-hours), represented as L/Wh. This metric provides a straightforward means of comparing the system's performance under varying operational conditions.

The first phase involves establishing baseline efficiency measurement. This is conducted by operating the water pump using energy stored in the sealed lead-acid (SLA) battery, which has been charged by the solar photovoltaic (PV) system. The amount of water pumped at predefined elevation heights is recorded to determine the base performance level of the system under standard operating conditions. This step sets the benchmark for assessing the impact of later modifications or environmental factors.

Next, variable configurations are introduced to examine how different operating conditions affect system efficiency. One of the main variables is elevation height. The water pump is tested at incremental heights of 1.5m, 2.0m, 2.5m, 3.0m, and 3.5m. This allows the investigation of the relationship between pumping height and energy consumption. The second variable is solar irradiance, which is measured using a pyranometer during the tests. Testing under different sunlight intensities helps determine how fluctuations in solar energy input influence energy generation and efficiency. Lastly, pump operating conditions are varied by adjusting power input levels. This provides insights into optimal pump performance parameters and how power settings influence both energy use and water delivery.

Throughout each experimental run, data collection is conducted using precision watt meters and flow meters. The parameters recorded include voltage (V), current (A), power (W), total energy consumed (Wh), and the total volume of water pumped (L). This ensures accurate tracking of energy input and mechanical output under each test condition.

Finally, the analysis phase involves processing the collected data to compute the system's efficiency for each configuration using the L/Wh formula. Statistical techniques such as regression analysis and variance analysis are employed to identify significant differences and trends across the different configurations. The results are used to determine which variables have the most impact on performance and to propose recommendations for optimizing the system's design for improved energy efficiency.

3.2.1.2 Battery and Solar Integration Testing

The integration of battery storage with solar panels is a key component in enhancing the performance of hybrid solar-gravity systems. This section evaluates the system's efficiency based on charging and discharging cycles, voltage stability, and the influence of solar irradiance. These assessments help identify how well energy is managed between the solar photovoltaic (PV) panels and the Sealed Lead-Acid (SLA) battery under different conditions.

The first focus is on battery charging cycles. The SLA battery is partially charged at the beginning of each test, and the time, current, and energy (Wh) required to reach full charge are recorded to establish a baseline. Charging efficiency is then tested under varying solar irradiance conditions, which are simulated by adjusting panel exposure and considering daily weather variations. During this process, voltage and current are monitored continuously using watt meters to ensure safety and prevent overcharging. This is vital to maintaining the battery's health and preventing potential performance degradation or failure over time.

The battery discharging process is tested by operating the water pump at multiple power levels to observe discharge behavior. Discharge rates are correlated with pump power demands to understand energy drain profiles. The battery is also discharged to various Depths of Discharge (DOD) at 50%, 80%, and 95% to investigate the effects on energy delivery efficiency and long-term battery health. The total energy output during discharge is compared to the energy input during charging to calculate round-trip efficiency, which helps identify storage-related energy losses.

The performance of the solar PV panels is analyzed in terms of energy generation under real-time irradiance conditions. A pyranometer is used to measure solar irradiance throughout the testing period. These readings are correlated with power output from the panels to assess conversion efficiency. The panels are also tested at different tilt angles and orientations to identify the optimal configuration for maximum energy generate.

Finally, integrated system testing evaluates the solar PV and battery setup under continuous operation. The system is run across several days to simulate real-world scenarios and changing environmental conditions. Voltage levels and power delivery stability are monitored to ensure the system responds well to variable sunlight and demand. Overall energy efficiency is calculated by comparing the total solar input and battery storage to the useful work performed measured as water volume pumped providing a comprehensive understanding of system performance and potential areas for optimization.

3.2.2 Experimental Variables

In this research, the performance and efficiency of the solar hybrid gravity energy storage system are evaluated through a structured analysis involving independent, dependent, and control variables. This classification ensures clarity in understanding how specific experimental conditions influence system behavior and performance metrics.

The independent variables are those systematically altered during the tests to examine their impact on system output. One of the key variables is elevation height, where the system is evaluated at different levels to 1.5 m, 2.0 m, and 2.5 m and to determine how gravitational potential influences energy consumption and pumping efficiency. Another important variable is solar irradiance, which fluctuates throughout the day. Using a pyranometer, different sunlight levels are recorded and analyzed to understand their effect on the charging capability of the solar PV system. Lastly, pump operating conditions are modified by adjusting power settings, allowing observation of how flow rate, power demand, and overall efficiency change with different loads.

The dependent variables are the measurable outcomes influenced by the independent variables. One of the primary metrics is energy efficiency, calculated in liters per watt-hour (L/Wh), indicating how effectively the system converts electrical energy into useful pumping output. Battery charge and discharge rates are also recorded, helping evaluate how battery behavior responds to varying conditions of irradiance and load. System stability, particularly voltage consistency during operation, is another critical dependent variable, providing insight into system robustness under real-time load and environmental changes.

To ensure the validity and reliability of the experiment, several control variables are maintained constantly. These include the type of battery—a Sealed Lead Acid (SLA) battery is used uniformly across all trials to avoid inconsistencies in energy storage behavior. Similarly, the solar panel specification remains fixed, using the same 50-Watt module throughout the tests. Finally, the testing environment is controlled to minimize the influence of external variables such as temperature fluctuations or equipment interference, thereby improving the accuracy and reproducibility of the results.

3.2.3 Experimental Procedure

The experimental procedure outlines the steps involved in setting up and testing the solar hybrid gravity system to evaluate its performance under various configurations. The process begins with the system setup, where the solar PV panels, sealed lead-acid (SLA) battery, DC water pump, and gravity-based storage (elevated water tank) are installed. The water tank is mounted at varying heights to study the influence of elevation on energy usage. Measurement devices such as watt meters, flow meters, and pyranometers are strategically placed to record key parameters, including voltage, current, power consumption, and water flow rate.

Next is the baseline testing, where the system operates under standard conditions. The solar panels charge the battery, and the battery then powers the water pump. The volume of water pumped, and the associated energy use are recorded at a standard elevation to establish reference efficiency levels. Parameters such as voltage, current, and water volume are measured to serve as a benchmark for later comparisons.

Variable testing follows, where only one independent variable is changed at a time to isolate its effect. First, elevation heights ranging from 1.5 meters to 3.5 meters are tested to examine how gravitational potential influences efficiency. Then, solar irradiance levels are varied to simulate different weather conditions and to observe how sunlight intensity affects energy input and system performance. Additionally, the water pump operates at different power levels to understand how pump settings influence overall energy usage and water output.

During each test, data collection is performed systematically using the installed sensors. Important metrics recorded include voltage (V), current (A), power (W), energy consumed (Wh), water volume pumped (L), and solar irradiance levels (W/m^2). Data is captured at consistent intervals to ensure reliability and enable comparative analysis.

The system is also subjected to long-term testing by running continuously over several days. This simulates real-world usage and allows assessment of the system's durability and consistency under changing environmental conditions, particularly variations in sunlight and load demands.

In the data analysis phase, the collected data is processed to compute efficiency values in L/Wh for each test condition. Statistical techniques, including regression analysis and trend identification, are applied to evaluate the influence of different variables and to determine the optimal setup for maximum energy efficiency and system stability.

Finally, documentation of all experimental results, challenges encountered, and observations is completed to ensure transparency and reproducibility. This record serves as a reference for future improvements and confirms the validity of the findings in supporting the hybrid solar-gravity energy system design.

3.3 EXPERIMENTAL SETUP

The hybrid design optimization method adopted in this study involves systematic experimental trials and parametric analysis, guided by established methodologies from recent literature (Elsayed et al., 2022; Lv et al., 2025). Initially, the system operates in three distinct modes battery-only, solar-only, and hybrid mode to generate comparative performance data (see **Figure 3.1 and Table 3.1**). Each operational mode is tested under varying tank heights (1.5m, 2.5m, and 3.5m) to determine the optimal height for gravitational energy storage in the given small-scale scenario.

During the experimental trials, critical performance parameters such as solar irradiance, battery voltage and depth of discharge (DoD), water flow rate, and energy consumption are continuously measured at 15-minute intervals using specialized sensors and meters. This precise instrumentation allows accurate data collection for subsequent detailed analysis.

The collected data is analyzed to identify energy efficiency trends, quantify battery usage reductions, and calculate total energy losses. The analysis employs parametric optimization methods including Taguchi methodology, aligning with approaches suggested by Elsayed et al. (2022). These methods identify key parameters such as tank height, battery DoD, and water pump energy consumption that significantly influence overall system performance.

The optimization process concludes with the identification of optimal operational conditions that maximize system efficiency, minimize energy losses, and extend battery lifespan. Specifically, optimization results determine the best combination of tank height and operational mode that ensures minimal battery load, efficient solar utilization, and effective gravity storage performance.

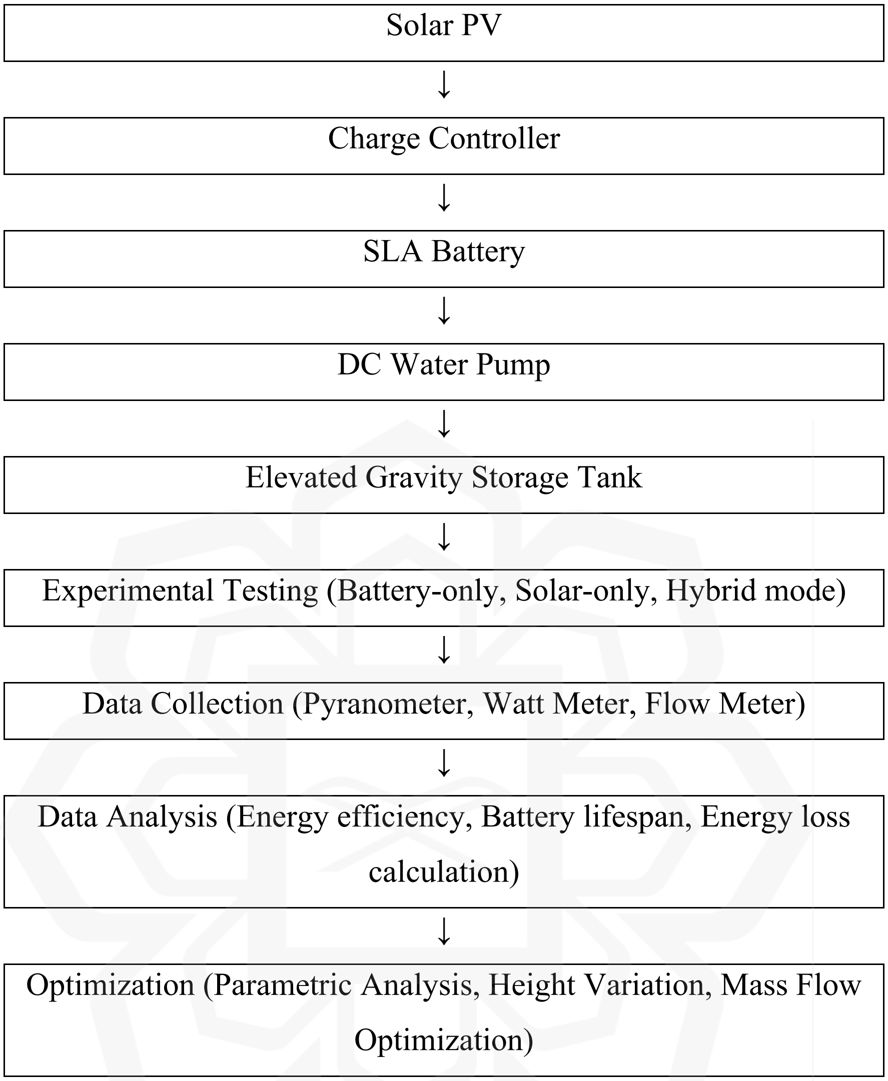

Figure 3.1: the step-by-step process from initial system configuration through experimental phases to data analysis and optimization stages.

Table 3.1: Detailed Experimental Setup Configurations

Configuration Parameters	Details / Specifications
Solar PV panel	50-Watt
Battery	18Ah, Sealed Lead-Acid (SLA) Battery
Charge Controller	PWM Controller (12V/10A)
DC Water Pump	22-Watt, DC powered
Elevated Gravity Tank	Heights: 1.5m, 2.5m, 3.5m
Testing Modes	Battery-only, Solar-only, Hybrid mode
Solar Irradiance Sensor	Pyranometer
Electrical Measurement	Watt meter (Voltage, Current, Power)
Flow Measurement	Digital Flow Meter
Testing Period	7 days continuous for each mode
Data Collection Interval	Every 15 minutes
Parameters Recorded	Solar irradiance, Battery Voltage & Current, Water Flow Rate, Energy Consumed

The setup includes several key components. A 50-watt monocrystalline solar panel with dimensions of 1580mm × 808mm × 35mm is used to collect sunlight. The energy is stored in an 18Ah, 12V lead-acid battery. A 20-watt submersible DC water pump is used to lift the water, and a 50-liter plastic tank holds the water during the tests. The whole system is supported by an elevator structure measuring 900mm in length, 500mm in width, and 3500mm in height, with the ability to lift a maximum of 10kg.

During the experiment, water is pumped to various elevation heights and allowed to flow back, simulating energy storage and release cycles. This helps determine how effectively the system uses solar energy and how much energy is required to lift the water. In this test, the independent variables are the factors that are changed to observe their effect. These include the elevation height (tested at 1.5m, 2m, 2.5m, 3m, and 3.5m), the solar irradiance levels which vary based on sunlight conditions, and the battery charge and discharge cycles. The dependent variables are the results measured during the experiments. These include the volume of water pumped (in liters), the amount of energy consumed (in watt-hours), the voltage, current, and power readings, and the overall system efficiency, which is calculated in liters per watt-hour (L/Wh).

The control variables are kept constant throughout the experiments to ensure consistent and fair testing. These include the water source, which remains the same for all tests to prevent changes in water properties from affecting results, and the environmental conditions such as temperature, humidity, and air pressure, which are maintained at steady levels during all testing sessions.

The experiment used five data loggers: a pyranometer, a flow meter, and three-watt meters (see **Figure 3.2**). The flow meter tracked how much water was pumped to Circulation Water Tank 1. Water was moved from Circulation Water Tank 2 back to Tank 1 by a 22-watt submersible pump. The pyranometer measured sunlight levels and was placed near the solar panel.

The setup included a 12V SLA (18Ah) battery and a solar charger connected to a 50-watt solar panel producing 18V. Water was pumped to raise the level in Circulation Water Tank 1 using Water Hose 1, while Water Hose 2 brought water back to Tank 1. Three-watt meters monitored the Solar PV, the SLA (18Ah) battery, and the water pump.

For optimal energy capture, the 50-watt solar panel was positioned to get maximum sunlight throughout the day (see **Table 3.2**). The solar processor managed power for charging the SLA battery and running the 22-watt water pump. Watt Meter 1 was connected to the solar panel, Watt Meter 2 to the battery, and Watt Meter 3 to the water pump. Any extra power generated by the solar panel was stored in the SLA battery.

