ISSN 2462-2052 | eISSN 2600-8718
DOI: https://doi.org/10.37134/jsml.vol12.2.12.2024

Journal of Science and Mathematics Letters
Volume 12, Issue 2, 151-160, 2024

Research Article

Optimization of Solar Hybrid Gravity System with Battery Energy Storage for Elevation Systems

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Received: 13 April 2024; **Accepted:** 26 June 2024; **Published:** 1 July 2024

ABSTRACT

This research studies the performance and efficiency of a solar hybrid gravity system integrated with battery energy storage. The study aims to optimize the design using a 50-Watt Solar PV, an 18Ah SLA Battery, and a Water Gravity Energy Storage Tank. Energy consumption was evaluated using the SLA Battery, Solar PV, and a 22-Watt Water Pump at various tank heights to measure efficiency improvements and battery lifespan extension. The methodology involved three procedures with five data loggers: a flow meter, a pyranometer, and three unit Watt Meter. Initially, a fully charged SLA Battery was tested at different tank heights (1.5m to 3.5m) every 15 minutes. Subsequently, the 50-Watt Solar PV was tested directly at a 3-meter height. Lastly, the Solar Hybrid Gravity System with Battery Energy Storage was monitored for seven days at a 3-meter height. Results indicated a 600% increase in battery performance at 80% Depth of Discharge (DOD), suggesting the battery's optimal use as a backup power source, thereby extending its lifespan. The SLA Battery shows a 22.1% charging and discharging loss at 5% DOD, while the 22-Watt Water Pump is achieved an 11.0 L/min rate at peak solar radiation, with a maximum motor power of 24.32 Watts. The minimum solar radiation required for efficient pump operation was 300 W/m². In conclusion, the study optimizes the solar hybrid gravity system's energy efficiency, reduces battery dependence, and enhances battery lifespan, promoting sustainable solutions for elevation applications.

Keywords: Solar energy, gravity energy storage, battery efficiency, water pumping, energy optimization

1. INTRODUCTION

Renewable energy is essential to counter global energy issues, especially reducing carbon emissions and depending on fossil fuels. Solar energy is an option for power generation because it is sustainable and naturally available (Shahsavari & Akbari, 2018). However, solar energy systems are faced with high battery costs and short battery lifespans, which make them less cost-effective (Meza et al., 2014). Previous studies have highlighted various issues with battery systems in solar-powered applications. Doucette & McCulloch (2011) noted that batteries present inefficiencies and high costs with energy losses of around 20-25% during charging and discharging. Waldmann et al. (2014) discussed the importance of cycle life in batteries that battery aging can reduce the performance to hold a battery charge by approximately 15-20% over 100 cycles and will decrease efficiency and reliability. Additionally, Amini & Mohammadi-Ivatloo (2017) reported a 30-35% energy loss during electricity conversion due to inefficiencies in battery systems. Johnson & Smith (2015) addressed elevation changes that affect the energy required to pump water at a higher level with high energy consumption and reduced system efficiency. Research by Blanco et al. (2018) supports the use of gravity-based storage and the potential to improve energy storage efficiency and sustainability. Reza et al. (2024) showed that optimized hybrid systems could enhance energy storage efficiency, reduce operational costs, and improve the reliability of solar-powered applications. Amini & Mohammadi-Ivatloo (2017) also reported that hybrid systems could reduce energy losses and improve system performance by integrating multiple energy storage methods. However, Doucette & McCulloch (2011) and Waldmann et al. (2014) have shown that battery energy losses can be minimized and extend battery life by advanced battery technologies and management systems.

