The Indonesian Journal of Computer Science
www.ijcs.net
Volume 15, Issue 1, February 2026
https://doi.org/10.33022/ijcs.v15i1.5101

Optimization of Charging and Discharging Performance in a PV-Integrated Piston-Based Gravity Energy Storage System

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Article Information

Received : 1 Feb 2026
Revised : 27 Feb 2026
Accepted : 28 Feb 2026

Keywords

Piston-Based Gravity Energy Storage, Photovoltaic Power, Energy Storage Systems, Dynamic Modeling, MATLAB/Simulink

Abstract

The rapid integration of photovoltaic systems into modern power networks has created operational challenges due to their intermittent and fluctuating output. To maintain power balance and enhance grid stability, large-scale and efficient energy storage solutions are essential. This paper presents the dynamic modeling and simulation of a piston-based gravity energy storage system integrated with PV power plant. A detailed MATLAB/Simulink model is developed, including the PV array, power electronic converters, motor–pump system, piston-based gravitational storage mechanism, and generator–load interface. During periods of surplus PV generation, the system operates in charging mode by driving the motor–pump unit to lift the piston, thereby storing energy as gravitational potential. During low PV output, the stored energy is released through the turbine–generator unit to support the load. Simulation results verify stable electrical performance, smooth transition between operating modes, and effective mitigation of PV power fluctuations, demonstrating the technical feasibility of the proposed PGES configuration.

A. Introduction

The rapid expansion of photovoltaic (PV) power generation has become a key driver in the global transition toward low-carbon and sustainable energy systems. Due to declining installation costs, modularity, and environmental benefits, large-scale PV plants are increasingly integrated into modern power grids. However, the inherent intermittency and variability of solar energy introduce significant challenges, including power fluctuations, voltage instability, and reduced reliability of energy supply. These challenges necessitate the deployment of efficient and scalable energy storage technologies to ensure stable grid operation and effective utilization of renewable energy resources[1].

Energy storage systems play a crucial role in mitigating the mismatch between energy generation and demand in PV-dominated power systems. Conventional storage technologies, such as electrochemical batteries, offer fast response times and high energy density but suffer from limited lifespan, high capital costs, environmental concerns, and performance degradation under large-scale, long-duration operation[4, 5]. Pumped hydro energy storage (PHES), while widely adopted, requires specific geographical conditions and large water reservoirs, which restrict its deployment potential [5,6]. Other technologies, including compressed air energy storage and flywheel systems, present additional limitations related to efficiency, cost, or scalability.

Gravity-based energy storage has recently emerged as a promising alternative for large-scale and long-duration energy storage applications. Among the various gravity storage concepts, piston-based gravity energy storage (PGES) systems offer unique advantages, such as high durability, mechanical simplicity, long service life, and minimal environmental impact[2, 3]. In a PGES system, surplus electrical energy is stored by lifting a massive piston using hydraulic pressure, while energy is recovered by allowing the piston to descend and drive a hydraulic turbine or generator. This mechanism enables effective energy storage without the geographical constraints associated with traditional pumped hydro systems[7, 8].
Despite the growing interest in gravity-based energy storage technologies, existing studies have primarily focused on conceptual designs, material selection, or standalone system analyses[11,12]. Limited research has been conducted on the detailed modelling and performance evaluation of piston-based gravity energy storage systems when integrated with renewable energy sources, particularly photovoltaic power plants. Furthermore, the dynamic interaction between PV generation profiles and PGES charging and discharging operations remains insufficiently explored in the literature[13,14].

To address these research gaps, this paper presents the modelling and performance analysis of a piston-based gravity energy storage system integrated with a photovoltaic power plant. Mathematical models describing the PV generation, hydraulic dynamics, piston motion, and energy conversion processes are developed. The proposed system is evaluated under realistic operating scenarios to assess its ability to smooth PV power fluctuations, enhance energy dispatch reliability, and improve overall system performance. The findings of this paper demonstrate the technical feasibility and effectiveness of piston-based gravity energy storage as a viable solution for large-scale photovoltaic energy integration.