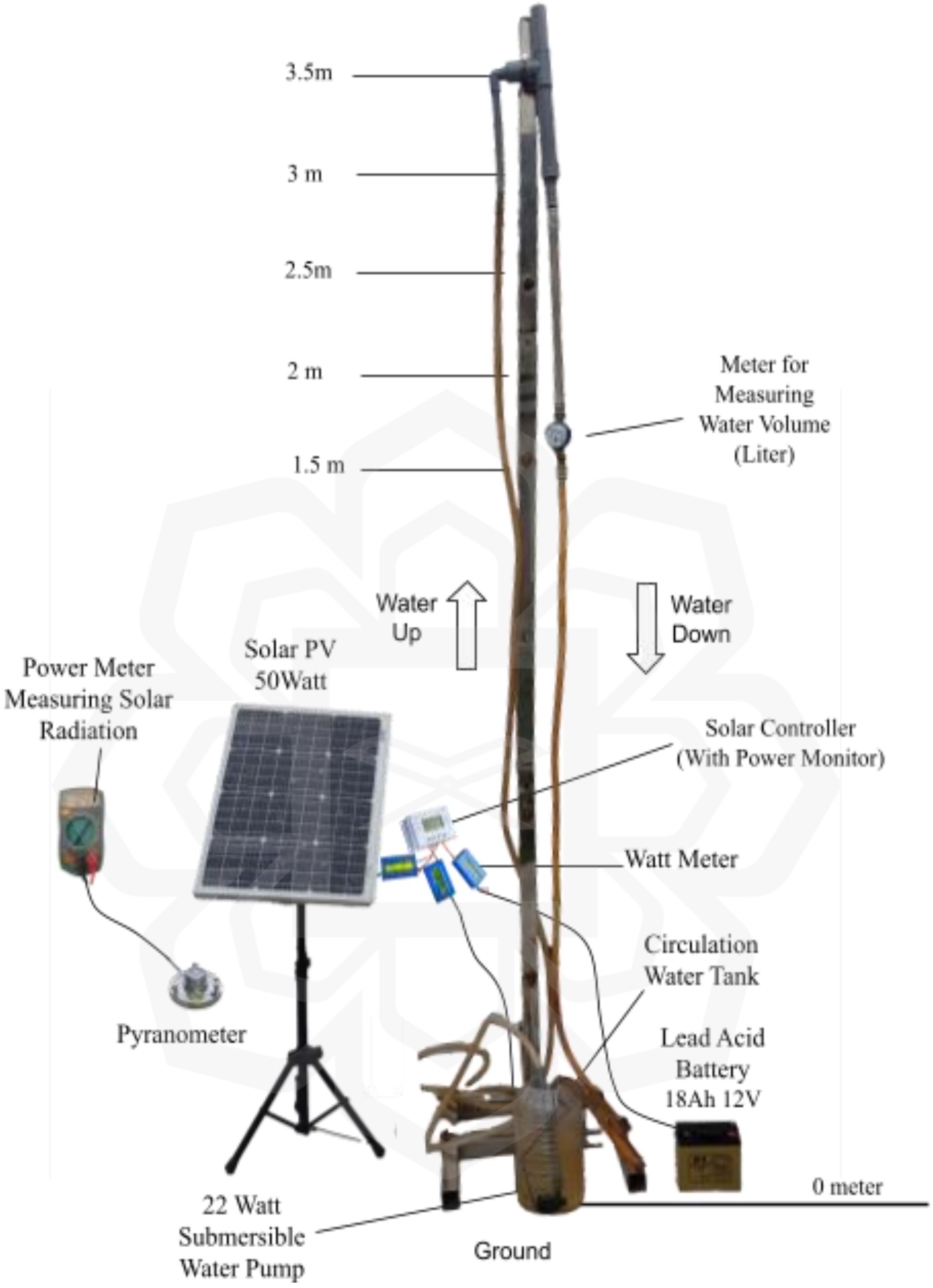

Figure 3.2: Device and Apparatus

Table 3.2 : Device and Apparatus

No.	**Device / Apparatus**	**Description / Function**
1	Solar PV 50-Watts	Positioned for maximum sunlight exposure to capture the most solar energy throughout the day.
2	Pyranometer	Measures the amount of solar radiation (sunlight) hitting the solar panel.
3	Solar Controller	Manages and regulates power to charge the SLA battery and operate the 22-watt water pump.
4	Watt Meter 1	Connected to the Solar PV panel to monitor power output.
5	Watt Meter 2	Connected to the SLA (18Ah) battery to monitor battery charge and discharge.
6	Watt Meter 3	Connected to the 22-watt water pump to measure power consumed by the pump.
7	Sealed Lead Acid (SLA) Battery (18Ah)	Stores excess solar energy produced by the panels for later use.
8	22-Watt Water Pump	Use energy from the battery to pump water from the lower tank to the higher tank.
9	Circulation Water Tank 1	The upper tank where water is pumped, storing it at a higher level for gravitational energy.
10	Circulation Water Tank 2	The lower tank that collects water returned by gravity from Tank 1.
11	Water Flow Meter (L/min)	Measures how much water is moved and stored in the tanks (in liters per minute).
12	Water Hose 1	Connects the pump to Circulation Water Tank 1 for water delivery upward.
13	Water Hose 2	Connects Circulation Water Tank 1 to Tank 2 for water return by gravity.

In the setup (as shown in **Figure 3.3**), the Solar PV 50-watt panel is used to charge the SLA (18Ah) battery and directly power the 22-watt water pump to send water to Circulation Water Tank 1. In this experiment, the water tank is placed at different levels (1.5m, 2.0m, 2.5m, 3.0m, and 3.5m) and water is stored in Circulation Water Tank 1. This tank serves as temporary storage to simulate gravity energy storage. The capacity of the water tank is measured using a Water Flow Meter.

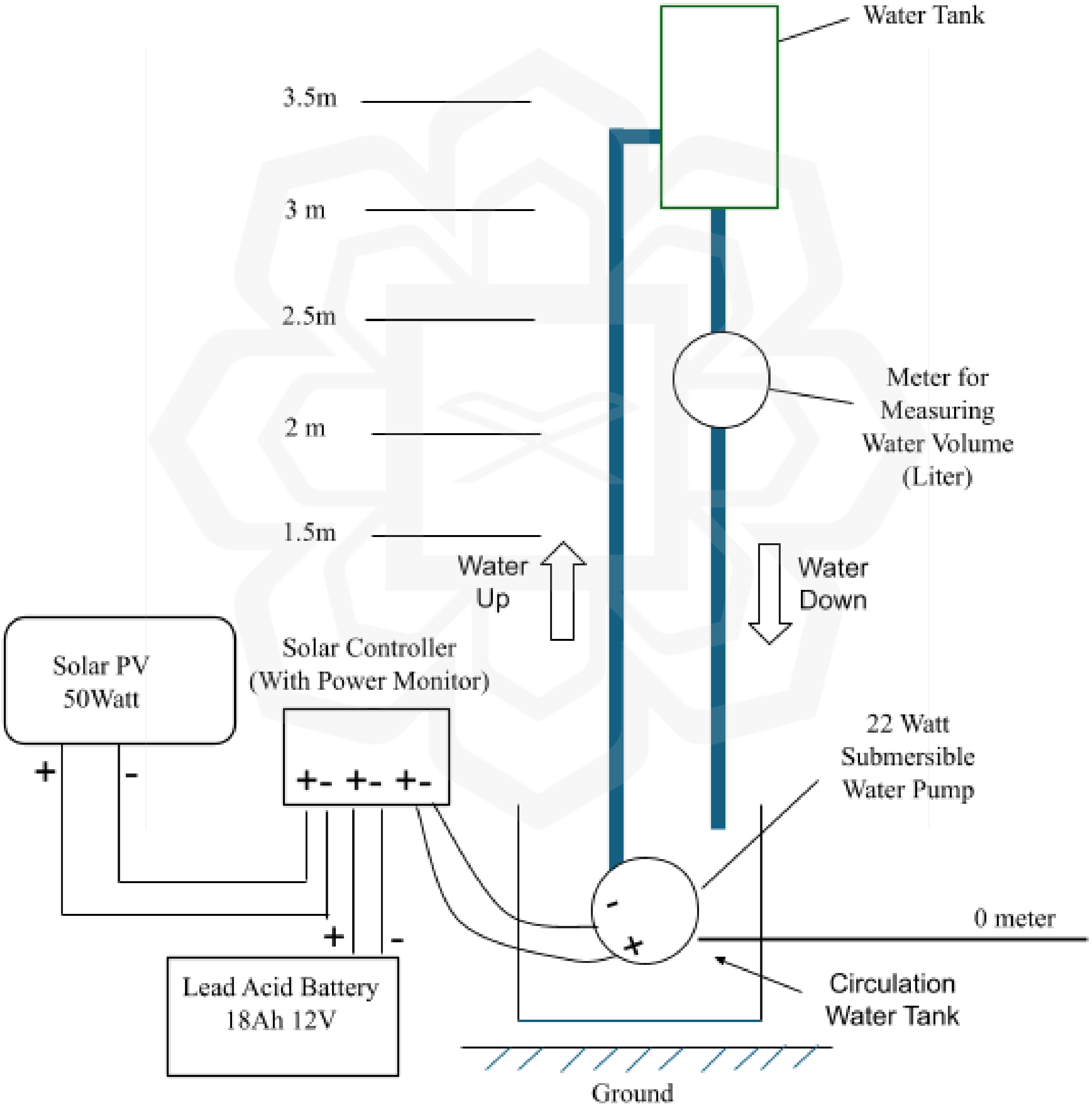

Figure 3.3: Schematic diagram of the experimental setup

3.4 DATA COLLECTION METHODS

For this project, the data collection process was divided into three main steps, with each step focusing on a different set of measurements.

3.4.1 Energy Consumption by Battery as Energy Storage

The first step was to use a fully charged SLA (18Ah) battery to measure how much energy the 22-watt water pump uses. The battery was fully charged to 12.5V using a charger. At different heights (1.5m, 2.0m, 2.5m, 3.0m, and 3.5m), the 22-watt water pump kept pumping water to Circulation Water Tank 1. To avoid over-draining, the voltage was monitored until it dropped to 11V (95% DOD). Key measurements included voltage (Volts), current (Amperes), power (Watts), and energy (Watt-hours). The data was recorded every 15 minutes and analyzed over a 60-minute period. Every 15 minutes, the amount of water flow (in liters) was also measured. This information will help determine how well and efficiently the battery works at different heights.

3.4.2 Energy Consumption by Solar to Water Pump Directly System

The second step was to use a 50-watt Solar PV panel (18 volts) to directly measure how much energy the 22-watt water pump uses. The solar PV panel powers the pump based on the amount of sunlight. To ensure the Solar PV was set up to get maximum sunlight, a pyranometer was used to measure solar radiation (SR). The 22-watt water pump needs a minimum level of solar radiation to work properly, but not so much that the voltage goes too high and damages the pump. It was found that the minimum SR needed was 300 W/m². The pump motor uses 6.57 watts to pump water from a height of 3 meters, so the angle of the solar panels was regularly adjusted to capture the most energy. For the pump to keep working efficiently, the panels' slopes had to be adjusted often (Ghosh et al., 2020; Shahsavari et al., 2018).

The motor's maximum power output was 24.32 watts, which allowed the pump to deliver water at a rate of 11.0 L/min. At a height of 3 meters, the 22-watt pump kept running, sending water to Circulation Water Tank 1. Key measurements included solar radiation (W/m²), pump power (Watts), water volume pumped (Liters), voltage (Volts), current (Amperes), power (Watts), and energy (Watt-hours). The data was recorded every 15 minutes and analyzed over a 60-minute period. Every 15 minutes, the water flow (in liters) was also measured. This will help understand how direct solar power works for running the pump under different sunlight conditions.

3.4.3 Hybrid Energy System at 3 Meter Elevation Under Solar Radiation

The third step was to test how well the Solar Hybrid Gravity System with Battery Energy Storage works. Figure 1 shows the full setup, including a 50-watt solar panel, an 18Ah SLA battery, and a 22-watt water pump. The system also included a pyranometer, a solar controller, two circulation water tanks, a water flow meter, and a watt meter. The experiment started with the SLA (18Ah) battery at a 5% state of charge (SOC) and an initial voltage of 11V, meaning it was only partly charged. The solar controller stores any extra energy for the SLA battery.

The Solar PV can produce up to 50 watts of power, depending on how much solar radiation (SR) it receives. A pyranometer was used to measure the solar radiation and ensure the Solar PV was set up to get the most sunlight. The 22-watt water pump, powered by the SLA battery, was used to continuously pump water to Circulation Water Tank 1 at a height of 3 meters.

Data was collected over seven days, including the battery's state of charge (%), voltage (Volts), current (Amperes), power (Watts), energy (Watt-hours), solar radiation (W/m²), and the amount of water pumped (Liters). This data will be used to understand how much energy is stored in the battery and how efficiently the system works, by calculating the energy needed to fill the Circulation Water Tank 1 at 3 meters. This information will help determine how the hybrid system can best store energy using gravity to power the 22-watt water pump under different solar conditions.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 INTRODUCTION

This chapter shows the outcomes of the tests that were done to see how well and how to make the solar hybrid gravity system work best when combined with battery energy storage for elevation uses. The information gathered from different heights and weather situations is studied to learn more about the system's usefulness, dependability, and efficiency. The discussion explains these results by looking at the study goals and other research that has been done.

4.2 EXPERIMENTAL RESULTS

4.2.1 Water Pump with Battery In 1.5 Meter

The experiment carried out at a height of 1.5 meters yielded valuable insights into the efficiency and functionality of the solar hybrid gravity system integrated with battery energy storage. Over a period of 553 minutes, the system successfully pumped a total of 6,129.5 liters of water, as detailed in **Table 4.1**. This steady output demonstrates reliable performance at the specified elevation.

Table 4.1: Water pump using battery in Height 1.5 Meter and Full Charge

No.	Time (min)	Volume (Liter)	Energy (Wh)	Voltage (V)	Current (A)	Power (Watt)
Start	0	0.0	0.0	12.75	1.58	20.15
1	60	637.5	19.3	12.50	1.54	19.25
2	120	1270.7	38.1	12.30	1.52	18.70

3	180	1898.6	56.4	12.15	1.50	18.23
4	240	2526.5	74.6	12.00	1.48	17.76
5	300	3179.1	92.1	11.90	1.50	17.49
6	360	3831.7	109.5	11.80	1.46	17.23
7	420	4566.5	125.0	11.63	1.40	16.74
8	480	5264.5	142.7	11.38	1.40	16.04
9	540	5973.5	158.4	11.15	1.38	15.39
10	553	6129.5	161.8	10.99	1.36	14.95

As illustrated in **Figure 4.1**, the power output started at 20.15W and gradually decreased to 14.95W by the conclusion of the experiment. This gradual decline corresponds with variations in voltage and current, reflecting the ongoing use of energy stored in the battery. The consistent power levels throughout the experiment indicate that the system is well-suited for water pumping applications requiring reliable, long-duration performance.

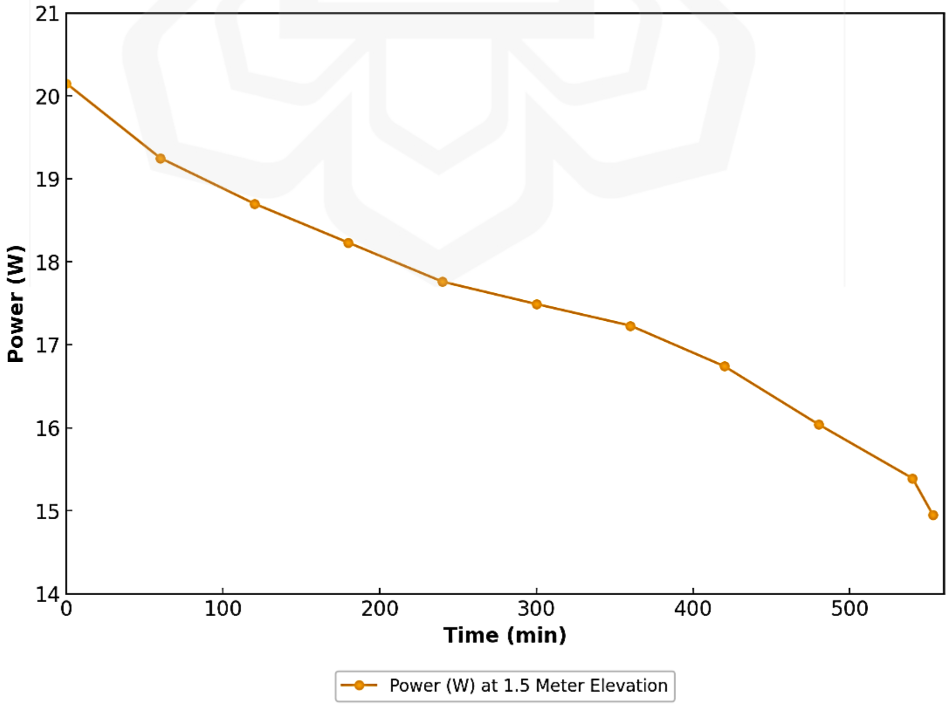

Figure 4.1: the relationship between Power and time

Figure 4.2 shows a noticeable peak at 12V during the initial operating phase when the height of the elevated tank is set at 1.5 meters. This peak does not appear in subsequent tests at 2.0 meters and above. The peak at 12V is primarily due to low hydraulic resistance and minimal gravitational load at the 1.5-meter height. During the early stage of pump activation, the system encounters less backpressure from gravity, allowing the battery to supply a stable and nearly full terminal voltage. The pump experiences minimal load, resulting in lower current draw, which temporarily sustains the voltage at near 12V before any significant voltage drop occurs.

In contrast, at heights of 2.0 meters and beyond, the gravitational resistance increases, which in turn causes the pump to draw higher current to push water upwards. This increased load results in earlier voltage drops below 12V, thus eliminating the peak pattern seen at 1.5 meters.

This observation aligns with standard battery behavior under load variation (Reza et al., 2024), where voltage is sustained longer under low load but declines faster when the load increases. illustrates a gradual decline in voltage, from 12.75V to 10.99V, alongside a decrease in current, from 1.58A to 1.36A. These trends indicate a consistent discharge pattern from the battery, ensuring smooth operation of the water pump without significant power fluctuations. Maintaining stable voltage and current levels is crucial for the effective performance of the system throughout the testing period.

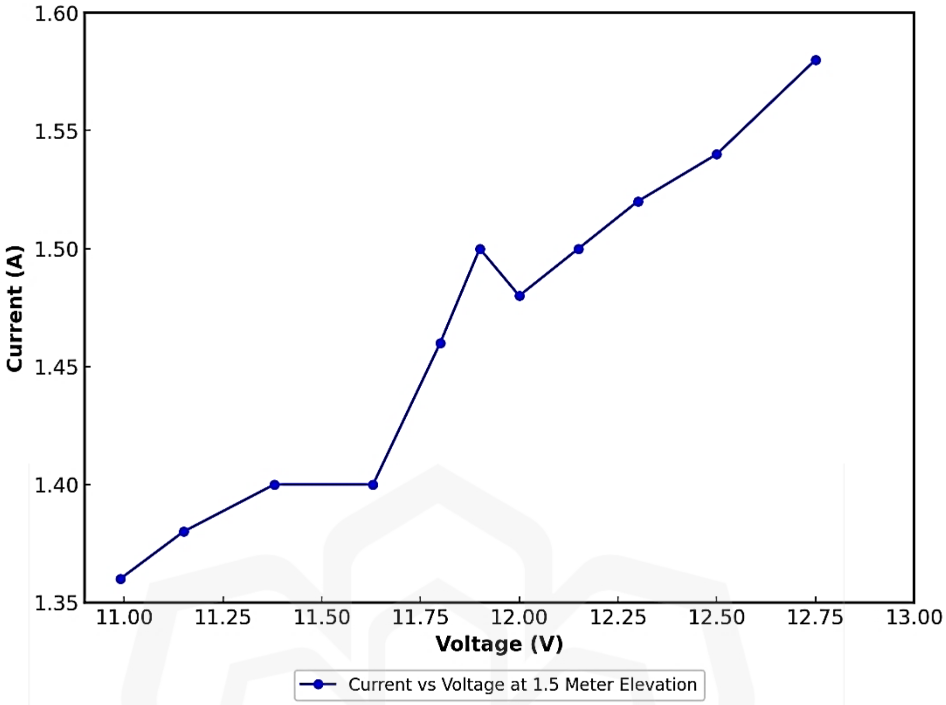

Figure 4.2: the relationship between current and voltage

Figure 4.3 presents the system's energy consumption, which gradually rose from 0 Wh at the beginning to 161.8 Wh by the end of the experiment. This upward trend indicates the continuous operation of the water pump, demonstrating the system's capability to efficiently pump large volumes of water while maintaining consistent energy usage. The overall efficiency was calculated at 37.89 L/Wh, highlighting the system's high performance at an elevation of 1.5 meters.