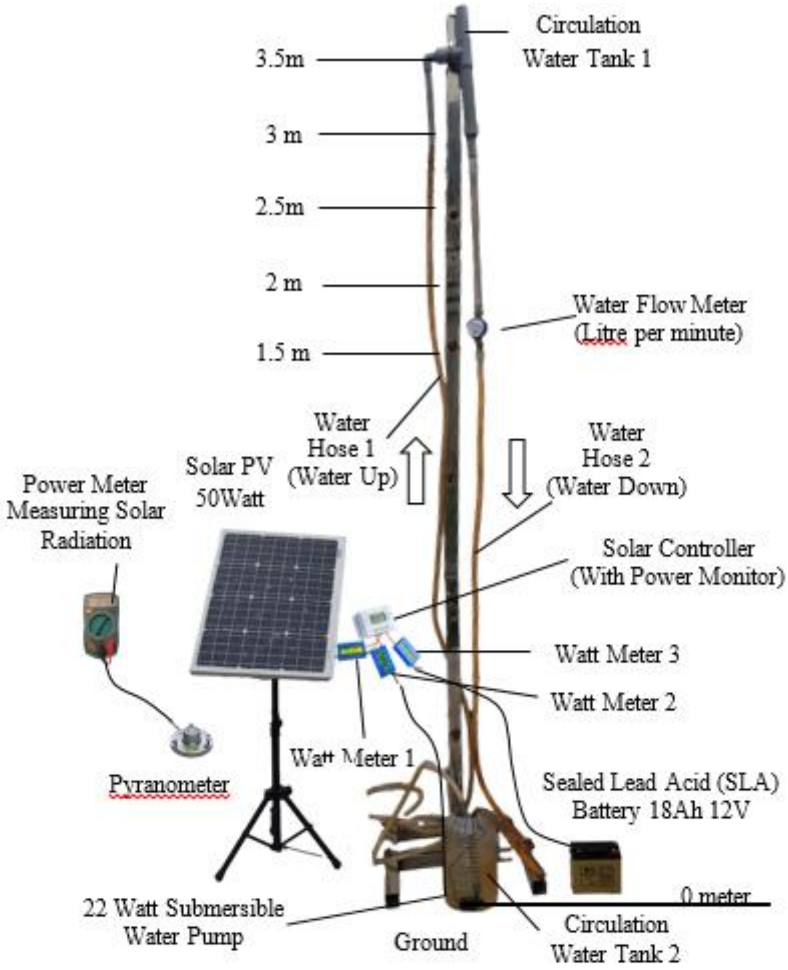
This study focuses on the inefficiencies of conventional solar-powered water pumping systems, especially at different elevations. Elevation changes impact the energy required to pump water, leading to higher energy consumption and reduced system efficiency. By incorporating gravity-based mechanisms as energy storage, this research proposes a solar hybrid gravity system with an SLA (18Ah) Battery. The gravity-based energy uses a water pump to increase water storage to a higher level and store it in the water tank. This system is designed to reduce energy usage on batteries and enhance gravity energy performance at higher elevations.

2. MATERIALS AND METHODS

This study will perform an experimental research design to evaluate the performance of a solar hybrid gravity system integrated with battery energy storage for water pumping at higher levels of water storage applications. The primary focus is assessing energy consumption, efficiency, and battery lifespan at different elevations. The experimental setup includes a solar PV hybrid gravity and a battery storage system.

2.1. Devices and Apparatus

The experiment employed five data loggers: a flow meter, a pyranometer, and three units of watt meters, as in Figure 1. The flow meter recorded the volume of water pumped at Circulation Water Tank 1. Circulation Water Tank 2 will be used to return the water from the water pump to Circulation Water Tank 1. The submersible water pump used is 22-Watt to circulate the water from circulation Water Tank 1 to circulation Water Tank 2. Pyranometers are used to measure solar radiation from sunlight. It will be placed parallel to the solar panel. Solar PV 50-Watts (18 Voc) is used with a 12V SLA (18Ah) Battery together with a solar controller. The water pump will be connected to Water Hose 1 to increase the level of water and fill in the Circulation Water Tank 1. Water Hose 2 is used to return the water to Circulation Water Tank 1. Three units of watt-meter will be used to record from the Solar PV, SLA (18Ah) Battery, and Water Pump. The Solar PV 50-Watts is positioned to receive maximum sunlight throughout the day, ensuring optimal energy capture, as illustrated in Figure 2. It is connected to the solar controller which will manage the power to charge the SLA (18Ah) battery and 22-Watt Water Pump. The Watt Meter will be connected to the solar controller where Watt Meter 1 is connected to Solar PV 50-Watts, Watt Meter 2 is connected to SLA (18Ah) Battery, and Watt Meter 3 is connected to a 22-Watts Water Pump. An SLA (18Ah) Battery stores the excess energy generated by the solar panels. Below is the description of the experiment device and apparatus setup used in the experiment:



Description

1. **Solar PV 50-Watts**: Positioned to receive maximum sunlight throughout the day, ensuring optimal energy capture.
2. **Pyranometer**: used to measure solar radiation from sunlight
3. **Solar Controller**: manage power to charge the SLA (18Ah) battery and 22-Watt Water Pump
4. **Watt Meter 1**: Connected to Solar PV 50-Watts
5. **Watt Meter 2**: Connected to SLA (18Ah) Battery
6. **Watt Meter 3**: Connected to a 22-Watts Water Pump
7. **Sealed Lead Acid (SLA) Battery**: Stores excess energy generated by the solar panels.
8. **22-Watts Water Pump**: Pumps water from the circulation water tank to the water tank at different heights using energy generated by the battery.
9. **Circulation Water Tank 1**: Stores pumping water from circulation Water Tank 2 at a higher elevation, creating gravitational potential energy at different heights.
10. **Circulation Water Tank 2**: Stores return water from Circulation Water Tank 1.
11. **Water Flow Meter (Litre per minute)**: Measure the volume of water stored in the tank.
12. **Water Hose 1**: C onnection hose for running pumping water from 22-Watts Water Pump to Circulation Water Tank 1.
13. **Water Hose 1**: C onnection hose for running gravitational water from Circulation Water Tank 1 to Circulation Water Tank 2.

Figure 1. Device and apparatus

The setup, as illustrated in Figure 2, the Solar PV 50-Watts used to charge SLA (18Ah) Battery and directly drive the 22-Watts Water Pump to pump the water to Circulation Water Tank 1. In this experiment, the water tank will be placed at different levels (1.5m, 2.0m, 2.5m, 3.0m, and 3.5m) and stored in the Circulation Water Tank 1. Circulation Water Tank 1 is a temporary water tank storage that is used to replace the actual water tank and to generate gravity energy storage. Water tank capacity has been recorded using a Water Flow Meter.

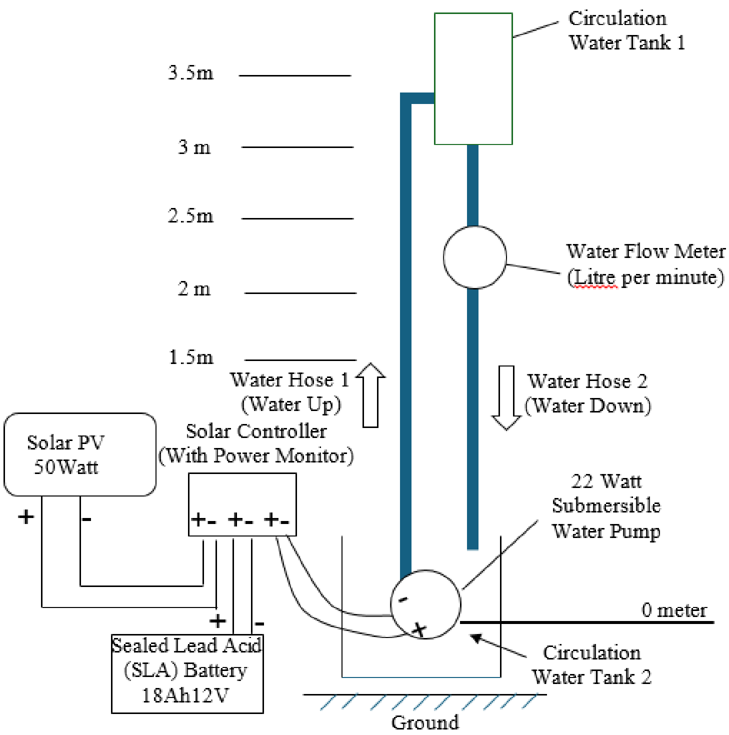


Figure 2. Schematic diagram of the experimental setup

2.2. Data Collection Procedure

The data collection procedure for this experiment was divided into three main procedures, each focusing on the specific parameters to be measured.