B. Gravity Energy Storage with PV Supply System

The proposed system consists of a photovoltaic (PV) power plant integrated with piston-based gravity energy storage (GES) system to enable efficient energy storage and dispatch. As shown in Figure 1, the electrical power generated by the PV array is first regulated using a DC–DC boost converter to maintain a stable DC voltage level. This regulated power is then converted into alternating current through a DC–AC inverter to drive multiple electric motors.

During the charging mode, the motors convert electrical energy into mechanical energy to lift the piston within the gravity energy storage unit, thereby storing energy in the form of gravitational potential energy. In the discharging mode, the downward motion of the piston drives multiple generators, which convert the stored mechanical energy back into electrical energy. The generated power is then supplied to the connected load.

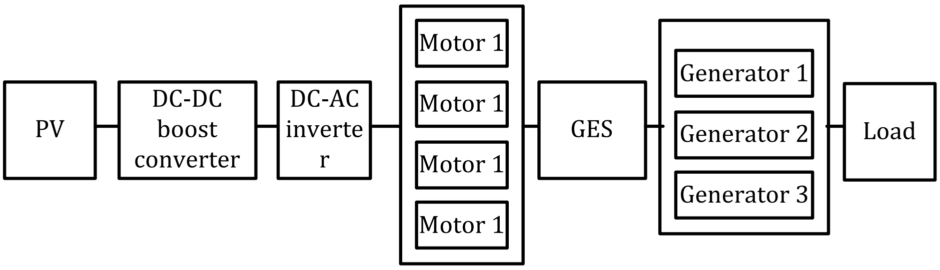


Figure 1. Block diagram of the PV-integrated piston-based gravity energy storage (GES) system

C. Piston-Based Gravity Energy Storage System

Figure 2 illustrates the primary components of the gravity storage system explored in this research. The PGES system stores energy in the form of gravitational potential energy by vertically lifting a massive piston within a cylindrical container[15,16]. The system primarily comprises a reinforced container, a high-density piston, hydraulic fluid, a reversible pump-turbine unit, and an electrical generator. The piston is guided within the container to ensure stable vertical motion while minimizing frictional losses.

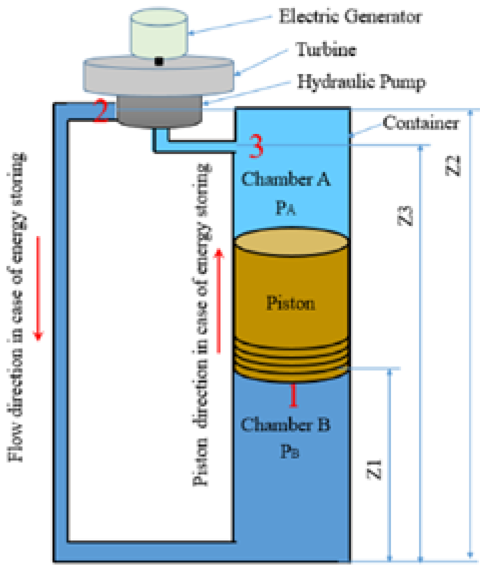


Figure 2. Schematic illustration of gravity energy storage [9,10]

During the charging process, excess electrical power from the PV plant drives the hydraulic pump, which pressurizes the working fluid beneath the piston. The increased hydraulic pressure lifts the piston upward, thereby storing energy as gravitational potential energy. The amount of stored energy is directly related to the piston mass, vertical displacement, and gravitational acceleration.

During the discharging process, the piston descends under gravitational force. The downward motion forces the hydraulic fluid through the turbine, which drives the generator to produce electrical power. The generated electricity is supplied to the load or injected into the grid, compensating for reduced PV generation. Flow control valves and braking mechanisms are employed to regulate piston velocity and ensure stable power output during energy recovery.

In place of conventional battery storage, a utility-scale solar power plant in Yinmarpin Township, Monywa District, Sagaing Region, is being developed with a gravity energy storage (GES) system. This study focuses on optimizing the storage component of solar energy integration by identifying the most efficient and feasible solution for large-scale applications. Predictive data are analysed to determine selection trends and optimal storage capacity in the chosen site, adhering to international energy storage standards. The site, located at latitude 22.1099° N and longitude 95.0607° E is illustrated in Figure 3. In addition to environmental benefits, the selected location aims to reduce the overall construction cost of the GES facility.

