

Article

Storage Gravitational Energy for Small Scale Industrial and Residential Applications

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Abstract: Photovoltaic cells produce electric energy in a short interval during a period of low demand and show high levels of intermittency. One of the well-known solutions is to store the energy and convert it into a more stable form, to transform again into electricity during periods of high demand, in which the energy has a higher value. This process provides economic viability for most energy-storage projects, even for the least efficient and most common, such as batteries. Therefore, this paper aims to propose a storage system that operates with gravitational potential energy, considering a small-scale use. The development of this methodology presents the mathematical modeling of the system and compares the main characteristics with other systems. The dimensions of the considered system are 12-m shaft, 5-m piston height, and 4 m of diameter; it presented an energy storage of 11 kWh. Also, it has an efficiency of about 90%, a lifetime of 50 years, and higher storage densities compared to other systems.

Keywords: solar energy; gravitational energy; storage system

1. Introduction

The production of electricity from renewable sources has grown due to the clean energy policies in many countries [1,2]. The increased demand for energy, without increasing CO₂ emissions and exclusive reliance on finite resources, such as fossil fuels, has made necessary the development of advanced renewable energy technologies [3,4]. Many authors have been conducting research to find solutions for the optimal and quality generation, distribution and use of renewable sources [5–14].

Developments in photovoltaic energy technology lead to lower manufacturing costs, which allows solar energy to increase its percentage of electricity in the generation matrix [15,16]. Thus, photovoltaic electricity is one of the best options in comparison to other renewable sources [17,18]. However, solar power is a variable, intermittent, and generally dispersed source when compared to large-scale power plants such as hydroelectric and thermoelectric plants [19,20].

Energy storage systems are applied in response to intermittence and to use the solar source in suitable periods [21]. The use of energy storage systems increases energy reliability and security, supports greater integration of renewable energy, compensates for the levels of intermittency and can lead to a more efficient use of renewable energy sources, avoiding the interruption of the system due to intermittency [22–24]. This system operates at the peak of generation, around midday, transferring the excess generation to a peak of demand. Thus, the energy generated by photovoltaic solar installations during the hours of low demand can be stored and deployed in the early night, when the demand for energy is high, and the cost of electricity is higher, as shown in Figure 1. This procedure is particularly

relevant for the service sector and residential users, for which demand shows considerable changes during the day [25,26].

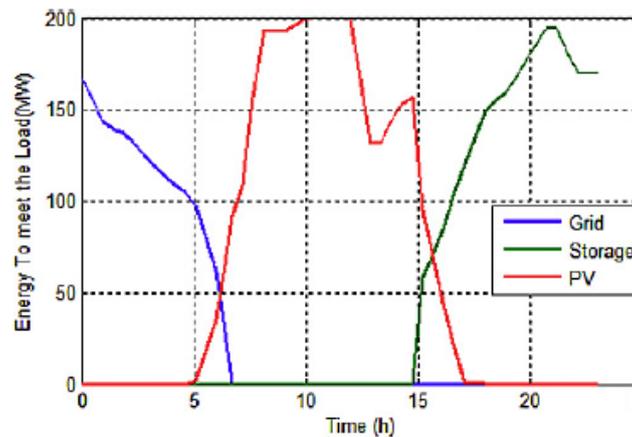


Figure 1. Energy generation to meet the demand [27].

The potential benefits of integrated network storage technologies include reducing the need for new transmission and generation capacity, improving load, providing a spinning reserve, correcting frequency, voltage and power factors, as well as indirect environmental advantages [28,29].

The energy storage is classified as mechanical, electrochemical, or hydrogen [30]. Electrochemical systems, especially acid batteries, are the most widely used accumulators for storing photovoltaic energy [31,32]. Most research on solar energy storage aims to find an efficient way to store energy, but only considers conventional battery storage. However, battery usage requires a high initial cost, is not cost-effective, does not support high cycling rates, and does not store large amounts of energy in a small volume [33,34]. Besides, there is the impact of metal depletion during battery production, as well as fossil energy consumption and consequent pollution with the use of batteries [35,36].

Each energy storage system has specific characteristics of time response, the limit of stored energy quantity, energy level, charge and discharge cycles, energy density, useful lifetime, efficiency, environmental impact, cost, technological maturity, etc. These characteristics are considered in all energy applications [37,38].

This work applies the principle of gravitational energy for energy storage dedicated exclusively for the storage of photovoltaic solar energy and sized for small industries or residences. Therefore, the mechanism is the same as in other inventions. However, the applications shown in this study consider require novel features that the proposed system has, as was detail explicitly in the paper. Therefore, this work describes a new gravitational potential energy storage system based on existing energy storage principles for a small scale. A review of some mechanical storage methods, especially those using the gravitational potential energy principle, is performed in Section 2, with a comparison in terms of power, energy rating, and round-trip efficiency. Section 3 presents the sizing, and Section 4 presents the dimensions and some characteristics of the proposed storage system. Finally, Section 5 presents the conclusions drawn from the paper.

2. Background

Storage system analysis requires assessing several characteristics, as different renewable resources have unique integration requirements and network services, depending on various details, such as the type and location of the renewable source. This section introduces some mechanical energy storage technologies. However, it mainly addresses one subcategory, the gravitational storage of energy. Thus, it discusses the working principle of these technologies, the limitations, their fundamental characteristics, and the existent literature.

Table 1 presents storage technologies, flywheel (FES), compressed air energy storage (CAES), pumped hydroelectric energy storage (PHES), underwater ocean storage systems (UOSS), gravity power module (GPM), hydraulic hydro storage (HHS), ground-breaking energy storage (GBES), advanced rail energy storage (ARES), and Gravitricity, as well as their fundamental characteristics: energy rating, power rating, energy density, power density, lifetime, discharge time, and roundtrip efficiency.