2.2.1. Energy Consumption by Battery as Energy Storage

The first procedure is to measure the energy consumption of the 22-Watts Water Pump using a fully charged SLA (18Ah) Battery. The battery charger is used to charge the SLA (18Ah) battery to 12.5V with 100% SOC. The 22-Watt Water Pump was operated continuously, pumping water to Circulation Water Tank 1 at different elevation heights (1.5m, 2.0m, 2.5m, 3.0m, and 3.5m). The voltage was monitored until dropping to 11V (DOD 95%) to prevent over-discharge. The recorded data was taken for 15 minutes (during the analysis it will be run in 60 minutes) with key parameters including voltage (Volt), current (Ampere), power (Watt), and energy (Watt hour). Additionally, the volume of Flow Water Volume (Litres) is also taken every 15 minutes. These data will help to understand the battery's performance and efficiency at various elevations.

2.2.2. Energy Consumption by Solar to Water Pump Directly System

The second procedure is to measure the energy consumption of the 22-Watts Water Pump directly using Solar PV 50-Watts with 18 Voc. Solar PV is used to power the 22-Watts Water Pump directly depending on sunlight conditions. A pyranometer was used to measure the solar radiation (SR) to ensure the Solar PV 50-watts were positioned to receive maximum sunlight. The 22-Watts Water Pump needs a minimum of solar radiation (SR) to run smoothly but without exceeding the voltage limit that could damage the 22-Watts Water Pump. The minimum SR determined was 300 W/m². It is necessary to power the 22-Watts Water Pump motor to pump water at a height of 3 meters and produce a motor power at 6.57 Watts. So, the angle of the solar panels was consistently adjusted to ensure optimal energy received. Consistent adjustment of solar panel angles is important for maintaining high water pump performance (Ghosh & Dutta, 2020; Shahsavari & Akbari, 2018). The maximum motor power measured was 24.32 Watts and produced a water pump rate of 11.0 L/min. The 22-Watt Water Pump was operated continuously, pumping water to Circulation Water Tank 1 at different three-meter elevation heights. The recorded data was taken for 15 minutes (during the analysis it will be run in 60 minutes) with key parameters including solar radiation (W/m²), water pump power (Watt), water volume pumped (Litres), voltage (Volt), current (Ampere), power (Watt), and energy (Watt hour). Additionally, the volume of Flow Water Volume (Litres) is also taken every 15 minutes. This data will help to understand the efficiency of direct solar power in running water pump under different solar radiation conditions.

2.2.3. Hybrid Energy System at 3 Meter Elevation Under Solar Radiation

The third procedure is to measure the performance of the Solar Hybrid Gravity System with Battery Energy Storage. The system as shown in Figure 1 is fully set up with a Solar PV 50-Watts and SLA (18Ah) Battery to power a 22-Watts Water Pump. The system included a pyranometer, solar controller, circulation water tank 1, circulation water tank 2, water flow meter, and watt meter. The SLA (18Ah) Battery was set to a 5% state of charge (SOC) with an initial voltage of 11V when starting the experiment in a partially drained battery condition. The solar controller is used to manage the power to store the excess energy for SLA (18Ah) Battery generated by the Solar PV is 50 Watts depending on the amount of Solar Radiation SR. A pyranometer was used to measure the solar radiation (SR) to ensure the Solar PV 50-watts were positioned to receive maximum sunlight. The 22-Watts Water Pump was operated continuously and powered by an SLA (18Ah) Battery pumping water to Circulation Water Tank 1 at an elevation of 3 meters height. The recorded data was taken in seven days of monitoring with parameters battery SOC (%), voltage (Volt), current (Ampere), power (Watt), energy (Watt hour), solar radiation (W/m²) and water volume pumped (Litres). From the data, the energy stored in the battery and system performance will be measured by getting data on the energy needed to fill the circulation water 1 at the 3-meter elevation. These data will help to understand the potential of the hybrid system to optimize gravity energy storage in running the 22-Watts Water Pump under different solar radiation conditions.

3. RESULTS AND DISCUSSION

This section presents the results of the experiments conducted to evaluate the performance of the solar hybrid gravity system at various elevations. The findings are discussed in detail, focusing on energy consumption, efficiency, and battery lifespan. Figures and tables are included next to the relevant text for clarity.

3.1. Energy Consumption by Battery as Energy Storage

SLA (18Ah) Battery 12 Ah 12 V shows the charging and discharging loss is 22.1%. High energy loss indicates inefficiency, emphasizing the need for more efficient battery systems (Doucette & McCulloch, 2011). It found that during charging the energy is used to store energy while during discharging energy is used directly to the load. The hysteresis applies to the battery characteristics. In this experiment, the Deep of Discharge (DOD) has been set up to 5% which is too low for battery life, as shown in Figure 3. With this DOD Value, the SLA (18Ah) Battery only can have a minimum life cycle which is 200 cycles. Normally, SLA (18Ah) Battery can be used for longer cycles which has been set up to DOD 50% and can achieve 400-500 cycles.