Figure 3. Location of Selected Site and Neighbouring Mine

Conducting a load profile analysis represents the initial stage in the design of an electric power system. The load profile depends on the characteristics of electrical loads and the behaviour of consumers. This analysis is crucial for determining load sizing and estimating daily energy consumption in kilowatt-hours (kWh). In this study, a total of 26,000 households were considered to evaluate the 24–hour load demand of the proposed gravity energy storage (GES) integrated with a photovoltaic (PV) system. The load demand in the study area was assessed at different times of the day to derive the average daily load profile. The hourly load demand for Yinmarpin Township is illustrated in Figure 4.

D. Power Conversion and Control Strategy

A power electronic interface is used to manage energy flow between the PV plant, PGES system, and the electrical grid or load. During periods of surplus PV generation, the control system prioritizes direct power supply to the load, while excess energy is allocated to the PGES charging process. Conversely, when PV output falls below the required level, the control system initiates the PGES discharging mode to maintain continuous power delivery.

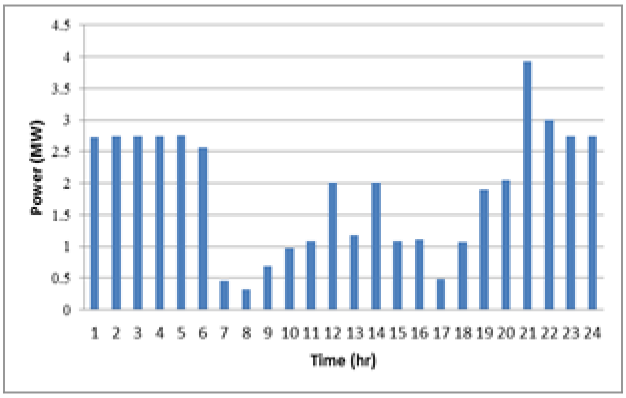


Figure 4. Daily Load Profile

The control strategy is designed to ensure smooth transitions between charging, idle, and discharging modes while preventing excessive mechanical stress on the piston and hydraulic components. Sensors are employed to monitor piston position, hydraulic pressure, flow rate, and electrical power, enabling real-time feedback control and safe system operation.

E. Mathematical Modelling Of The System

This section presents the mathematical models of the photovoltaic (PV) power plant and the piston-based gravity energy storage (PGES) system. The developed models describe the energy conversion processes, piston dynamics, and hydraulic behaviour governing the charging and discharging operation. The output power of the PV plant depends primarily on solar irradiance and cell temperature. The instantaneous electrical power generated by the PV array can be expressed as:

$$P_{PV}(t) = \eta_{PV} A_{PV} G(t) \quad (1)$$

Where
η_{PV} is the PV conversion efficiency,
A_{PV} is the total PV array area (m^2), and
$G(t)$ is the solar irradiance (W/m^2).

The electrical energy produced by the PV plant over a time interval, t is given by

$$E_{PV} = \int_0^t P_{PV}(t)dt \quad (2)$$

When the PV power exceeds load demand, the surplus power is directed to the PGES system for energy storage. The PGES system stores energy in the form of gravitational potential energy by lifting a massive piston vertically. The stored gravitational energy is expressed as

$$E_{GES} = mgh \quad (3)$$

Where

m is the piston mass (kg),

g is gravitational acceleration (9.81 m/s^2), and h is the vertical displacement of the piston (m). The resultant force acting on the piston is determined by the combined effects of hydraulic pressure, gravitational loading, and damping forces associated with hydraulic and mechanical losses. The net force equation becomes:

$$F_{net} = F_h - F_g - F_d \quad (4)$$

The maximum energy storage capacity depends on the allowable piston stroke and container height. The vertical motion of the piston is governed by Newton's second law. The force balance on the piston during motion is given by

$$m\frac{d^2h}{dt^2} = F_h - mg - F_f \quad (5)$$

In the proposed piston-based gravity energy storage (GES) system, the hydraulic force plays a critical role in governing the motion of the piston during both charging and discharging operations. The hydraulic force acting on the piston is primarily generated by the pressure difference across the piston surface and is directly related to the hydraulic head and fluid properties. The hydraulic force is defined as

$$F_h = P_h A_p \quad (6)$$

Where

F_h is the hydraulic force acting on the piston (N),

F_f represents frictional and mechanical losses (N),

P_h is the hydraulic pressure beneath the piston (Pa), and A_p is the piston cross- sectional area (m^2).