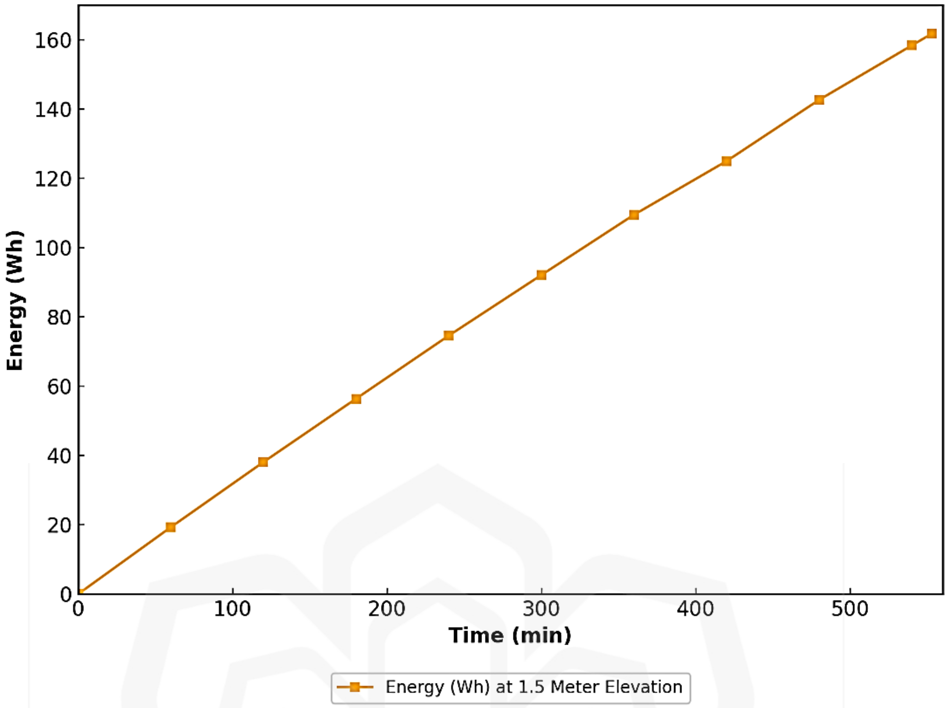

Figure 4.3: the relationship between energy and time

The solar hybrid gravity system, integrated with battery energy storage, demonstrated strong performance at an elevation of 1.5 meters, efficiently pumping significant volumes of water with minimal energy usage. Achieving an efficiency of 37.89 L/Wh, the system effectively transported large amounts of water while consuming less energy. The stable trends in voltage, current, and power further highlight the system's reliability, making it a suitable option for water pumping applications at this height.

4.2.2 Water Pump with Battery In 2 Meter

The experiment conducted at an elevation of 2 meters provided further insights into the performance of the solar hybrid gravity system with battery storage at greater heights. As shown in **Table 4.2**, the system pumped 5,500 liters of water over a period of 580 minutes. This slightly lower output, compared to the 1.5-meter elevation, indicates that higher energy consumption is required at increased elevations.

Table 4.2: Water pump using battery in Height 2 Meter, Full Charge

No.	Time (min)	Volume (Liter)	Energy (Wh)	Voltage (V)	Current (A)	Power (W)
Start	0	0	0.0	12.76	1.49	19.01
1	60	597	17.9	12.43	1.43	17.77
2	120	1187	35.4	12.25	1.41	17.27
3	180	1776	52.9	12.07	1.39	16.78
4	240	2366	69.3	11.93	1.37	16.34
5	300	2924	85.1	11.79	1.35	15.92
6	360	3491	100.8	11.68	1.33	15.53
7	420	4058	116.4	11.55	1.31	15.13
8	480	4622	131.7	11.39	1.29	14.69
9	540	5158	149.5	11.20	1.25	14.00
10	580	5500	160.5	11.00	1.22	13.42

The data indicates that energy consumption began at 0 Wh and rose to 160.5 Wh by the end of the 580-minute period, resulting in an efficiency of approximately 34.28 L/Wh. This efficiency is slightly lower than the 37.89 L/Wh observed at 1.5 meters, highlighting the impact of increased elevation on energy usage and overall system efficiency.

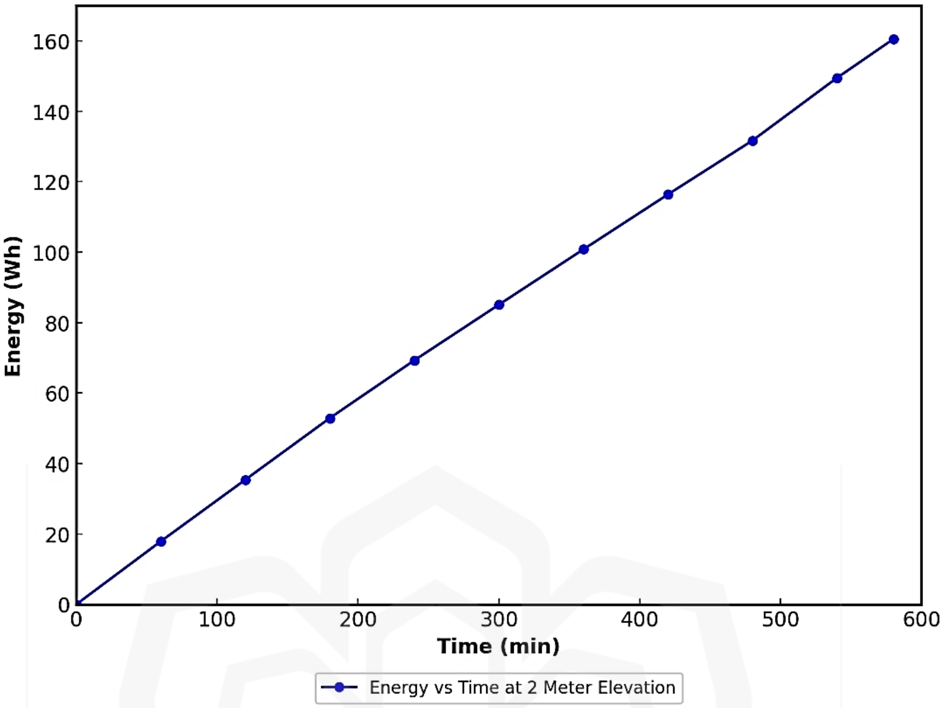

Figure 4.4: the relationship between energy and time

Energy consumption rose from 0 Wh to 160.5 Wh by the end of the experiment, leading to an efficiency of about 34.28 L/Wh, as illustrated in **Figure 4.4**. This is slightly lower than the 37.89 L/Wh was achieved at 1.5 meters, indicating that higher elevations demand more energy, resulting in reduced efficiency.

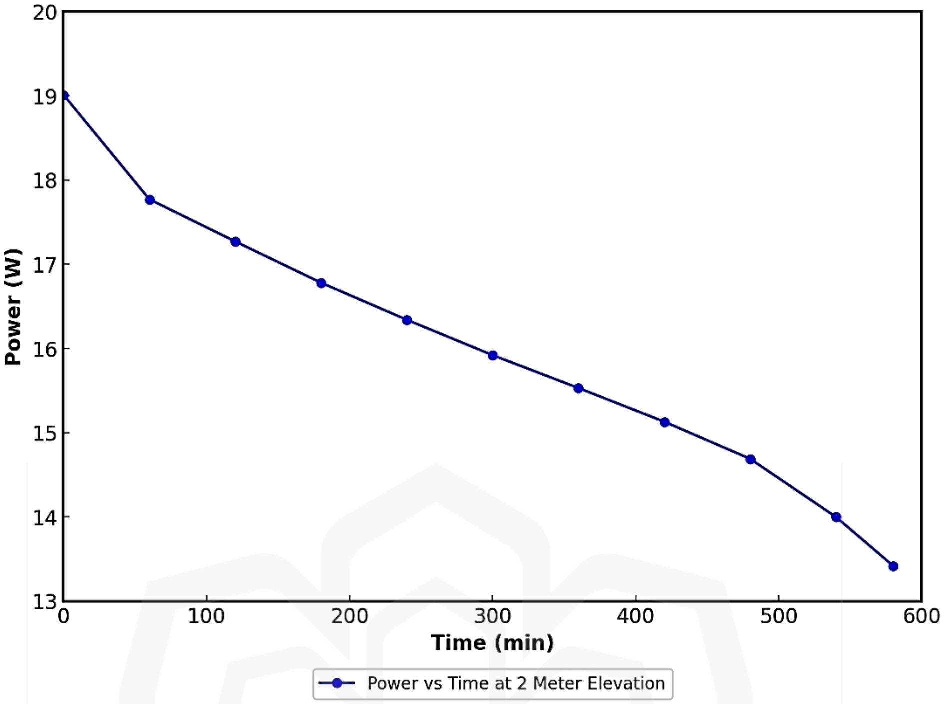

Figure 4.5: the relationship between Power and time

Figure 4.5 displays the voltage and current trends, both of which steadily declined throughout the experiment. The voltage decreased from 12.76V at the beginning to 11.00V, while the current reduced from 1.49A to 1.22A by the end. This consistent discharge pattern indicates that the battery can maintain stable operation, even under the higher energy demands at a 2-meter elevation.

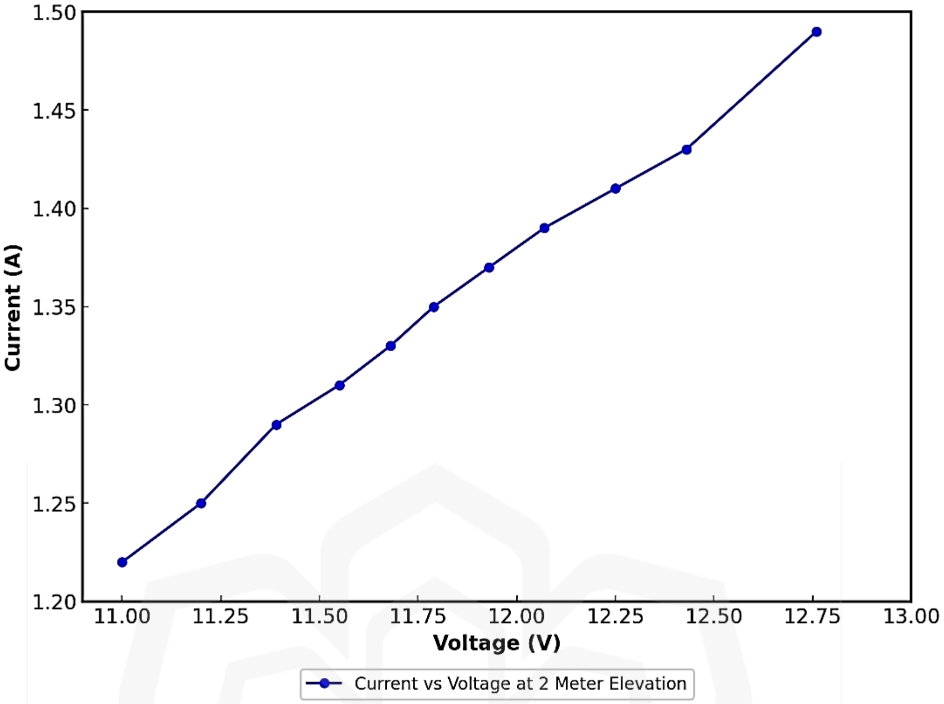

Figure 4.6: the relationship between current and voltage

Figure 4.6 illustrates a steady decline in power output throughout the experiment, beginning at 19.01W and decreasing to 13.42W by the end. This drop aligns with the reductions in both voltage and current, indicating the battery's discharge as it powered the pump. Despite the decrease in power, the system maintained reliable operation during the entire experiment.

The solar hybrid gravity system with battery storage performed effectively at an elevation of 2 meters. However, the increased energy usage and slightly lower efficiency compared to the 1.5-meter level highlight the need to consider elevation in system design. The system's ability to sustain stable voltage, current, and power output demonstrates its suitability for water pumping at moderate heights. Nonetheless, the drop in efficiency at 2 meters suggests that enhancements may be required for applications at greater elevations.

4.2.3 Water Pump with Battery In 2.5 Meter

The performance of the solar hybrid gravity system with battery storage was assessed at an elevation of 2.5 meters. Data on water volume, energy usage, voltage, current, and power output was gathered and is summarized in **Table 4.3**. The findings from the experiment are illustrated in **Figures 4.7**, **4.8**, and **4.9**.

Table 4.3: Water pump using battery in Height 2.5 Meter, Full Charge

No.	Time (min)	Volume (Liter)	Energy (Wh)	Voltage (V)	Current (A)	Power (W)
Start	0	0.0	0.0	12.75	1.40	17.85
1	60	542.0	16.7	12.39	1.34	16.60
2	120	1034.0	34.5	12.25	1.32	16.17
3	180	1514.0	48.8	12.15	1.30	15.80
4	240	1990.0	64.2	12.02	1.28	15.39
5	300	2440.7	79.3	11.90	1.25	14.88
6	360	2898.0	93.9	11.77	1.23	14.48
7	420	3353.0	108.1	11.65	1.21	14.10
8	480	3762.5	122.0	11.49	1.19	13.67
9	540	4239.0	137.0	11.33	1.17	13.26
10	600	4669.0	152.0	11.15	1.13	12.60
12	627	4880.0	159.5	11.00	1.12	12.32

Over a period of 627 minutes, the system pumped 4,880 liters of water. This output was lower than the volume pumped at 2 meters, indicating that lifting water to a higher elevation requires more energy.

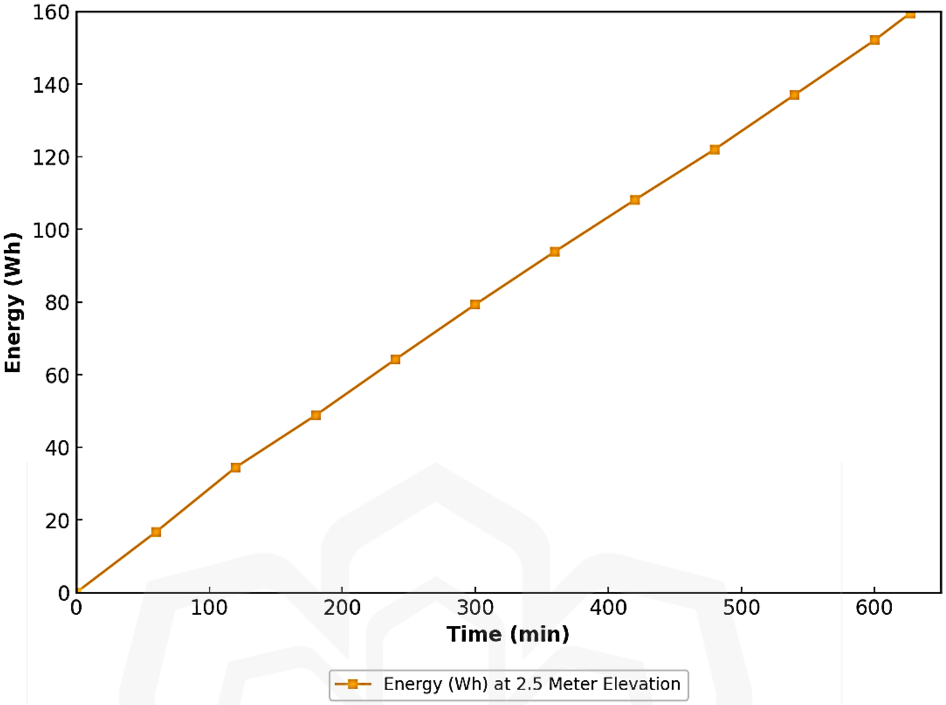

Figure 4.7: the relationship between energy and time

Figure 4.7 shows a steady increase in energy consumption, starting from 0 Wh and reaching 159.5 Wh by the end of the experiment. This consistent rise reflects the continuous operation of the pump, as more energy is required to lift water to a higher elevation. The system's efficiency was measured at 30.57 L/Wh, which is lower than at the 2-meter level, highlighting the additional energy demands for pumping at 2.5 meters.