The cycle of the battery also reduces the energy capacity, storage with cycle and time. Reduced cycle life at 5% DOD suggests optimizing DOD can improve battery longevity (Waldmann et al., 2014).

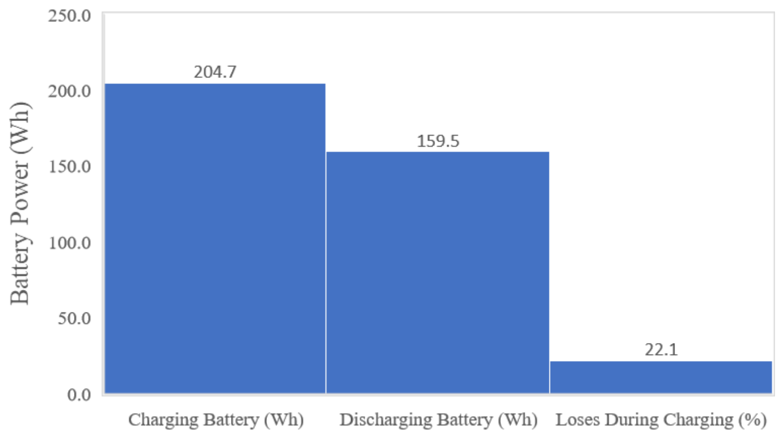


Figure 3. Charging and Discharging SLA (18Ah) Battery

Experiment using the pump SLA (18Ah) Battery to pump the water from base 0m to maximum height 3.5 m, see Figure 4. A water Pump of 22 watts may reach a maximum Height of 6.5 m which can be calculated using Equation 1:

$$W_v = -1.32W_h^3 + 16.3W_h^2 - 1282.9\, W_h + 8015.6 \qquad \textit{Equation 1}$$

W_v = Water volume collected in the water tank W_h = Water level height

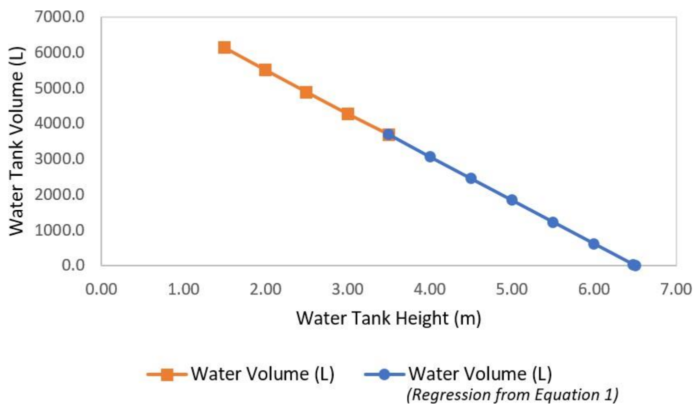


Figure 4. Water Tank Volume (L) vs Water Tank Height (m)

The limitation of this study, it uses a new SLA (18Ah) battery which is the cycle still in high performance. As the SLA (18Ah) battery reduces its performance with several cycles and time, the water storage using the water pump by the battery also will be reduced. Increased energy consumption at higher elevations indicates the importance of optimizing pump efficiency and battery management (Amini & Mohammadi-Ivatloo, 2017).

3.2. Energy Consumption by Solar to Water Pump Directly System

The results of this experiment show minimum solar radiation (SR) to drive the water pump motor to pump the water to the level 3.0 m is 300 w/m^2 from the solar panel 50 watts, which produces the motor power is 6.57 watts. The rate of the water pump increases with the increment of solar radiation intensity followed by the motor power. The maximum of motor power is 24.32 watts which means the rate of the water pump to the tank is 11.0 L/min, see Figure 5. To ensure optimal energy capture, solar panels were consistently adjusted (Jain & Agarwal, 2018). The system effectively utilizes solar energy, reducing reliance on battery storage during peak solar radiation (Ghasempour & Kamal, 2021).