The hydraulic pressure required to lift the piston during charging is expressed as

$$P_h = \frac{mg}{A_P} + \Delta P_{loss} \quad (7)$$

Where ΔPloss represents pressure losses due to pipe friction, valves and fittings. The volumetric flow rate of the hydraulic fluid is related to piston velocity as

$$Q = A_P \frac{dh}{dt} \quad (8)$$

During the charging mode, the hydraulic force opposes the upward motion of the piston, requiring the motors to supply sufficient mechanical force to overcome both the hydraulic force and the piston weight. The electrical power required by the pump is

$$P_{pump} = \frac{P_h}{\eta_{pump}} \tag{9}$$

Where η_{pump} is the pump efficiency. The charging condition is defined as $P_{PV} > P_{load}$. Under this condition, the piston is lifted, and energy is stored as gravitational potential energy. During the discharging mode, the hydraulic force assists the downward motion of the piston and contributes to the torque applied to the generators. The electrical power output is expressed as

$$P_{out} = \eta_t \eta_g P_h \tag{10}$$

Where η_t is the turbine efficiency, and η_g is the generator efficiency. The recovered electrical energy over a discharge period is

$$E_{out} = \int_0^t P_{out}(t)\,dt \tag{11}$$

F. Simulation Setup and Parameters

To evaluate the performance of the proposed photovoltaic–piston gravity energy storage (PV–PGES) system, a comprehensive simulation model was developed using MATLAB/Simulink. The simulation framework integrates the PV generation model, hydraulic subsystem, piston dynamics, and electrical power conversion components to analyse system behaviour under realistic operating conditions.

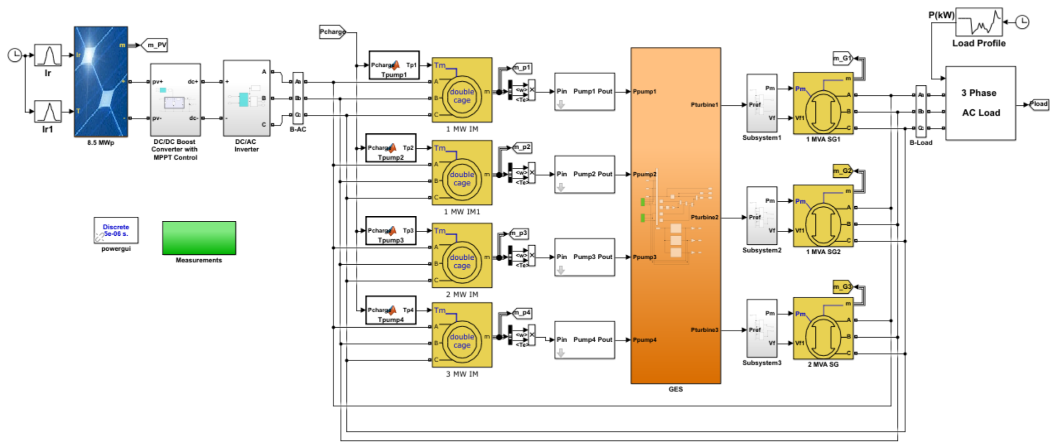


Figure 5. Simulation Model of the Proposed PGES Integrated with PV Supply System

The simulation of the system was implemented in MATLAB/Simulink due to its flexibility in modeling multi-domain energy systems and its widespread use in renewable energy research. The model consists of interconnected subsystems representing the PV plant, hydraulic pump-turbine unit, piston motion, and electrical generator. Continuous-time simulations were performed to capture the dynamic interaction between PV power fluctuations and PGES charging and discharging processes.

A fixed-step solver was employed to ensure numerical stability and accurate tracking of piston motion and hydraulic flow. The total simulation duration was selected to represent one full day of operation, allowing the evaluation of system performance over varying solar irradiance conditions.

The PV plant was modelled using a time-varying solar irradiance profile representing a typical daily solar pattern. The irradiance data were applied as an input signal to the PV subsystem, resulting in fluctuating electrical power output throughout the simulation period. Temperature effects were assumed constant to focus on the impact of irradiance variability on system performance. The PV output power was continuously compared with the load or grid demand to determine the operating mode of the PGES system. When PV generation exceeded demand, the system entered charging mode; otherwise, the PGES system operated in discharging mode.