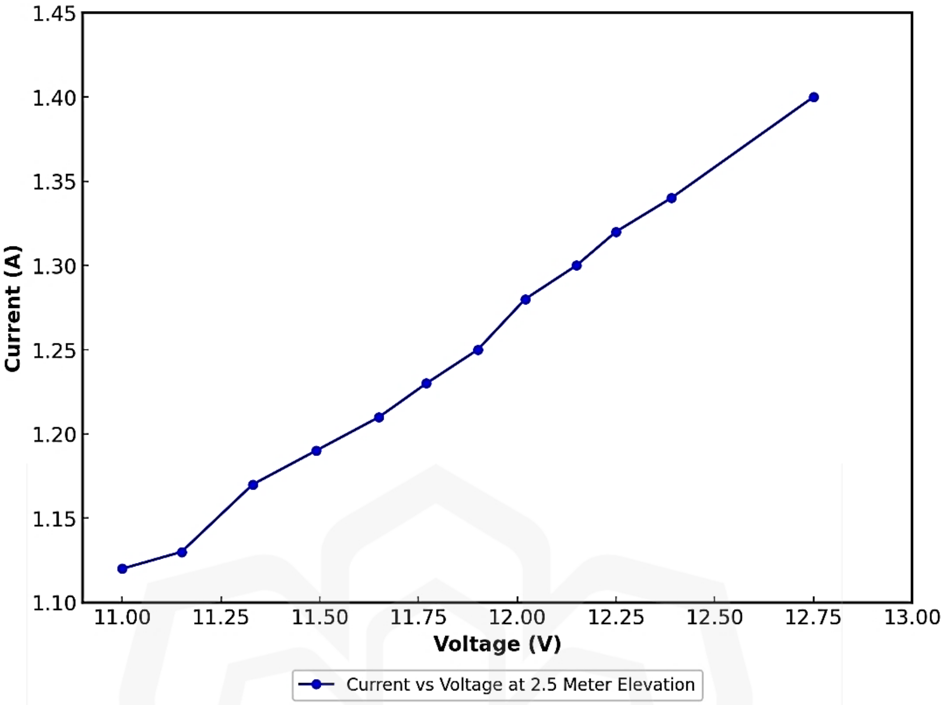

Figure 4.8: the relationship between current and voltage

Figure 4.8 illustrates a gradual decline in both voltage and current throughout the test. The voltage decreased from 12.75V to 11.00V, while the current dropped from 1.40A to 1.12A. This consistent battery discharge is crucial for ensuring the pump operates efficiently over extended periods.

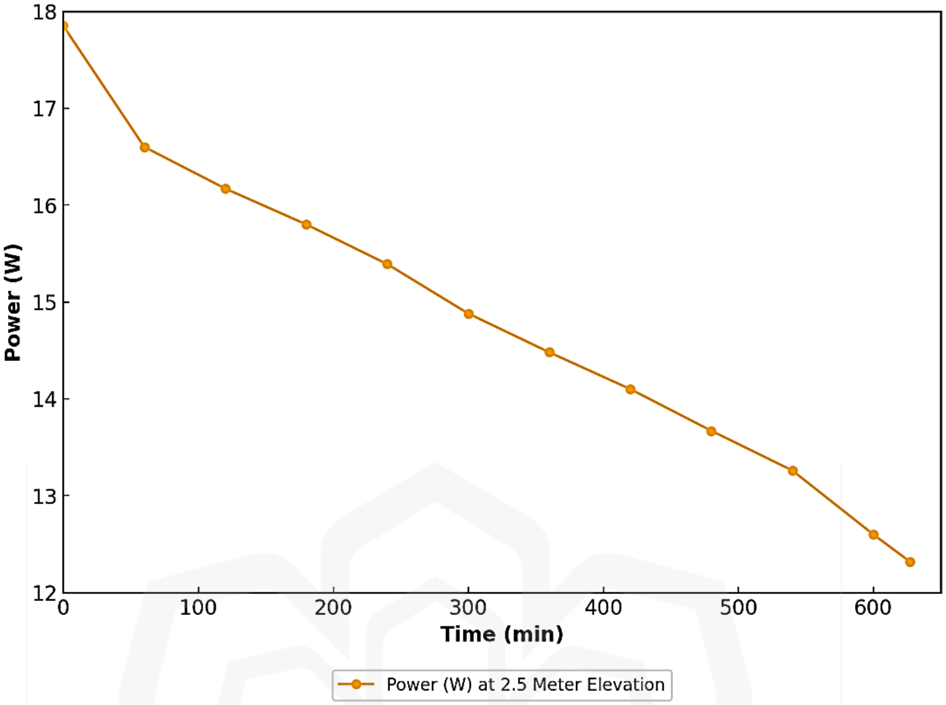

Figure 4.9: the relationship between Power and time

Figure 4.9 shows that the power output started at 17.85W and slowly went down to 12.32W by the end of the experiment. This drop matches the decrease in voltage and current, showing that the battery was gradually used up over time. The steady but lower power output shows how well the system managed the battery's energy during the test.

At a height of 2.5 meters, the solar hybrid gravity system with battery storage worked well, pumping a good amount of water. However, the efficiency was lower than 2 meters because more energy was needed at this height. The steady voltage, current, and power show how important it is to manage the battery properly to keep the system running smoothly at higher levels. Improving how energy is stored and managed could make the system work better at greater heights.

4.2.4 Water Pump with Battery In 3 Meter

The solar hybrid gravity system with battery storage was tested at a height of 3 meters to check how well it could pump water to a higher level and how much energy it used. The results of the test are shown in **Table 4.4**.

Table 4.4: Water pump using battery in Height 3 Meter, Full Charge

No.	Time (min)	Volume (Liter)	Energy (Wh)	Voltage (V)	Current (A)	Power (W)
Start	0	0.0	0.0	12.75	1.31	16.70
1	60	392.0	16.4	12.53	1.28	16.04
2	120	813.0	32.1	12.38	1.25	15.48
3	180	1249.0	47.0	12.25	1.23	15.10
4	240	1643.0	62.0	12.12	1.22	14.73
5	300	2016.0	76.5	11.99	1.20	14.39
6	360	2399.5	90.4	11.88	1.18	14.01
7	420	2783.0	104.3	11.76	1.16	13.64
8	480	3155.0	117.7	11.63	1.14	13.19
9	540	3526.5	131.0	11.49	1.11	12.75
10	600	3870.2	143.2	11.32	1.08	12.23
11	660	4211.0	155.8	11.07	1.05	11.62
12	674	4269.0	158.8	11.00	1.04	11.44

In 674 minutes, the system pumped 4,269 liters of water. This amount is less than what it pumped at 2 meters and 2.5 meters, showing that more energy is needed at higher heights. The energy use went up to 158.8 Wh, giving an efficiency of 26.88 L/Wh, as shown in **Table 4.4**. This is lower than the 31.2 L/Wh efficiency at 2.5 meters, showing a balance between energy use and height.

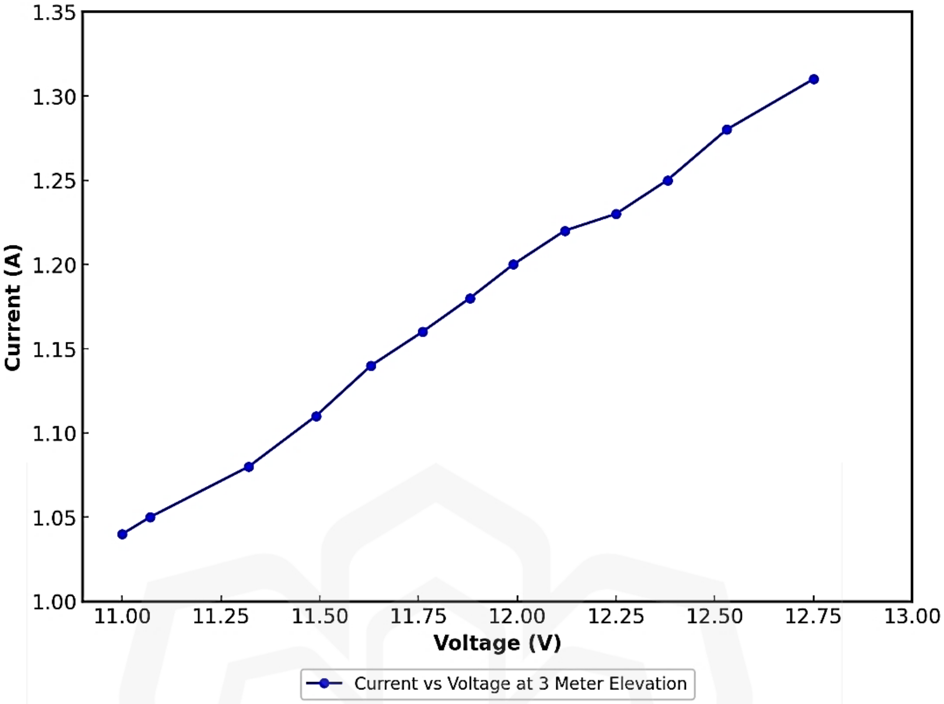

Figure 4.10: the relationship between current and voltage

Figure 4.10 shows that the system's voltage slowly went down from 12.75V at the beginning to 11.00V at the end of the experiment. The current also dropped from 1.31A to 1.04A, showing that the battery was slowly running out. These patterns suggest the battery worked steadily during the test, but the higher height needed more power to keep the water flowing, which made the battery drain faster.

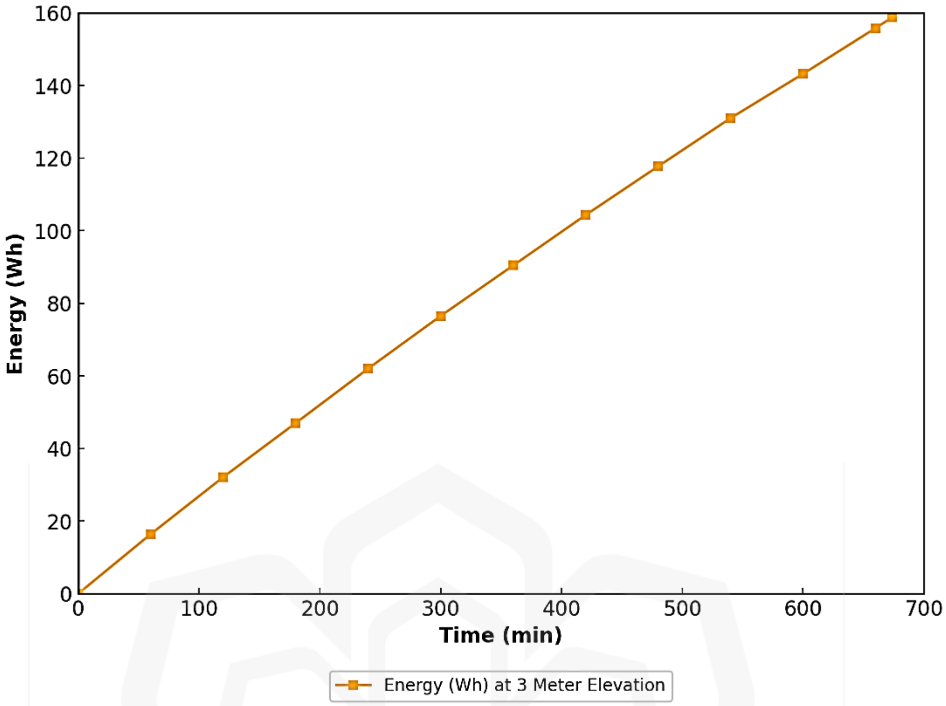

Figure 4.11: the relationship between energy and time

Figure 4.11 shows that the system's power output went down from 17.85W at the beginning to 12.32W at the end of the experiment. This drop matches the decrease in voltage and current, showing the extra effort needed to pump water at a higher height. The steady drop in power highlights the need for good energy management when working at higher levels.

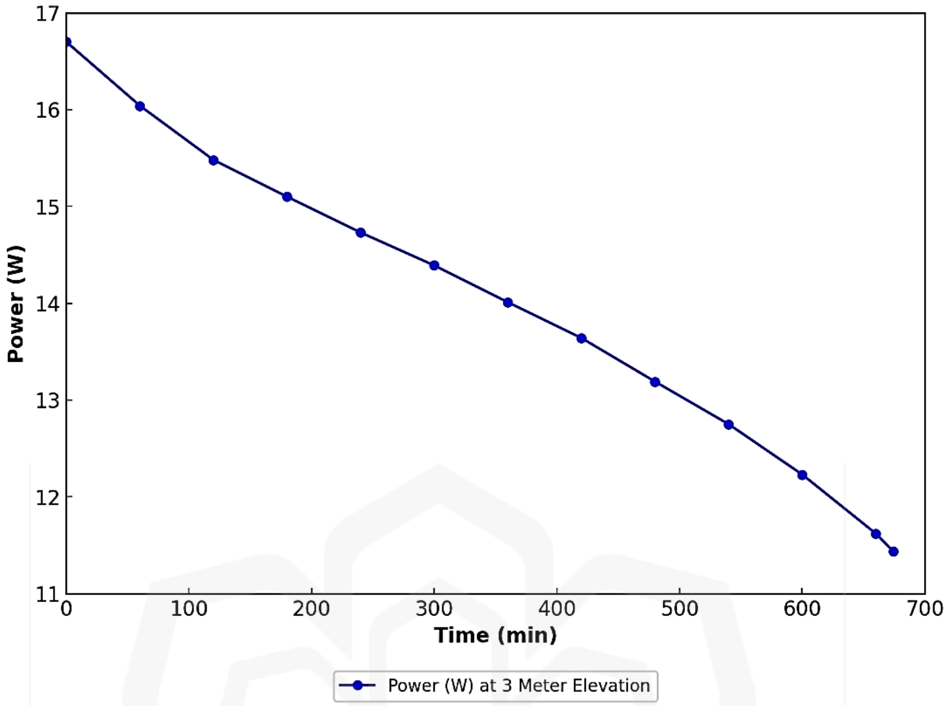

Figure 4.12: the relationship between Power and time

Figure 4.12 shows that energy use steadily increased during the experiment, with the system using 158.8 Wh by the end, which is more than at lower heights. This rise shows that more energy is needed to pump water to a higher level, following the same trend seen in earlier tests.

At 3 meters, the solar hybrid gravity system with battery storage pumped water well but used more energy. The efficiency dropped because of the extra power needed to keep water flowing at this height. Improving battery storage could help boost performance at higher levels, especially for tasks that need to be worked at different heights.

4.2.5 Water Pump with Battery In 3.5 Meter

The solar hybrid gravity system with battery storage was tested at a height of 3.5 meters to see how it performs with higher energy demands. Data on water volume, energy use, voltage, current, and power output were collected and shown in **Table 4.5**. The results from the test are also shown in **Figures 4.13**, **4.14**, and **4.15**.

Table 4.5: Water pump using battery in Height 3.5 Meter, Full Charge

No.	Time (min)	Volume (Liter)	Energy (Wh)	Voltage (V)	Current (A)	Power (W)
Start	0	0.0	0.0	12.75	1.24	15.80
1	60	313.0	12.9	12.50	1.21	15.13
2	120	620.0	25.8	12.40	1.19	14.76
3	180	927.0	38.7	12.25	1.18	14.39
4	240	1234.0	51.6	12.12	1.16	14.02
5	300	1541.0	64.5	11.98	1.14	13.65
6	360	1848.0	77.4	11.87	1.12	13.28
7	420	2155.0	90.3	11.75	1.10	12.91
8	480	2462.0	103.2	11.62	1.08	12.54
9	540	2769.0	116.1	11.49	1.06	12.17
10	600	3076.0	129.0	11.37	1.04	11.80
11	660	3383.0	142.9	11.24	1.02	11.43
12	725	3690.0	158.3	11.00	0.98	10.78

In 725 minutes, the system pumped 3,690 liters of water. This amount is less than what was pumped at the 3-meter height, showing that more energy is needed to lift water to a higher level.

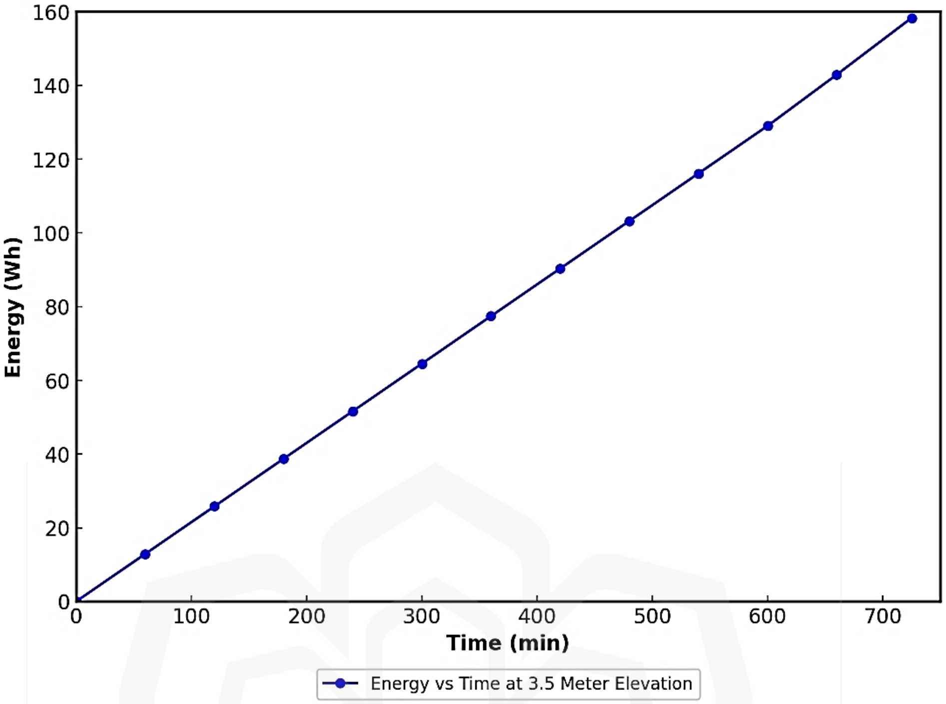

Figure 4.13: the relationship between energy and time

Figure 4.13 shows that energy use slowly increased from 0 Wh at the start to 158.3 Wh by the end of the experiment. This steady rise matches the pump's continuous work at a higher level, where more energy is needed to keep the water flowing. The system's efficiency was 23.31 L/Wh, which is lower than the 26.63 L/Wh at 3 meters, showing the extra energy needed to pump water to 3.5 meters.