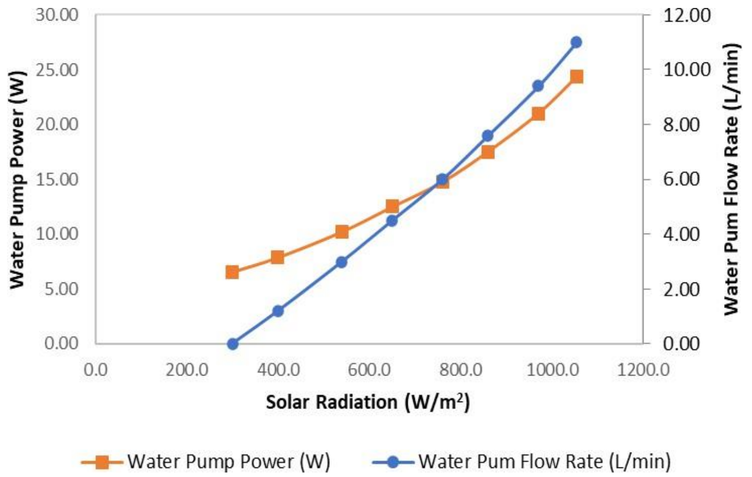


Figure 5. Solar Radiation and water pump for 3m Water Tank Level

Solar radiation shows the power of the water pump power increases with intensity. It can be defined as in Equation 2 by referring to the chart in Figure 5. The relationship between solar radiation and pump power suggests optimization of solar panel orientation can maximize efficiency (Chen & Lee, 2022).

$P_w = 0.0000000147\, Sr^3 - 0.0000124516 Sr^2 + 0.0180597019 Sr + 1.8211572845$ *Equation 2*
Sr = Solar Radiation (W/m^2) P_w = Water Pump Power (W)

The Water pump driven by the Solar PV 50-Watt can be converted into energy storage by a water tank at the 3.0 m level as Equation 3.

W_v=0.000355722P_w3)-0.0276856658P_w2)+1.1907428723P_w–6.6960578923 *Equation 3*
P_w = Water Pump Power (W)
W_v = Water tank Flow Rate (L/min)

The results show that when the solar radiation is high, the water pump can directly power the water pump to the tank, which means no power from the battery being used. Consistent adjustment of solar panel angles is crucial for maintaining high water pump performance (Shahsavari & Akbari, 2018).

3.3. Solar Hybrid Gravity System with Battery Energy Storage

In the Solar Hybrid Gravity System with Battery Energy Storage, the battery will not be used to store energy but will be combined with higher water storage levels. The battery will store the electric energy and water with a higher level will be stored in the tanks as Potential Energy. It has been defined as a gravity hybrid with a battery because both energy will be used for the system that requires different levels in height such as the elevator system requiring potential energy in their application. Hybrid systems' use of gravitational potential energy complements solar energy storage, enhancing efficiency and reducing battery dependency (Lukic et al., 2006).

ISSN 2462-2052 | eISSN 2600-8718
DOI: https://doi.org/10.37134/jsml.vol12.2.12.2024

The result of seven days of experiment under solar radiation showed that both a battery and a higher level of water storage can be used to store the potential energy due to gravity. SLA (18Ah) batteries with DOD 95% can only have approximately 200 cycles, which is normal for SLA (18Ah) batteries (Table 1). The water storage in a tank has less maintenance, and the water circulation will remain at its volume. The results show that the characteristics of the battery will drop their energy performance with the cycle but water storage in the tank by water pump circulation remains. After the SLA (18Ah) battery reaches its full cycle the water storage by the tank increases its ratio to 100% performance, the SLA (18Ah) battery needs to be changed but water storage remains. Consistent water storage performance indicates the advantages of gravity-based energy storage over battery degradation (Amini & Mohammadi-Ivatloo, 2017).