Figure 6 illustrates the MATLAB/Simulink realization of the mathematical model. The hydraulic force acting on the piston is computed according to (Eq. (5)). The net force acting on the piston is obtained by combining the hydraulic force, gravitational force, and loss-related damping terms, as expressed in (Eq. (4)). The resulting piston acceleration is calculated using Newton's second law in (Eq. (5)), and the piston velocity and displacement are derived through successive integration. MATLAB Function blocks are employed to implement the force equations and loss models, while the Simulink integrator blocks represent the continuous-time dynamics of the piston. The model outputs piston force, velocity, and position signals, which are used for system performance evaluation and control strategy implementation.

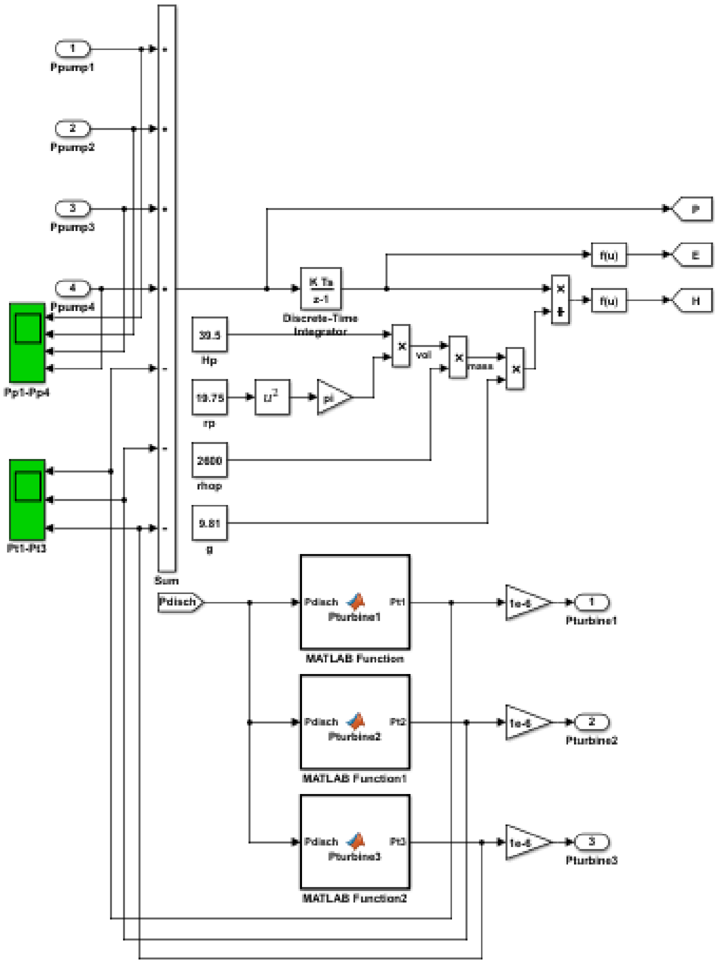


Figure 6. MATLAB/Simulink Implementation Of The Hydraulic Force And Piston Dynamic Model For The Proposed PGES System

Table 1 summarizes the key parameters used in the simulation. These values were selected based on typical design considerations and previously reported studies on gravity energy storage systems.

Table 1. Simulation parameters of the PV-PGES system

Parameter	**Symbol**	**Value**	**Unit**
Piston mass	m	1.0×10^7	kg
Piston diameter	D_p	50	m
Gravitational acceleration	g	9.81	m/s^2
Pump efficiency	η_{pump}	0.9	-
Turbine efficiency	η_t	0.92	-
Generator efficiency	η_g	0.95	-
PV efficiency	η_{PV}	0.18	-
Simulation time	T	24	h

G. Result and Discussion

This section presents and discusses the simulation results of the integrated photovoltaic–piston gravity energy storage (PV–PGES) system. The results evaluate the system's ability to store surplus PV energy, mitigate power fluctuations, and deliver stable electrical output under variable solar conditions.