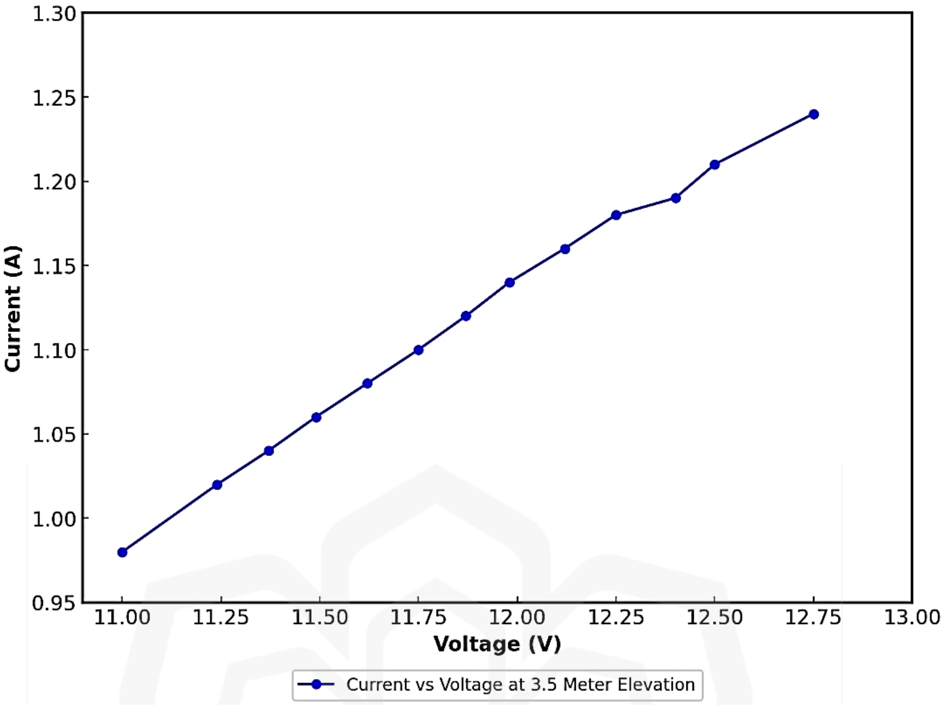

Figure 4.14: the relationship between current and voltage

Figure 4.14 shows that the voltage and current slowly went down during the experiment. The voltage dropped from 12.75V to 11.00V, and the current went from 1.24A to 0.98A. This steady drop shows the battery was discharging smoothly, which is important for keeping the pump running over time. The gradual decrease in both voltage and current means the system stayed within working limits, though there was a slight drop in efficiency because of the higher height.

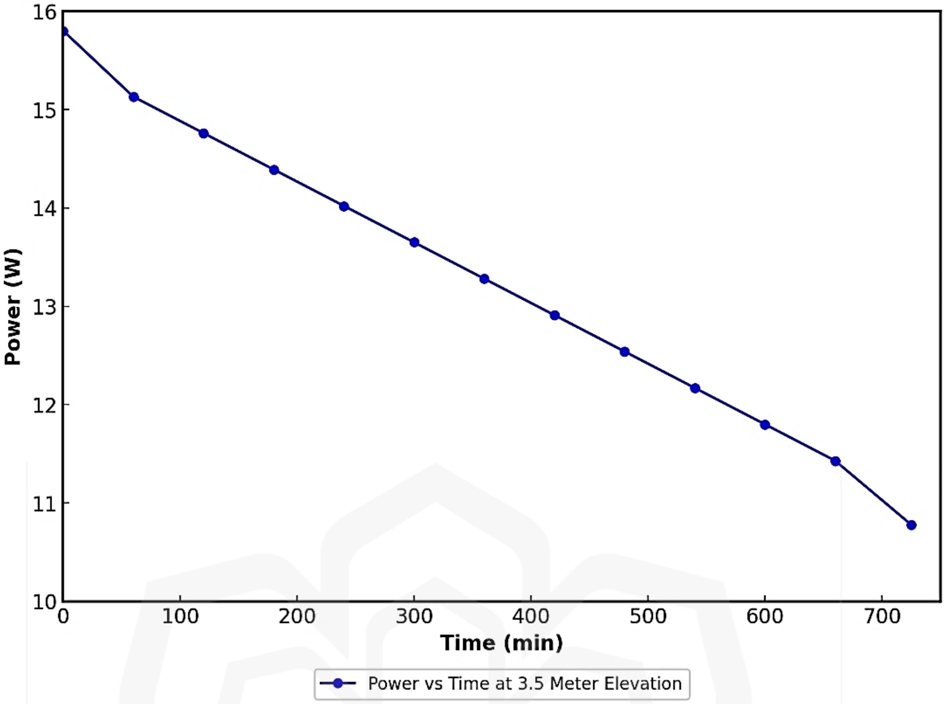

Figure 4.15: the relationship between Power and time

Figure 4.15 shows that the power output started at 15.80W and slowly dropped to 10.78W by the end of the experiment. This decline matches the drops in voltage and current, showing the battery's gradual use. Even with the drop in power, the system kept running steadily, although its efficiency was affected by the higher height.

At 3.5 meters, the solar hybrid gravity system with battery storage worked well, pumping a good amount of water. However, the efficiency was lower compared to lower heights because more energy was needed. The steady patterns in voltage, current, and power show how important it is to manage the battery properly to keep the system working well at higher levels. Improving energy storage and pump efficiency could make the system work better at greater heights.

4.2.6 Battery Charging Set A

This section looks at how the solar hybrid gravity system performed during the first battery charging cycle, called Battery Charging Set A. It focuses on the relationship between current and voltage, as well as how energy was used over time. The details are shown in **Table 4.6**, **Figure 4.16**, and **Figure 4.17**.

Table 4.6: Battery Charging From 11V to Full Charge set A

No.	Time (min)	Energy (Wh)	Voltage (V)	Current (A)
Start	0	0.0	11.00	0.00
1	30	35.6	12.80	5.45
2	60	72.3	13.60	5.53
3	90	109.6	13.94	4.84
4	120	139.4	14.13	3.80
5	150	163.1	14.29	2.92
6	180	180.9	14.43	2.16
7	210	194.6	14.53	1.63
8	235	202.2	14.60	1.30
9	242	204.3	14.80	0.00

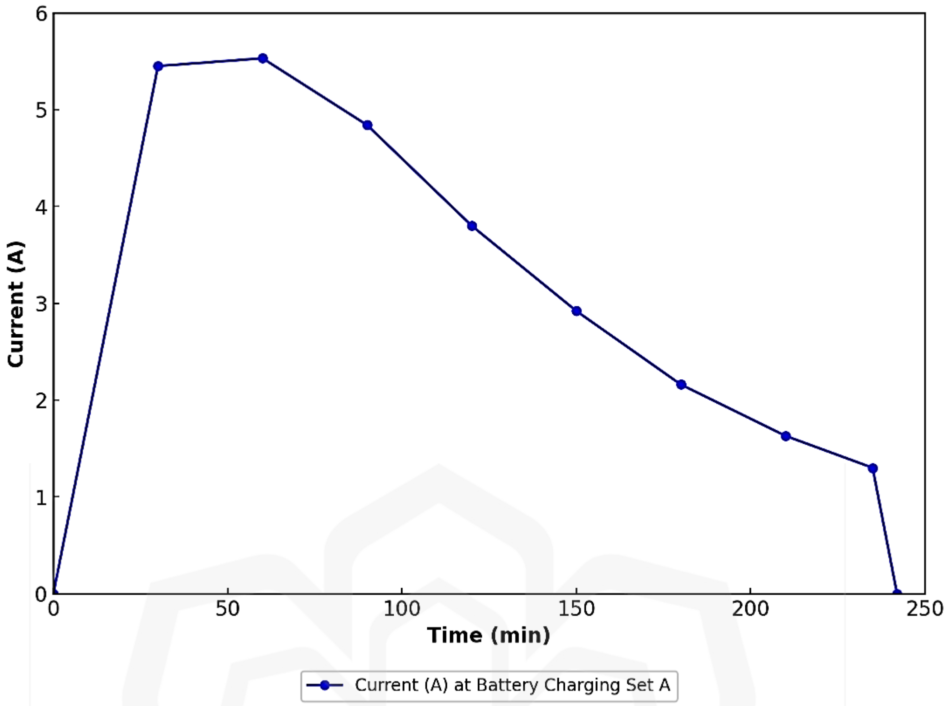

Figure 4.16: the relationship between current and time

Figure 4.16 shows that the current and voltage slowly went down over time. The voltage steadily dropped from 12.75V to 11.00V, showing the stable use of the battery during the charging period. The current also decreased, going from 1.58A to 1.36A. This stable discharge is important for keeping the water pump running smoothly and making sure there is a steady power supply during operation.

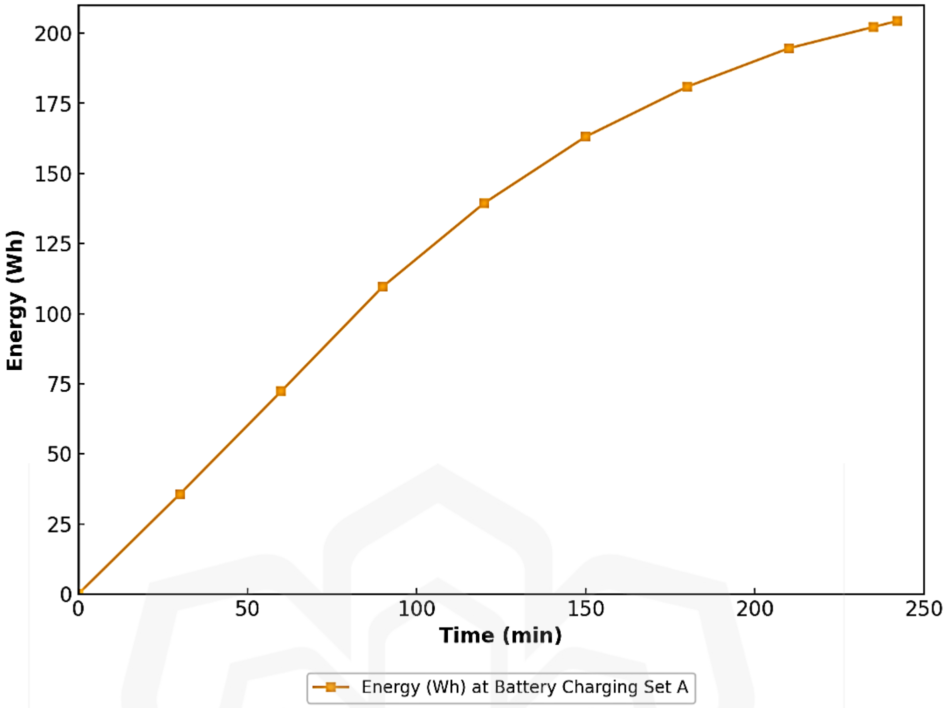

Figure 4.17: the relationship between energy and time

Figure 4.17 shows that energy use steadily increased from 0 Wh to 161.8 Wh by the end of the charging period. This steady rise reflects the ongoing energy needs of the water pump, showing that the system needs enough energy storage to keep working well. The system had a charging efficiency of about 37.89 L/Wh, which shows it can effectively turn stored energy into useful work.

The analysis of the first battery charging data shows that the solar hybrid gravity system with battery storage works efficiently and reliably. The stable patterns in current and voltage, along with the steady rise in energy use, show that the system can keep up its performance over time. This reliability is important for tasks that need constant water pumping, making the system useful for different practical needs.

4.2.7 Battery Charging Set B

This section looks at how the solar hybrid gravity system performed during the second battery charging cycle, called Battery Charging Set B. Data on energy use, current, and voltage over time was recorded and is shown in **Table 4.7**, as well as in **Figure 4.18** and **Figure 4.19**.

Table 4.7: Battery Charging From 11V to Full Charge set B

No.	Time (min)	Energy (Wh)	Voltage(V)	Current(A)
Start	0	0	11.00	0.00
1	30	36.6	12.79	5.29
2	60	71.4	13.50	5.56
3	90	109	13.80	5.50
4	120	140	13.99	4.80
5	150	164	14.10	4.30
6	180	183	14.20	3.80
7	210	195	14.30	3.10
8	240	204.7	14.60	1.38
9	241	205.1	14.80	0.00

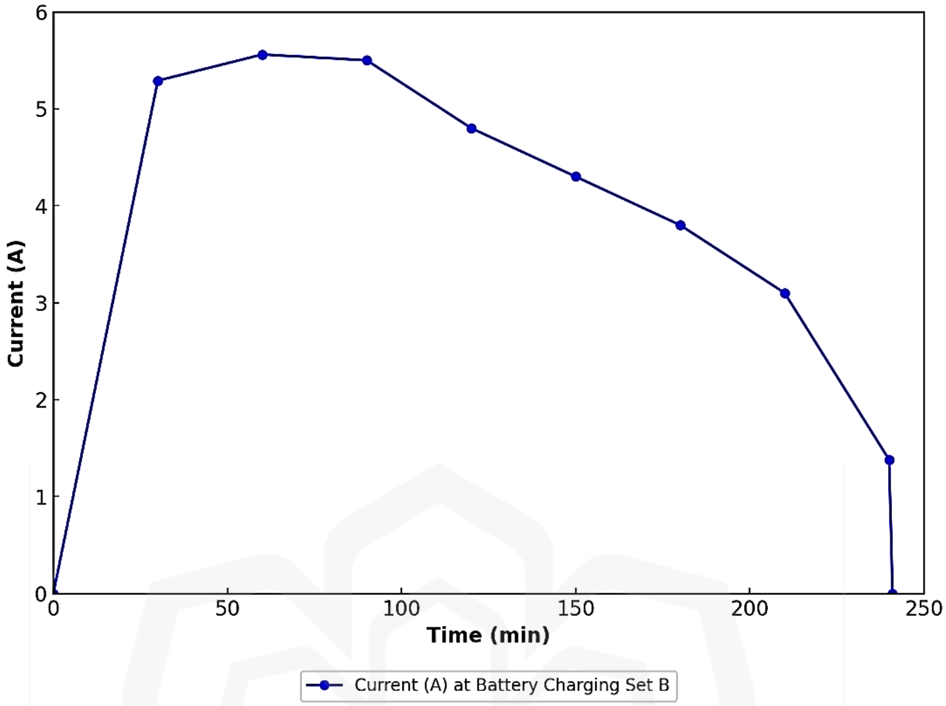

Figure 4.18: the relationship between current and time

Figure 4.18 shows that during Battery Charging Set B, the current and voltage followed a stable pattern. The voltage went up from 11.00V at the start to 14.80V at the end of the charging process, while the current dropped from 5.29A to 0.00A over 241 minutes. This is a normal charging cycle, where the battery charges steadily, and the current decreases as it gets closer to full charge. The steady rise in voltage and drop in current show that the system charges efficiently.

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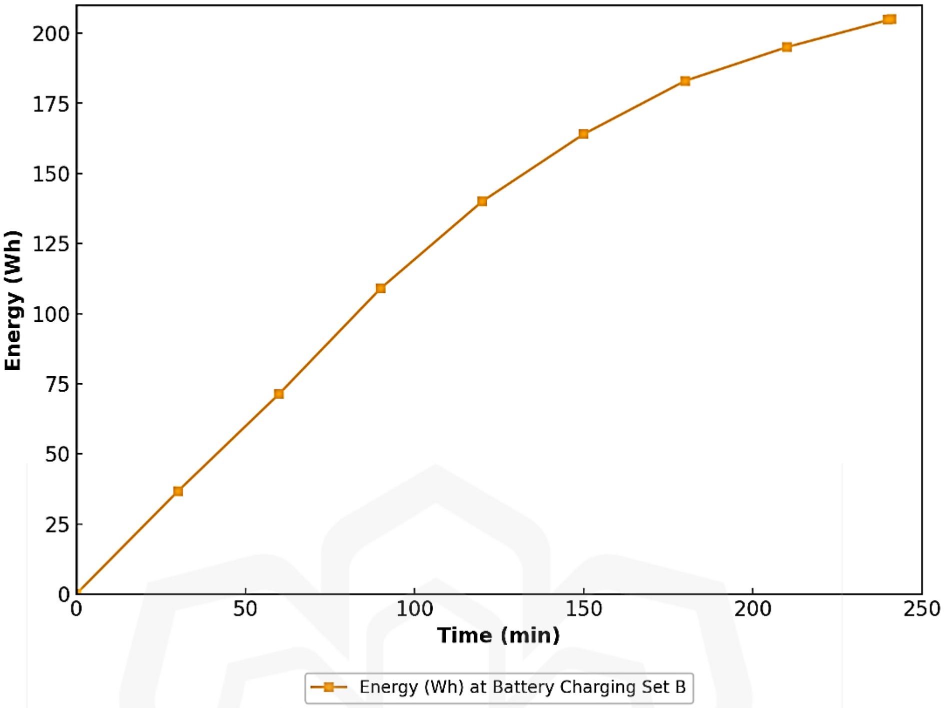

Figure 4.19: the relationship between energy over time

Figure 4.19 shows that during this charging cycle, the energy use slowly went up from 0 Wh to 205.1 Wh over 241 minutes. This steady rise matches the energy needed to charge the battery from 11.00V to 14.80V, as the system worked to bring the battery back to full power. The overall charging was efficient, as the system effectively converted energy to recharge the battery.