Table 1. Solar Hybrid Gravity System with Battery Energy Storage

Details	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**
	20-Mar-24	**21-Mar-24**	**22-Mar-24**	**23-Mar-24**	**24-Mar-24**	**25-Mar-24**	**26-Mar-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 50Watt DIRECT to pump to 3m water tank/day (Wh)	55.6	77.5	102.3	115.2	84.2	107.0	114.9
SLA Battery Energy (Charging by Solar PV 50Watt/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)	77.9	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 (Litre)**	**950.0**	**1562.9**	**2224.8**	**2609.3**	**1526.1**	**2361.9**	**2616.8**
Total Water Tank Storage by DIRECT Solar PV 50Watt 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	22.1	26.3	28.2	22.1	27.1	29.0
*** SLA Battery energy DOD 95% (discharging water pump at EARLY Cycle (Litre)**	**2092.9**	**2701.4**	**3211.4**	**3448.0**	**2700.2**	**3310.2**	**3552.9**
SLA Battery energy DOD 95% (discharging water pump after HALF Cycle (Litre)	1046.5	1350.7	1605.7	1724.0	1350.1	1655.1	1776.5
SLA Battery energy DOD 95% EARLY (discharging water pump after FULL Cycle (Litre)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
%Ratio of Water Pump (Tank storage) and SLA Battery storage (Litre) at EARLY cycle (DOD 95%)	31%	37%	41%	43%	36%	42%	42%
%Ratio of Water Pump (Tank storage) and SLA Battery storage (Litre) after HALF Cycle (DOD 95%)	48%	54%	58%	60%	53%	59%	60%

%Ratio of Water Pump (Tank storage) and SLA Battery storage (Litre) after FULL Cycle (DOD 95%)	100%	100%	100%	100%	100%	100%	100%
*** Total Water Tank Storage (Litre) at 3m level with direct water pump (22Watt) 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**

* indicate the 7 days experiments of HYBRID Water Tank Storage and SLA Battery storage

From this finding, the battery energy storage chooses that DOD only reduces the cycle but actually, the true performance of the battery energy storage remains the same. The performance of the SLA (18Ah) Battery can be increased by reducing the DOD of the battery, where integrating with the circulation water tank 1 may improve the hybrid performance of energy storage. By lowering the DOD of the battery, it will increase the cycle of the battery furthermore it will reduce the cost of energy storage by the battery. For the SLA battery, the cycle for DOD 100% is 200 cycles, for 50% is 500 cycles and 30% is 1200 cycles. From this experiment using Hybrid Gravity System with Battery Energy Storage may increase to 600% of battery performance at DOD 80% and the battery can be only used as a backup power (UPS) which means the replacement for the battery will be longer. Suppose there is no gravity energy storage included in this system and only relies on the battery with the same circulation water tank level storage (3 meters). In that case, it will required to change the battery every 200 cycles (DOD 95%). As a result, the system will be more cost-effective with the least dependence on SLA (18Ah) batteries, contributing to the higher cost of system maintenance. Future optimizations should balance DOD to extend battery life while maintaining system performance (Waldmann et al., 2014; Chen & Lee, 2022).

By utilizing a gravity-based system that pumps water to a higher level and stores it in a tank, this solar hybrid gravity system aims to lower energy consumption and improve battery performance across various elevations (Chen & Lee, 2022). Hybrid systems can be applied to elevators to lift humans or goods, especially in residential applications. The system can fill a water tank with up to 3,000 litres of storage supported by elevator loads. This aligns with studies on gravity-based energy storage systems for elevators, demonstrating the feasibility of efficiently using gravitational energy to power elevators (Lift Energy Storage Technology, 2022).

4. CONCLUSION

This study has achieved its objectives in optimizing the design and performance of a solar hybrid gravity system with battery energy storage. It was found that using a Hybrid Gravity System with Battery Energy Storage may increase 600% of battery performance at DOD by 80%. The battery can only be used as a backup power (UPS) which means the replacement for the battery will be longer. The SLA (18Ah) Battery shows a charging and discharging loss is 22.1% with 5% Deep of Discharge. At the same time, the 22-Watt Water Pump achieved a rate of 11.0 L/min at peak solar radiation, with a maximum motor power of 24.32 Watts while the minimum solar radiation required for efficient operation of the water pump was 300 W/m². In conclusion, this study has optimized the solar hybrid gravity system on efficiency energy consumption, reducing battery dependency and increasing the battery lifespan cycle, to move toward a sustainable solution for elevation applications.

Declaration of Interest

The authors declare that there is no conflict of interest.

Acknowledgment
The authors wish to express their gratitude to Kulliyyah of Engineering (KOE), International Islamic University Malaysia (IIUM) and ENVIRO-AXIS SDN. BHD. for lab facilities and technical knowledge support.

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