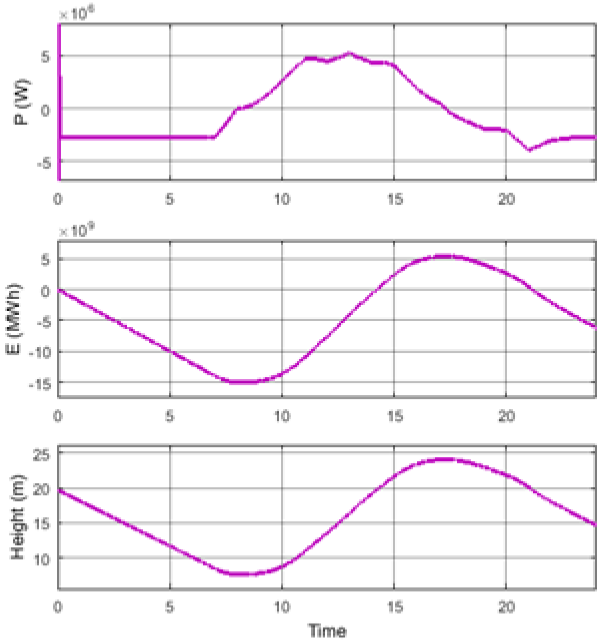


Figure 7. Power, Energy and Height of Piston at GES

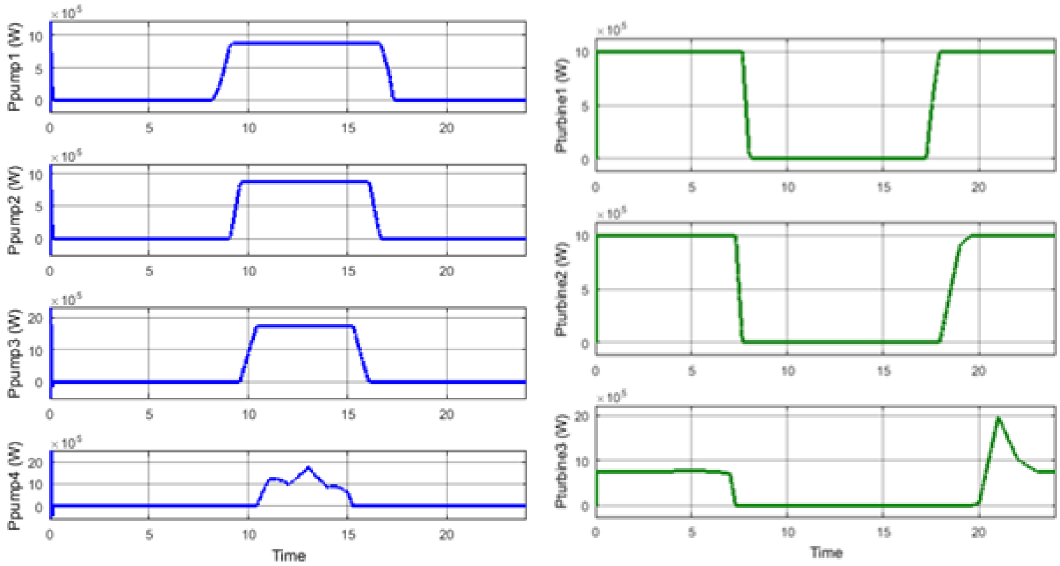


Figure 8. Power of Each Pump and Turbine during Charging and Discharging

Figure 7 shows the time-domain behavior of the PGES system in terms of water height, stored energy, and power output over one operating cycle. The variation in water height in Fig. represents the pumping and generating modes of operation, while the corresponding stored energy in Fig. follows a similar trend due to its dependence on elevation. The power profile in Fig. reflects smooth transitions between pumping and generation without significant fluctuations. These results indicate stable PGES operation and confirm the strong coupling between height variation, energy storage, and power output, demonstrating the effectiveness of the system for energy storage applications.

Figure 8 illustrates the free-body diagram of the piston used in the Piston Gravity Energy Storage (PGES) system, highlighting the dominant forces governing its vertical motion during charging and discharging modes. The piston is subjected to an upward hydraulic force generated by the pressurized working fluid, a downward gravitational force due to its mass and resistive forces associated with hydraulic losses and mechanical damping.