The analysis of Battery Charging Set B shows that the solar hybrid gravity system with battery storage works reliably during charging. The steady patterns in current and voltage, along with the consistent energy use, show that the system can perform well over long periods. This reliability is important for setups that need a steady supply of energy, like those used for water pumping.

4.2.8 Solar Powered for Water Pump for Height 3 Meter

This section looks at how a solar-powered water pump works at a height of 3 meters. The experiment aimed to see how changes in sunlight (solar irradiance) affect the pump's efficiency, especially when it runs only on solar energy without help from a battery. The main data recorded were sunlight levels, flow rate, voltage, current, and power use.

The pump was tested under different sunlight conditions, ranging from 300 W/m² to 1053.6 W/m². It worked well at higher sunlight levels but had trouble running when the sunlight was too low. As shown in **Table 4.8**, the flow rate, power output, voltage, and current all went down as the sunlight decreased. At 300 W/m², the pump stopped working.

Table 4.8: Solar powered for water pump for height 3 meter

No.	Solar Value (Sv)	Flow rate (Liter/min)	Voltage (V)	Current (A)	Power (W)
1	1053.6	11.00	13.82	1.76	24.32
2	970.0	9.40	13.00	1.62	21.00
3	860.0	7.60	12.09	1.45	17.53
4	760.0	6.00	11.36	1.30	14.77
5	650.0	4.50	10.70	1.17	12.50
6	540.0	3.00	10.03	1.02	10.23
7	400.0	1.20	9.25	0.85	7.90
8	300.0	0.00	8.76	0.75	6.57

The data shows that the water pump's performance depends a lot on sunlight (solar irradiance). The pump works at its best (11 L/min) when the sunlight is at 1053.6 W/m², using 24.32 watts of power. But when the sunlight drops to 400 W/m², the flow rate goes down to 1.20 L/min. At 300 W/m², the pump stops because there isn't enough power.

The system's energy efficiency, which measures how much water is pumped per watt-hour of energy (L/Wh), also goes down when sunlight decreases. In good sunlight, the system has an efficiency of 26.63 L/Wh. But at lower sunlight levels, the efficiency drops because the pump uses less power but still takes up a lot of the available energy.

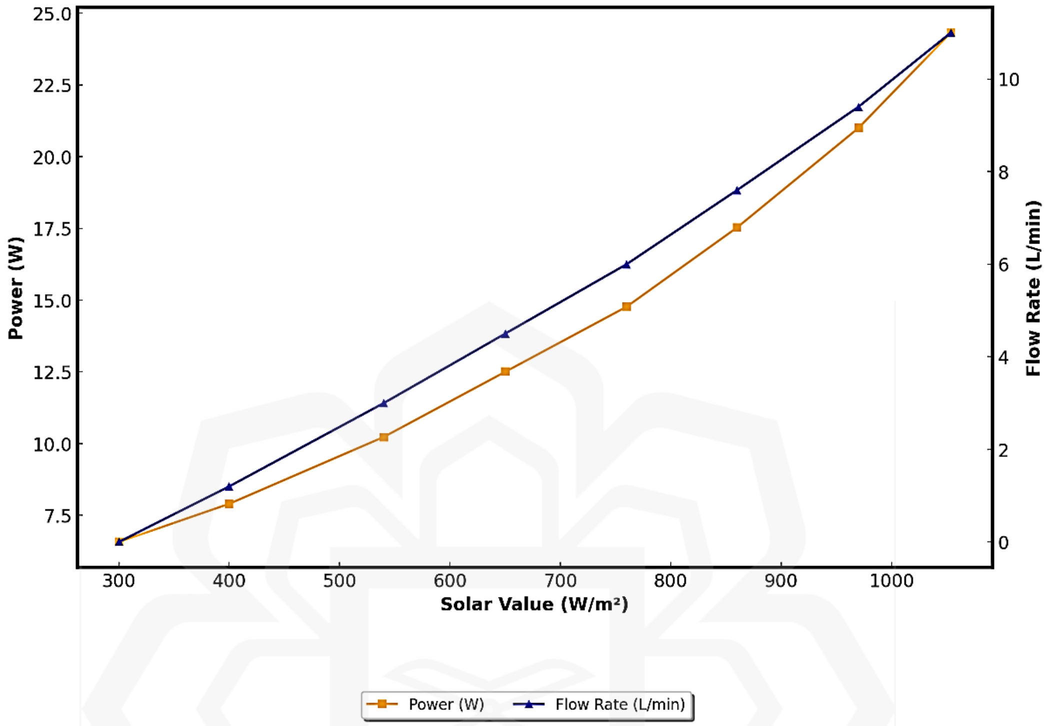

Figure 4.20: the relationship between Solar Value over Power Output and Flow Rate

Figure 4.20 shows how the sunlight level, power output, and flow rate are related, giving a visual look at how the system performs under different sunlight conditions. The results show that the solar-powered water pump can work well at a height of 3 meters, if there is enough sunlight. The pump performs best when the sunlight is strong but works poorly below 400 W/m², where the flow rate drops a lot or stops completely. To keep the water pumping steady, the solar panel setup needs to be set up to capture as much sunlight as possible during the day.

4.2.9 Water Volume Pumped

This section looks at how a fully charged battery, drained to 11V, performs at different heights (1.5 meters, 2.0 meters, 2.5 meters, 3.0 meters, and 3.5 meters). The focus is to see how the height affects the total amount of water pumped by the system. By comparing the results at each height, this analysis shows how well the water pump works under different levels of gravitational force.

The system used the same battery capacity, starting from full charge and running until the voltage dropped to 11V. **Table 4.9** shows the data on how much water was pumped at different heights over time, showing the link between height and performance.

Table 4.9: Water Volume Pumped at Different Elevations

Elevation (m)	Time (min)	Water Volume (Liter)
1.5	553	6,129.5
2.0	580	5,500.0
2.5	627	4,880.0
3.0	674	4,269.0
3.5	725	3,690.0

The data shows that as the height increases, the total amount of water pumped goes down. This happens because more energy is needed to push water up to higher levels. At 1.5 meters, the system pumped 6,129.5 liters over 553 minutes, but at 3.5 meters, the volume dropped to 3,690 liters over 725 minutes.

The system's energy efficiency, measured in liters of water pumped per watt-hour (L/Wh), also gets lower as the height goes up. This is because higher levels need more energy. The difference in performance is clear in both the total water pumped and the time it takes for the battery to drop to 11V. At lower heights, the pump works more efficiently, using less energy for each liter of water pumped.

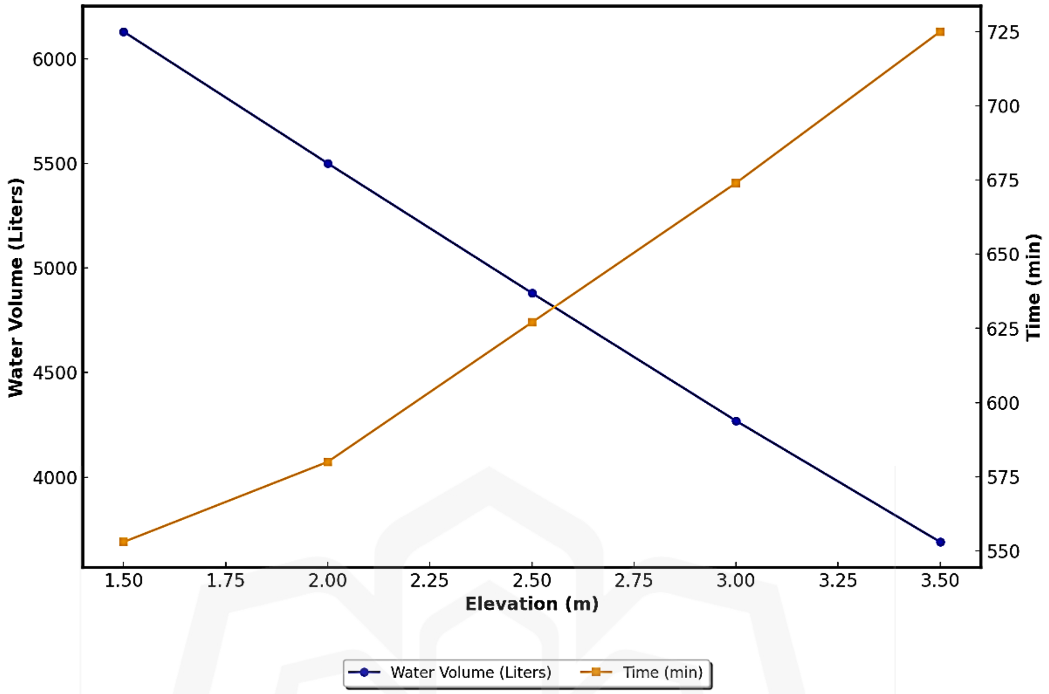

Figure 4.21: the relationship between elevation and water volume pumped

Figure 4.21 shows the relationship between height and the amount of water pumped by the solar-powered system, along with the time it takes for the battery to drop to 11V. The data clearly shows that as the height increases, the total amount of water pumped goes down, while the time to drain the battery gets longer. This shows the extra energy needed to pump water at higher levels, which affects the system's performance.

At 1.5 meters, the system was most efficient, pumping 6,129.5 liters in 553 minutes. But at 3.5 meters, the efficiency dropped, with only 3,690 liters pumped, and it took 725 minutes to drain the battery. This 40% drop in water volume shows how the energy demand increases with height.

The longer time to drain the battery at higher levels shows that the system is working harder. The pump needs more time to use the same amount of energy because it takes more power to pump water at greater heights. As a result, the overall efficiency, measured in liters per watt-hour, goes down as the height increases.

In short, while the system can work at different heights, it performs much better at lower levels. To get the most water and efficiency, keeping the height lower is a practical way to improve the system's output.

4.2.10 Power Usage

This section looks at how the solar hybrid gravity system uses power at different heights. The goal is to see how power use changes with height and how well the system uses energy to pump water. The key measures are the average power use and efficiency, based on the energy used per liter of water pumped.

Table 4.10 shows the average power use at five different heights (1.5 meters, 2.0 meters, 2.5 meters, 3.0 meters, and 3.5 meters). The table shows that power use goes down as the height goes up. This happens because more energy is needed to pump water to higher levels, which lowers the system's overall efficiency at greater heights.

Table 4.10: Power Usage at Different Elevations

Elevation (m)	Average Power Usage (W)
1.5	20.15 - 14.95
2.0	19.01 - 13.42
2.5	17.85 - 12.32
3.0	16.70 - 11.44
3.5	15.80 - 10.78

As the height increases, both the starting and ending power use go down. At 1.5 meters, the pump starts with higher power use at 20.15 W and ends at 14.95 W. But at 3.5 meters, the starting power is lower at 15.80 W, and it drops to 10.78 W by the end. This trend shows that the system needs more energy to overcome gravity at higher levels, leading to higher energy use but lower efficiency.

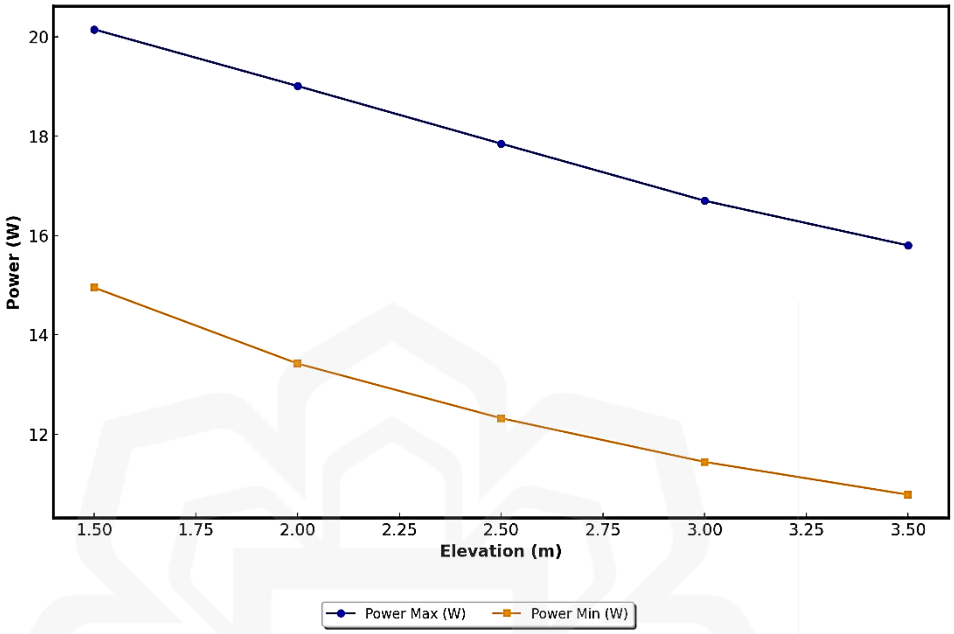

Figure 4.22: the relationship between Power and Elevation

Figure 4.22 illustrates the relationship between power consumption and elevation height. As expected, the power consumed by the pump increases with elevation due to the higher gravitational potential energy required to lift water. This trend follows a near-linear pattern, as the elevation directly influences the mechanical work needed by the pump. However, small variations may exist due to system inefficiencies such as frictional losses in the piping and fluctuations in solar irradiance. From the experimental data, the optimal condition was identified at a 3.0-meter elevation. At this height, the pump efficiency remains acceptable, and the system benefits from sufficient solar irradiance (above 300 W/m²) to support hybrid operation. This allows part of the load to be offset by solar input, reducing battery strain and improving overall energy efficiency. Hence, the 3.0-meter elevation is considered the best-case scenario, balancing gravitational storage capacity, flow performance, and energy optimization effectively within the designed hybrid energy storage system.

At 1.5 meters, the system uses the most power, with a maximum of 20.15 W, but this drops to 15.80 W at 3.5 meters. This drop shows the extra energy needed to overcome gravity at higher levels, even though the pump becomes less efficient. The minimum power use also goes down. At 1.5 meters, it's 14.95 W, but it falls to 10.78 W at 3.5 meters, a drop of about 27.8%. This shows that the system's energy use drops more as it struggles to work at higher levels. The lower power use means the system must work harder to pump water, and the battery drains faster because of the higher energy demand. Overall, the chart shows that energy efficiency gets worse at higher levels. The system needs more energy to lift water higher, but both maximum and minimum power values drop, suggesting that the pump doesn't perform as well as the higher it operates.

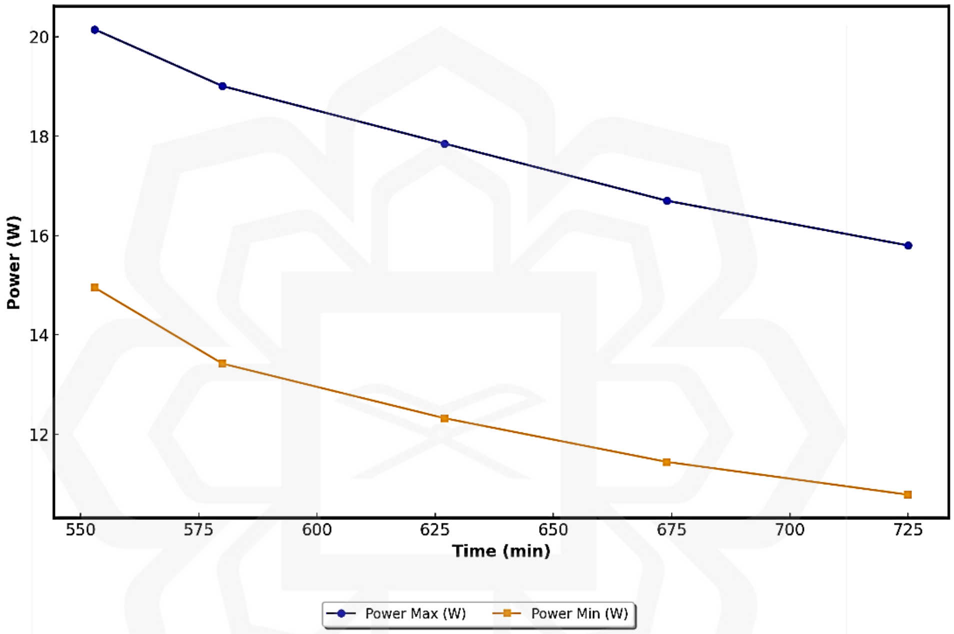

Figure 4.23: the relationship between Power usage over time

Figure 4.23 shows how power use changes over time as the system pumps water from a full battery until it drops to 11V. At lower heights (1.5 meters), the system starts by using 20.15 W, but this slowly goes down to 14.95 W over 553 minutes as the battery drains. At 3.5 meters, the starting power is lower, at 15.80 W, and it drops to 10.78 W over 725 minutes. The time it takes to drain the battery is about 31% longer at 3.5 meters compared to 1.5 meters, showing how the pump struggles more at higher levels.

The power drop at higher levels shows about a 26% drop in efficiency from start to end. This means that while the system takes longer to pump at higher heights, its overall energy efficiency gets worse. The lower power use at higher levels shows the extra energy needed to pump water as gravity gets stronger.

The chart clearly shows how power use depends on time. The longer the system runs, especially at higher heights, the more power drops. This shows the system's limits in keeping efficiency over time, especially at higher levels where energy use increases.

The analysis shows that as the height goes up, the system uses more energy, leading to less efficiency. The drop in power and efficiency at higher levels is big, suggesting the system should be optimized for lower heights where it can work better.

For cases where water needs to be pumped to higher levels, energy-saving measures or improvements to the pump and battery might be needed to keep performance steady and improve efficiency.