As shown in Figure 9, the PV power output increases significantly during the high-irradiance period, reaching a peak value of approximately 7 MW. When the PV generation exceeds the load demand, the surplus power is diverted to the pumping units, as indicated by the rise in P_{pump} between 8 h and 16 h. During this interval, the piston is lifted, and energy is stored in the form of gravitational potential energy.

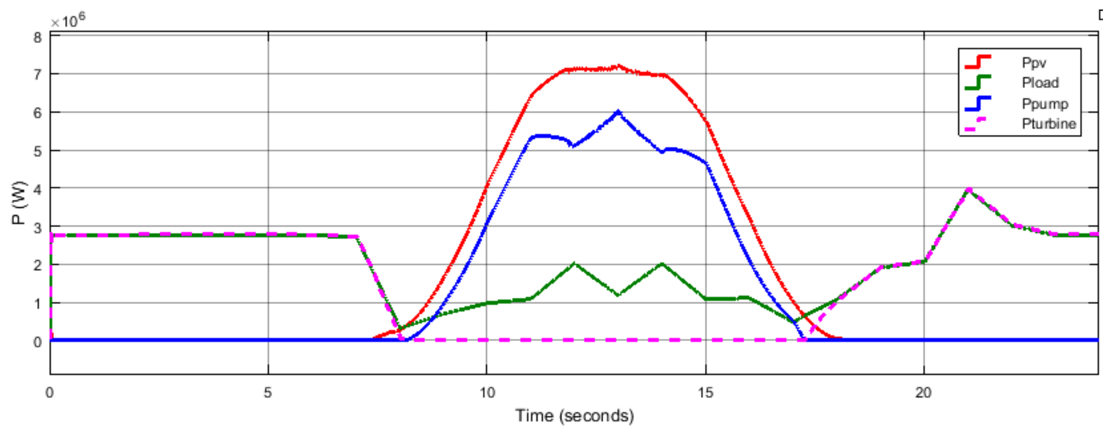
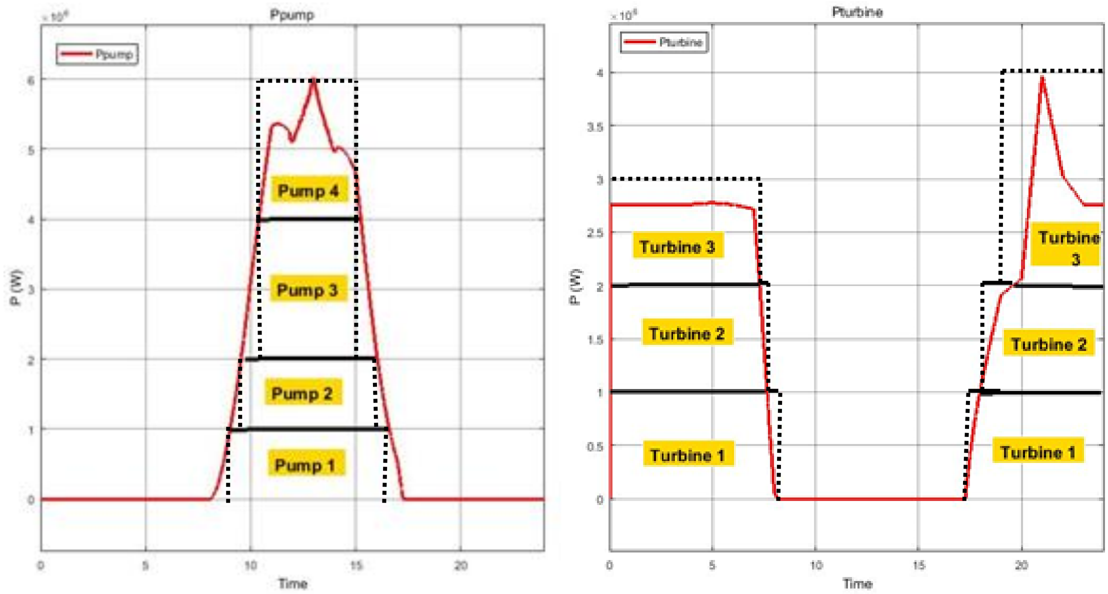


Figure 9. Power flow distribution of the PV-integrated piston-based gravity energy storage system

The load power remains comparatively lower and varies smoothly over time, demonstrating that the gravity energy storage system effectively absorbs PV power fluctuations. When PV power decreases after 16 h, the pumping power drops to zero, and the system transitions to the discharging mode. In this mode, the stored energy is released through the turbine-generator, as evidenced by the increase in $P_{turbine}$, which compensates for the reduction in PV generation and maintains supply to the load. The complementary behavior between P_{pump}, and $P_{turbine}$ confirms the bidirectional operation of the proposed system.

Figure 10(a) illustrates the dynamic pump power profile during the charging operation of the Piston Gravity Energy Storage (PGES) system. The total pump power increases progressively as additional pumps are activated in a staged manner. The operation is divided into four regions corresponding to Pump 1 through Pump 4 activation levels. Initially, Pump 1 operates alone at approximately 1 MW. As the required hydraulic head and flow rate increase, Pump 2 and Pump 3 are sequentially engaged, raising the total input power to approximately 2 MW and 3 MW, respectively. Finally, Pump 4 is activated, resulting in a peak charging power of approximately 6 MW. The non-linear fluctuations observed near the peak region are attributed to transient hydraulic effects and control system adjustments for flow stabilization. After the charging period (around t ≈ 16 h), all pumps are deactivated, and the power returns to zero.

The selection of a synchronous motor integrated with a variable frequency drive and closed-loop PID flow control ensures high-efficiency operation, precise speed regulation, reactive power control capability, and stable hydraulic output under varying head and photovoltaic power conditions. This configuration enhances system reliability, reduces mechanical stress, and improves overall round-trip efficiency of the PGES system



(a) (b)

Figure 10. Time-varying power profile with sequential activation (a) during charging mode (b) Discharging mode

Figure 10(b) presents the turbine power output during the discharging operation of the PGES system. The system operates under a staged turbine dispatch strategy to regulate power delivery based on demand requirements. At the beginning of the cycle, Turbine 1 operates to supply approximately 1 MW. As load demand increases, Turbine 2 and Turbine 3 are sequentially engaged, resulting in stepped increases in output power to 2 MW and approximately 2.7–3 MW. During the mid-cycle (t ≈ 8–17 h), the system remains idle, indicating a storage or standby condition. Later, during the high-demand period (t ≈ 18–21 h), the turbines are reactivated, and the output peaks at nearly 4 MW before gradually decreasing as stored energy is depleted.

The selection of a synchronous generator equipped with a hydraulic governor and automatic voltage regulator ensures stable frequency regulation, precise voltage control, reactive power support capability, and high conversion efficiency during discharging operation. This configuration enhances grid stability and improves the overall operational reliability of the PGES system under varying load conditions.

The simulation results confirm that the piston-based gravity energy storage system effectively complements photovoltaic power generation by storing excess energy and delivering stable output during low solar periods. Compared to electrochemical storage technologies, the PGES system offers advantages in terms of durability, scalability, and environmental sustainability. Unlike pumped hydro systems, it does not require specific geographical elevation or large water reservoirs, enhancing its deployment flexibility.

The findings also indicate that system performance is highly influenced by design parameters such as piston mass, container height, and hydraulic efficiency. Optimizing these parameters can further improve energy storage capacity and system efficiency. Overall, the proposed PV–PGES configuration demonstrates strong potential as a reliable and cost-effective energy storage solution for large-scale photovoltaic integration.

H. Conclusion

This paper presented the modelling and simulation of a piston-based gravity energy storage (PGES) system integrated with a photovoltaic power plant to mitigate solar intermittency and power fluctuations. A comprehensive mathematical model was developed and implemented in MATLAB/Simulink to evaluate system performance. Simulation results confirmed that the PGES system effectively stores excess PV energy during high irradiance periods and reliably supplies power during low PV output. Stable charging–discharging operation ensured smooth piston motion and consistent power generation.

The integration of PGES significantly improved power smoothing and dispatch reliability while maintaining operation within mechanical and hydraulic limits. The system demonstrated acceptable round-trip efficiency and advantages such as long service life, scalability, and low environmental impact. Overall, the results verify the technical feasibility of PGES as a promising large-scale, long-duration energy storage solution. Future work will focus on techno-economic assessment and experimental validation.

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