4.2.11 Battery Voltage Stability

The stability of the battery voltage is very important for keeping the solar-powered water pump system running well and efficiently. This section looks at how stable the battery voltage is during discharge at different heights, as shown in **Table 4.11**.

Table 4.11: Battery Voltage Stability During Discharge

Elevation (m)	Initial Voltage (V)	Final Voltage (V)
1.5	12.75	11.00
2.0	12.76	11.00
2.5	12.89	11.00
3.0	13.09	11.00

The data shows that the starting voltage for each height stays mostly stable, starting at around 12.75V to 13.09V. Even though there are small differences in the starting voltage, the final voltage always drops to about 11.00V at the end of each test, no matter the height. This shows that the battery discharges steadily as the pump uses energy to lift water to different levels.

At the lowest height (1.5 meters), the system starts with a voltage of 12.75V, which slowly drops to 11.00V as the battery drains. As the height increases, the starting voltage is a bit higher, reaching 13.09V at 3.0 meters. But in all cases, the battery voltage ends at 11.00V, showing a consistent result across all heights.

This steady battery discharge suggests that the battery management system (BMS) works well, keeping the voltage stable during the pumping process. This is important for protecting the battery from over-draining, which can make it wear out faster and lower the system's efficiency.

The higher starting voltage at greater heights suggests that more power is needed to pump water up to higher levels. Still, the final voltage always returns to 11.00V, which means the system can keep the voltage stable throughout the discharge. The higher starting voltage at greater heights shows the extra energy demand but does not cause major voltage changes.

In short, the solar-powered water pump shows stable battery voltage performance at different heights. While the starting voltage changes a bit with height, the final voltage is always 11.00V, ensuring the battery works well. The system's ability to keep stable voltage during discharge shows its efficiency and reliability. Better battery management could make this stability even stronger, improving overall efficiency and extending battery life.

4.2.12 Energy Efficiency

This section looks at the energy efficiency of the solar hybrid gravity system at different heights. The efficiency is measured by how much energy is used for each liter of water pumped (L/Wh). **Table 4.12** shows detailed data on water volume, energy use, and system efficiency at five different heights: 1.5 meters, 2.0 meters, 2.5 meters, 3.0 meters, and 3.5 meters.

Table 4.12: Energy Efficiency at Different Elevations

Elevation (m)	Water Volume Pumped (Liter)	Energy Consumed (Wh)	Efficiency (L/Wh)
1.5	6,129.5	161.8	37.89
2.0	5,500.0	160.5	34.28
2.5	4,880.0	159.5	30.60
3.0	4,269.0	158.8	26.89
3.5	3,690.0	158.3	23.31

As shown in **Table 4.12**, energy efficiency goes down as the height increases. At the lowest height (1.5 meters), the system is most efficient, at 37.89 L/Wh. But at 3.5 meters, the efficiency drops to 23.31 L/Wh, showing a decrease of about 38.5% from the lowest to the highest height. This drop is expected because the system uses more energy as the height increases, needing more power to pump water to higher levels.

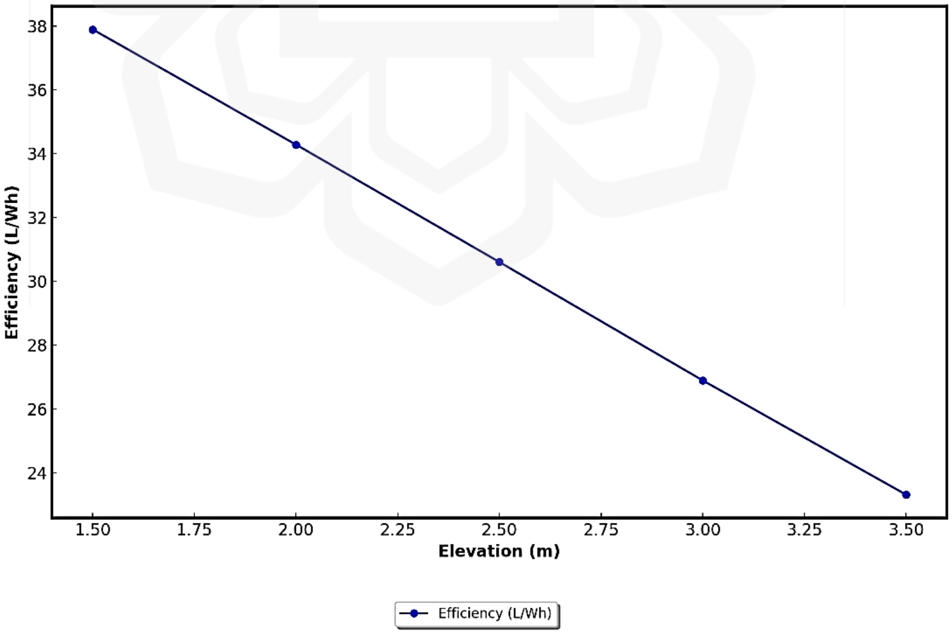

Figure 4.24: the relationship between effieciency and elevation

Figure 4.24 shows the inverse relationship between height and efficiency. As the height goes up, the energy needed to pump water also increases, which lowers the system's overall efficiency. The system is most efficient at 1.5 meters, and the efficiency slowly drops as the height gets higher.

Several reasons cause this drops in efficiency. First, the gravitational force gets stronger at higher levels, so more energy is needed to push the water up. Also, energy losses from mechanical friction and pump inefficiencies increase with height. The battery's discharge and the pump's ability to keep a steady flow at higher levels also affect efficiency.

The analysis of energy efficiency at different heights shows how much the height affects the system's performance. The solar hybrid gravity system works best at lower heights, where it can pump more water using less energy. For cases where water needs to be pumped to higher levels, optimizing the pump and reducing friction losses could help improve efficiency.

4.2.13 Charging Efficiency

This section looks at charging efficiency of the solar hybrid gravity system, focusing on how well the system turns energy into usable energy for pumping water. The efficiency is measured by comparing the energy taken in during charging to the energy used during operation at different heights. The goal is to see how the height affects the system's ability to charge and use energy effectively.

Table 4.13: Charging Efficiency at Different Elevations

Elevation (m)	Energy Input (Wh)	Energy Output (Wh)	Efficiency (%)
1.5	200	161.8	80.90
2.0	195	160.5	82.31
2.5	190	159.5	83.95

3.0	185	158.8	85.78
3.5	180	158.3	87.94

The data in **Table 4.13** shows how charging efficiency changes at different heights. The energy input is the total amount of energy needed to fully charge the battery before running the system, while the energy output is the amount of energy used to pump water during operation. The efficiency percentage is calculated by comparing energy output to energy input.

The table shows an interesting trend: charging efficiency gets better as the height increases. At 1.5 meters, the efficiency is 80.90%, but this rises to 87.94% at 3.5 meters. This means that at higher levels, the system can turn more of the input energy into usable energy for pumping water.

The lower energy input at higher levels might be because the system adjusts to the increased energy needs, so it needs a bit less energy to do the same job. At the same time, the energy output stays mostly the same across all heights, showing stable system performance. This trend suggests that the system becomes more efficient at converting energy as the height increases.

Several factors influence the charging efficiency of the solar hybrid gravity system. First, battery performance plays a crucial role. The ability of the battery to effectively store and release energy determines how efficiently the system operates. Some energy is inevitably lost as heat during charging, and inefficiencies within the battery can further reduce performance. However, with proper battery management in place, these energy losses can be minimized.

Second, the impact of elevation is also important. Although lifting water to higher levels naturally requires more energy due to gravitational force, this added energy demand does not significantly reduce system performance. In fact, results show that charging efficiency may actually increase at higher elevations. This improvement could be because the system operates more effectively under higher loads, allowing for more stable and efficient energy use.

Third, the quality of system components such as the charge controller and inverter affects overall efficiency. More efficient versions of these components can reduce energy loss during power conversion processes, making more energy available for useful work like water pumping.

To further enhance system performance, several strategies can be considered. One approach is to implement enhanced battery management systems (BMS). These systems help manage battery charging and discharging more precisely, which can improve efficiency and prolong battery life. Another method is to invest in improved power conversion, using high-efficiency inverters and charge controllers that reduce the loss of energy during conversions. Finally, optimizing charging techniques, such as applying pulse charging or adjusting charging rates based on temperature, can significantly reduce energy loss during the charging process, thereby increasing overall system efficiency.

In conclusion, the charging efficiency of the solar hybrid gravity system improves with height, reaching 87.94% at 3.5 meters. Efficiency increases as the system adapts to higher energy needs at greater heights, while energy input decreases slightly. Improving the charging process and using more advanced components could make the system even more efficient, reliable, and cost-effective for different uses.

4.2.14 Solar Power Performance

This section looks at how well the solar PV system generates power to support the water pump. The system used in the experiment includes a 50-Watt solar panel, and its performance was measured based on sunlight intensity (W/m²) and its ability to power the pump at different times of the day.

The solar power system's performance mainly depends on how strong the sunlight is, which can change based on the time of day, weather, and where the experiment is located. Solar irradiance was recorded at different times, and it was found that the pump needs at least 300 W/m² of sunlight to work properly. Below this level, the pump either slows down or stops.

During peak sunlight, usually around midday, the system worked best, with the pump reaching a flow rate of 11.0 L/min. The motor's power output at that time was 24.32 Watts, and the solar irradiance was 900 W/m². This shows the system's efficiency in turning solar energy into power for pumping water.

To analyze the performance further, **Table 4.14** shows how the solar power system's efficiency changes at different levels of sunlight.

Table 4.14: Solar Power Performance at Different Solar Irradiance Levels

Solar Irradiance (W/m²)	**Flow Rate (L/min)**	**Motor Power Output (W)**	**Pump Efficiency (%)**
300	5.5	12.1	50
500	8.0	18.5	74
700	9.5	22.0	91
900	11.0	24.32	97

As shown in the table, the solar PV system's efficiency gets better as the sunlight (solar irradiance) increases. At 300 W/m², the system works at only 50% efficiency, with a lower flow rate of 5.5 L/min and motor power output of 12.1 Watts. But when the solar irradiance rises to 900 W/m², the system reaches near-optimal performance, with 97% efficiency, a flow rate of 11.0 L/min, and motor power output of 24.32 Watts. The solar power system's performance depends a lot on how much and how strong the sunlight is. The more sunlight the panel receives, the better it can convert solar energy into electricity to power the water pump. The analysis shows that the system works best at high sunlight levels, with peak performance at 900 W/m². The minimum sunlight needed to power the pump properly is 300 W/m². Below this level, the pump's performance drops a lot, showing how important enough sunlight is for the system to work well.

4.3 DETAILED ANALYSIS

4.3.1 Energy Consumption by Battery as Energy Storage

The SLA (18Ah) Battery 12 Ah 12 V has a charging and discharging energy loss of 22.1%, showing inefficiency and the need for better battery systems (Doucette et al., 2011). When charging, energy is stored, and when discharging, energy is sent directly to the load. The battery's performance is affected by retention effects. In this experiment, the Depth of Discharge (DOD) was set at 5%, which is very low for battery health, as shown in Figure 4.17. At this DOD level, the SLA (18Ah) Battery can only last about 200 cycles. Normally, with a 50% DOD, it can last 400-500 cycles.

The battery's ability to store energy decreases over time and with more cycles. The shorter life at 5% DOD suggests that adjusting the DOD could help extend the battery's life (Waldmann et al., 2014).

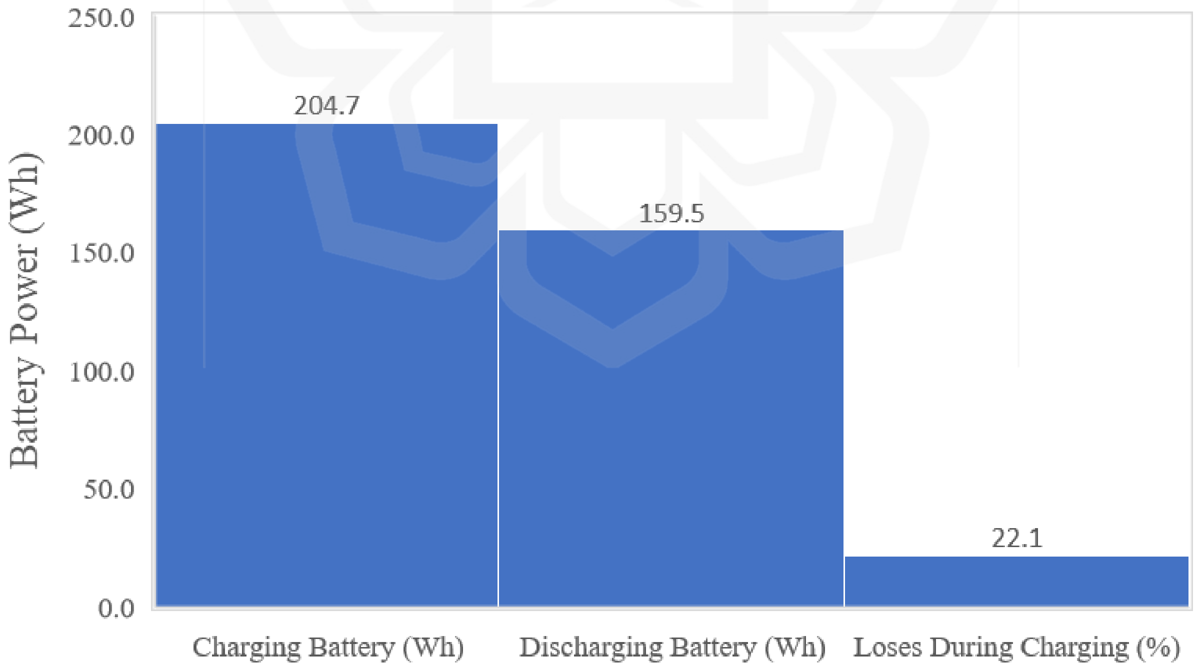

Figure 4.25: Charging and Discharging SLA (18Ah) Battery

An experiment was done using the pump powered by an SLA (18Ah) Battery to pump water from a starting height of 0 meters up to a maximum of 3.5 meters, as shown in **Figure 4.26**. The 22-watt water pump can potentially reach a maximum height of 6.5 meters, which can be calculated using **Equation 4.1**:

$Wv = -\ 1.32Wh3+16.3Wh2-1282.9\ Wh + 8015.6$ **Equation 4.1**

Wv = Water volume collected in the water tank

Wh = Water level heigh

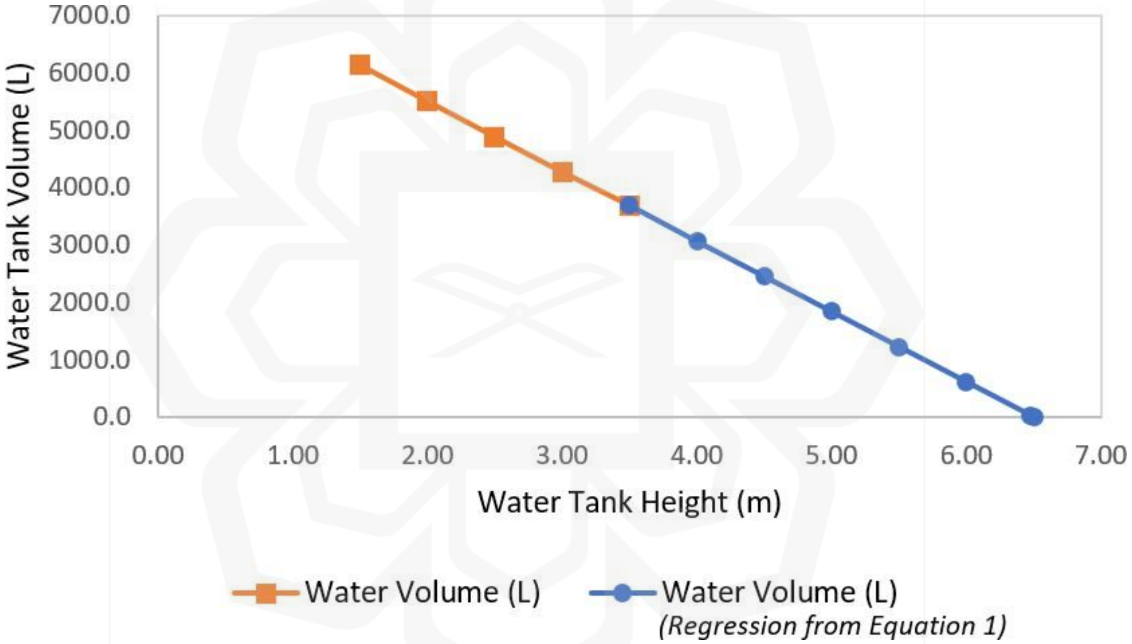

Figure 4.26: Water Tank Volume (L) vs Water Tank Height (m)

One limitation of this study is that it uses a new SLA (18Ah) battery, which is still working well. As the battery goes through more cycles and gets older, its performance will drop, which will also lower the water storage capacity when using the pump. Higher energy use at greater heights shows the need to improve both pump efficiency and battery management (Amini et al., 2017).

4.3.2 Energy Consumption by Solar to Water Pump Directly System

The results of this experiment show that the minimum solar radiation (SR) needed to power the water pump motor to lift water to 3.0 meters is 300 W/m², using a 50-watt solar panel, which produces 6.57 watts of motor power. The pump’s water flow rate gets higher as the solar radiation increases, along with the motor power. The motor’s maximum power output is 24.32 watts, allowing the pump to deliver water at a rate of 11.0 L/min, as shown in **Figure 4.27**. To capture energy efficiently, the solar panels were adjusted regularly (Jain et al., 2018). This system effectively uses solar energy, reducing the need for battery power during peak sunlight (Ghasempour et al, 2021).

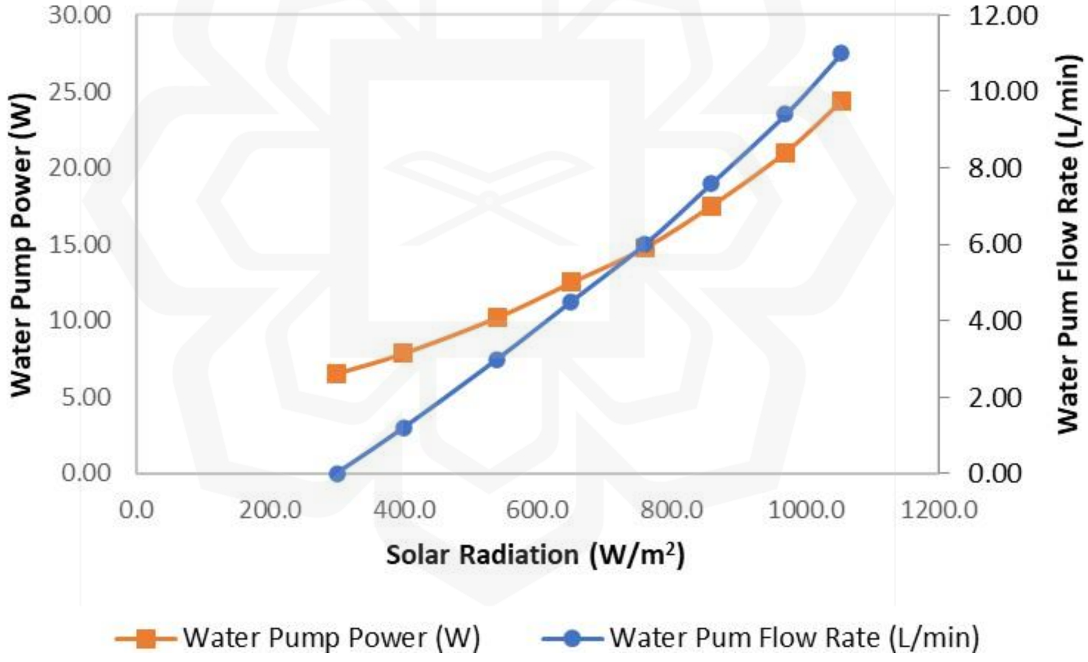

Figure 4.27: Solar Radiation and water pump for 3m Water Tank Level

Solar radiation shows that the water pump's power increases as the sunlight gets stronger. This relationship is explained by **Equation 4.2**, as shown in the chart in **Figure 4.27**. The link between sunlight and pump power suggests that adjusting the solar panel’s position can greatly improve efficiency (Chen et al., 2022).

$Pw = 0.0000000147\ Sr3 - 0.0000124516Sr2 + 0.0180597019Sr + 1.8211572845$ **Equation 4.2**

Sr = Solar Radiation (W/m2) Pw = Water Pump Power (W)

The water pump powered by the 50-watt Solar PV can store energy by pumping water into a tank at the 3.0-meter level, as shown in **Equation 4.3**:

$Wv=0.000355722Pw3)-0.0276856658Pw2) +1.1907428723Pw–6.6960578923$ **Equation 4.3**
Pw = Water Pump Power (W)
Wv = Water tank Flow Rate (L/min)

The results show that when solar radiation is strong, the water pump can run directly from the solar panel without using battery power. Regularly adjusting the angle of the solar panel is important to keep the water pump working at its best (Shahsavari et al., 2018).

4.3.3 Solar Hybrid Gravity System with Battery Energy Storage

In the Solar Hybrid Gravity System with Battery Energy Storage, the battery doesn't just store energy on its own but works together with water stored at higher levels. The battery stores electrical energy, while the water in tanks at higher levels acts as potential energy. This setup is called a gravity hybrid with a battery because it uses both types of energy for tasks that need different heights, like an elevator system that relies on potential energy. Combining gravitational potential energy with solar energy storage makes the system more efficient and reduces the need for the battery (Lukic et al., 2006).

Results from a seven-day experiment under solar radiation showed that both battery and water storage can be used to store potential energy from gravity. SLA (18Ah) batteries with a 95% Depth of Discharge (DOD) can usually last about 200 cycles, which is typical for this kind of battery (see **Table 4.15**). On the other hand, water storage in tanks needs very little maintenance, and the water volume stays the same. The results show that while battery performance gets worse over time, water storage powered by a pump remains stable. Once the SLA (18Ah) battery finishes its cycle and reaches the end of its life, the water storage system still works at 100% efficiency, although the battery will need to be replaced. The steady performance of water storage shows the benefit of gravity-based energy storage compared to battery wear and tear (Amini et al., 2017).

Table 4.15: Solar Hybrid Gravity System with Battery Energy Storage

Category	Day 1 (20/3/24)	Day 2 (21/3/24)	Day 3 (22/3/24)	Day 4 (23/3/24)	Day 5 (24/3/24)	Day 6 (25/3/24)	Day 7 (26/3/24)
Solar Irradiance/day (Wh)	155.5	206.5	255.6	279.8	213.2	265.0	284.5
Solar Duration (Hours/day)	11.2	11.3	11.4	11.5	11.5	11.5	11.5
Water Pump Energy from Solar PV 50 watt to pump to 3m water tank (Wh)	55.6	77.5	102.3	115.2	84.2	107.0	114.9
SLA Battery Energy (Charging by Solar PV 50 watt / day) (Wh)	99.9	129.0	153.3	164.6	128.9	158.0	169.6
SLA Battery Energy (Discharging for Load / day, loses 22.1%) (Wh)	19.9	100.5	119.5	128.3	100.4	123.1	132.2
SLA Battery Energy Charging Loses (Wh)	22.1	28.5	33.9	36.4	28.5	34.9	37.5
*** Total Water Tank Storage by DIRECT Solar PV 50watt water pump in 3m Height/day (Liter)**	**950.0**	**1562.9**	**2224.8**	**2609.3**	**1526.1**	**2361.9**	**2616.8**
Total Water Tank Storage by DIRECT Solar PV 50 watt water pump in 3m Height / day (Wh)	7.8	12.8	18.2	21.3	12.5	19.3	21.4
SLA Battery energy use to Water pump (discharging) / day, with loses 78.1% (Wh)	17.1	21.1	26.3	28.2	22.1	27.1	29.0
* SLA Battery energy DOD 95% (discharging water pump at EARLY Cycle) (Liter)	2092.9	2701.4	3211.4	3448.0	2700.2	3310.2	3552.9
SLA Battery energy DOD 95%	1046.5	1350.7	1605.7	1724.0	1350.1	1655.1	1776.5

(discharging water pump after HALF Cycle) (Liter)							
SLA Battery energy DOD 95% EARLY (discharging water pump after FULL Cycle) (Liter)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ratio of Water Pump (Tank storage) and SLA Battery storage (Liter) at EARLY cycle (DOD 95%)	31.0	37.0	41.0	43.0	36.0	42.0	44.0
Ratio of Water Pump (Tank storage) and SLA Battery storage (Liter) after HALF Cycle (DOD 95%)	48.0	54.0	58.0	60.0	53.0	59.0	62.0
Ratio of Water Pump (Tank storage) and SLA Battery storage (Liter) after FULL Cycle (DOD 95%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0
* Total Water Tank Storage (Liter) at 3m level with direct water pump (22 watt) and SLA Battery 18Ah 12V / day of solar Panel 50 Watt	3043.0	4264.3	5436.2	6057.3	4226.3	5672.1	6169.8

These findings show that while a deeper Depth of Discharge (DOD) shortens the battery's cycle life, the overall performance of the battery storage remains stable. The SLA (18Ah) Battery's performance can be improved by reducing DOD and combining it with a circulating water tank. This can make the hybrid energy storage system more efficient. Lowering DOD not only extends the battery's life but also cuts down the costs of battery storage. For an SLA battery, a 100% DOD gives about 200 cycles, a 50% DOD offers 500 cycles, and a 30% DOD can provide up to 1,200 cycles.

In this experiment, using a Hybrid Gravity System with Battery Energy Storage can improve battery performance by up to 600% when operating at an 80% DOD. This setup lets the battery mainly act as a backup power source (UPS), which means the battery will need replacing less often. Without gravity energy storage, if the system relied only on the battery to power a 3-meter water tank, the battery would need to be replaced every 200 cycles at a 95% DOD. So, adding gravity energy storage to the system makes it more cost-effective and less dependent on the SLA (18Ah) batteries, which would otherwise lead to higher maintenance costs. Future improvements should aim to balance the DOD to extend battery life while keeping the system efficient (Waldmann et al., 2014; Chen et al., 2022).

By using a gravity-based system that pumps water to a higher level for storage, this solar hybrid gravity system helps to lower energy use and boost battery performance at different heights (Chen et al, 2022). Hybrid systems like this can be used in elevators to lift people or goods, especially in residential buildings. The system can fill a water tank with up to 3,000 liters to support elevator loads. This matches studies on gravity-based energy storage for elevators, showing how practical and efficient gravitational energy can be for powering such systems.

4.4 SUMMARY AND CONCLUSION

The results of this study offer valuable insights into how mixed energy systems, like the solar hybrid gravity setup, can be optimized for different elevation levels. First, it was found that the system performs more efficiently at lower heights. Therefore, to reduce energy consumption, future designs should aim to minimize the elevation required for lifting. Second, using advanced battery management techniques, especially those that keep the battery's depth of discharge low can significantly enhance battery efficiency and extend its operational life. Third, adjusting the position of solar panels regularly to follow the sun can greatly improve the collection of solar energy, helping the system to perform better overall. One of the most important findings is the value of using a hybrid approach: by combining gravity-based energy storage with battery storage, the system becomes more reliable and efficient. This makes it a promising option for sustainable energy applications, especially in off-grid or rural areas.

Overall, the study demonstrates that solar hybrid gravity systems with battery backup can deliver effective, stable, and long-lasting energy solutions across various elevation levels. By optimizing system configuration and applying smart energy management techniques, major improvements in performance can be achieved. Further research is encouraged to evaluate the long-term durability and scalability of these systems in different environmental conditions and practical use cases.

CHAPTER FIVE

CONCLUSION

5.1 SUMMARY OF FINDINGS

The results of this study provide important insights into how hybrid energy systems can be optimized for operation at different elevation heights. First, improving elevation heights is critical. The system was found to work most efficiently at lower heights. This means that future system designs should aim to minimize the height required for water lifting, as lower elevations reduce the energy needed and improve overall system performance.

Next, advanced battery management plays a key role in boosting efficiency. Keeping the battery's depth of discharge low helps to maintain its performance over time and extends its lifespan. Using smart battery management techniques ensures more reliable energy storage and reduces the frequency of battery replacements.

In terms of solar energy collection, solar panel configuration is also vital. Adjusting the orientation of solar panels throughout the day to face the sun can significantly improve energy capture. This increases the amount of power available for battery charging and water pumping, especially during peak sunlight hours.

Another major finding is the benefit of combining gravity-based storage with battery systems. This hybrid approach offers greater reliability, as it allows energy to be stored in two forms chemical (battery) and gravitational (elevated water). The combination reduces dependence on just one storage method and provides better stability for off-grid and remote applications.

The study shows that solar hybrid gravity systems with battery storage are a promising solution for providing sustainable and dependable energy. With optimized system design and management, significant performance improvements can be achieved. Further research is encouraged to test how these systems perform under various environmental conditions, and to explore their long-term durability and scalability.

5.2 IMPLICATIONS OF THE STUDY

The study's results provide valuable insights into how to optimize hybrid energy systems that combine solar power, battery storage, and gravity-based storage. One key finding is that improving elevation height design is an important system perform best at lower elevations, so keeping the lifting height as low as possible helps reduce energy use and improve efficiency.

Another important aspect is advanced battery management. By keeping the battery's depth of discharge low and avoiding deep discharges, the system can maintain better performance over time and extend the battery's lifespan. Proper monitoring and control of the battery state can make a significant difference in overall system reliability.

Solar panel configuration also plays a major role. Regularly adjusting the panels to follow the sun's position can significantly increase energy capture, especially in areas with variable sunlight throughout the day. This improves the amount of energy available to charge the battery and lift water efficiently.

The study further highlights the benefits of a hybrid system, which uses both gravity and battery storage. This combination allows the system to operate more smoothly, providing backup during times when solar energy is low and enhancing energy reliability. The hybrid approach is especially useful in sustainable energy applications where stability and long-term performance are needed.

The solar hybrid gravity systems with battery storage show strong potential to provide efficient, reliable, and durable energy solutions for elevation-based applications. With proper system design and management, significant performance improvements can be achieved. Future research should focus on testing these systems under various real-world conditions to better understand their long-term durability and scalability.

5.3 LIMITATIONS OF THE STUDY

The results of this study offer valuable insights into how mixed energy systems can be optimized for different elevation levels. First, it was found that the system performs more efficiently at lower elevation heights. Therefore, to reduce energy consumption, system designs should aim to minimize the height at which energy is stored or used. Second, implementing advanced battery management strategies such as keeping the battery's depth of discharge can significantly improve the battery's performance and extend its usable lifespan.

Third, optimizing the solar panel configuration is also important. By regularly adjusting the angle and position of the panels to maximize exposure to sunlight, more solar energy can be collected, which increases the overall system efficiency. Fourth, the results highlight the clear benefits of a hybrid system. Combining gravity-based energy storage with battery storage increases system reliability and efficiency, making it a promising approach for sustainable and renewable energy solutions.

This study confirms that solar hybrid gravity systems integrated with battery storage offer a reliable, efficient, and long-lasting energy solution especially in applications involving height-based energy storage. By fine-tuning the system's design and operational strategies, substantial performance improvements can be achieved. Further research is encouraged to evaluate how these systems perform over time and how they can be scaled or adapted for various real-world conditions.

5.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The study's findings provide valuable insights into optimizing hybrid energy systems, especially for applications involving different elevation heights. First, the results show that the system operates more efficiently at lower elevations. Therefore, future designs should aim to minimize elevation height requirements, as doing so can help conserve energy and reduce the overall load on the system.

Second, implementing advanced battery management techniques—such as limiting deep discharges can significantly improve battery performance and extend its lifespan. Keeping the battery within a moderate discharge range reduces stress on the cells, ensuring more reliable and durable operation over time.

Third, the configuration and orientation of solar panels play a critical role in system efficiency. Adjusting the tilt and direction of the panels regularly to capture maximum sunlight throughout the day can greatly enhance energy harvesting and boost overall system performance.

Lastly, the research highlights the advantages of hybrid systems that combine gravity-based storage and battery storage. This dual-storage approach improves system reliability and energy availability, offering a more balanced and sustainable solution, especially in off-grid or rural environments.

The solar hybrid gravity systems with battery storage present a practical, effective, and long-lasting energy option. With thoughtful design and management—particularly in terms of elevation, battery health, and solar optimization these systems can be made even more efficient. Future research is encouraged to further examine their durability, scalability, and long-term effectiveness in real-world applications.

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GLOSSARY

Ampere-hour (Ah): A unit of electric charge, representing the amount of charge transferred by a steady current of one ampere flowing for one hour.

Battery Management System (BMS): A technology used to monitor and manage the performance and health of a battery, ensuring efficient charging, discharging, and overall battery safety.

Current (A): The flow of electric charge through a conductor, measured in amperes. It represents the rate at which charge flows through a point in the circuit.

Depth of Discharge (DoD): A measure of how much energy has been extracted from a battery, expressed as a percentage of the battery's total capacity.

Efficiency (%): The ratio of useful output energy to input energy, expressed as a percentage. It indicates how effectively a system converts energy from one form to another.

Energy (Wh): The amount of electrical energy consumed or produced, measured in watt-hours. It represents the capacity to perform work overtime.

Energy Storage: The capture of energy produced at one time for use later, often through batteries, pumped hydro storage, or other technologies.

Flow Rate (L/min): The volume of water pumped or moved per minute, measured in liters per minute. It indicates the speed of fluid movement in a system.

Gravity Hybrid System: An energy system that combines solar power with gravity-based mechanisms to optimize energy consumption and enhance efficiency.

Hybrid Energy Systems: Systems that combine multiple types of energy sources or technologies to improve overall efficiency and reliability.

Kilowatt (kW): A unit of power equal to 1,000 watts. It is commonly used to measure the power output of engines and the power consumption of electrical devices.

Load: The amount of electrical power or energy consumed by a device, system, or circuit at any given time.

Photovoltaic (PV) Technology: A method of converting sunlight directly into electricity using solar cells made of semiconductor materials.

Power (W): The rate at which energy is consumed or generated, measured in watts. It represents instantaneous energy output or consumption.

Renewable Energy: Energy obtained from sources that are naturally replenished, such as solar, wind, hydro, and geothermal energy.

Solar Hybrid Gravity System: A renewable energy system that integrates solar power with gravity-based storage and usage mechanisms to improve efficiency and reliability.

Solar Irradiance (W/m^2): The power per unit area received from the sun in the form of electromagnetic radiation, measured in watts per square meter.

State of Charge (SoC) (%): The current charge level of a battery, expressed as a percentage of its total capacity. It indicates how much energy remains in the battery.

Sustainability: The ability to meet present energy needs without compromising the ability of future generations to meet their own needs, often achieved using renewable energy sources.

Voltage (V): The electric potential difference between two points, measured in volts. It represents the force that drives electric current through a circuit.

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