Table 1. Technologies of energy storage and systems characteristics. Adapted from [39,40].

Storage Technology	Energy Density Wh/l	Power Density W/l	Energy Rating Wh	Power Rating W	Discharge Time h	Life Time years	Roundtrip Efficiency %
FES	20–80	10^3 – $2 \cdot 10^3$	-	$<2.5 \cdot 10^5$	<0.25	15	85–95
CAES	0.4–20	0.04–10	10^8	$5 \cdot 10^6$ – $3 \cdot 10^8$	1–24	20–60	50–89
PHES	0.13–0.5	0.01–0.12	10^6 – $2 \cdot 10^{10}$	10^8 – $5 \cdot 10^9$	1–24	40–60	65–87
UOSS	-	-	$<10^9$	$<10^9$	1–10	n/D	65–90
GPM	1.6	3.13	$1.6 \cdot 10^9$ – $6.4 \cdot 10^9$	$4 \cdot 10^7$ – $1.6 \cdot 10^9$	1–4	30+	75–80
HHS	-	-	10^9 – 10^{10}	$2 \cdot 10^7$ – $2.75 \cdot 10^9$	1–24	40+	80
GBES	-	-	$<2 \cdot 10^{10}$	10^8	24	40+	80
ARES	-	-	$<6 \cdot 10^9$	10^8 – $3 \cdot 10^9$	2–24	40+	75–86
Gravitricity	-	-	$<10^6$	$<4 \cdot 10^7$	<2	50+	80–90

Flywheel (FES) stores electrical energy in a movable disk in the form of kinetic energy. The disc is connected to an electrical machine, which can operate as a generator or in a motor mode. In charge mode, electrical power flows from the grid to FES, and disk speed increases (engine mode). In discharge mode, disk speed decreases, and the engine operates in generator mode [41]. FES is rated for speed, capable of low and high speeds with high and low inertia discs, respectively [42].

This system responds quickly to high power instant demands, has low maintenance costs, high power density, and storage density that is exceptionally high if compared to other existing storage units [43]. Limitations of this system are aerodynamic losses, bearing friction losses, shaft position, tilt stabilization, considerable energy loss with the stabilization control system, and high capital cost [44,45]. Therefore, the flywheel cannot be used to provide power quality and during long periods, but it is ideal for momentary variations.

Compressed air energy storage (CAES) stores large amounts of energy in the form of pressurized air. In this way, the potential energy of compressed gas (air) is stored in large tanks or underground voids [46,47]. Air pressure increases through electrically driven compressors, which convert electrical energy into potential energy [48]. Then, when the demand for electricity increases, the pressurized air is heated and then expands in a turbine, which drives a generator for power production. There are two commercial CAES plants, the Huntorf CAES plant in Germany with a 290 MW air storage gas turbine and also the 110 MW McIntosh CAES plant in Alabama, USA [49].

CAES presents low energy storage density. As such, it requires large storage units but has high storage capacity and long storage (hours to months) and is therefore suitable for large scale applications. Also, CAES costs between 300–700 euros per kW, which is lower than the cost of PHES and is also less restricted by the availability of suitable locations. However, PHES technology is more mature, shows a longer lifetime, and generally has a higher power rating [50,51].

According to Aneke and Wang [39], CAES's potential round-trip efficiency is 50%–89%; however, in commercial plants, it is around 42%–55%, which is lower than PHES's. Therefore, although CAES is developed, round-trip efficiency needs optimization. On the other hand, in general, CAES and PHES are the most cost-effective technologies for large-scale storage with frequent cycles.

Pumped hydroelectric storage (PHES) is currently the most widely used storage method, which corresponds to over 99% of the world's bulk energy storage capacity [52]. In short, the system stores energy in the form of potential energy in a higher water reservoir to which water is pumped during

off-peak hours. Water is released to the lower reservoir through turbines to generate electricity during periods of high demand.

This system has high energy storage potential, long term storage, and high round-trip efficiency, so it is suitable for large scale applications. However, as in the CAES, the expected efficiency for PHES is 90%, but most commercial installations have a round-trip efficiency of 72%–75% [39].

The low energy density of PHES is one of the limitations that require proper topography, with ample water reservoirs and high height variation between them for installation and operation. Thus, the implementation of PHES causes significant environmental impacts, social needs, problems with environmental acceptability, and confirmation of the economic viability, which requires high investment.

Underground pumped hydroelectric storage (UPHES) has the same operating principle as the previous one, but at least one of its reservoirs may be underground. The underground reservoir ensures a high vertical displacement without consuming a large surface area. Thus, Menédez et al. [53], Winde et al. [54], and Pujades et al. [55] considered case studies on the implementation of this storage system in abandoned mines, where appropriate infrastructure already exists.

The most representative cost of UPHES is underground work, followed by engineering and network connection [56]. According to Meyer [57], hybrid systems are preferable because they estimate that the costs of above-ground reservoirs are lower than underground ones. The total project cost of a UPHES system has been estimated at 257 million euros, and the cost per kW is 2215 euros [53]; the cost of traditional PHES per kW is 500–1700 euros [39]. Although this system has high efficiency, reliability, and availability, economic viability has a high level of uncertainty and needs to be better studied [53].

Underwater ocean storage systems (UOSS) are designed to work with a renewable power plant floating in the sea (solar or wind energy) [58,59]. The system is a submerged vessel, a reversible turbine attached to the vessel, and an electrical cable that connects the turbine to the generating unit. Water is pumped out of the vessel during the loading cycle and returns to the vessel when discharged. Cazzaniga et al. [58] scaled a system with a volume of 360 m³ to a depth of 1000 m, and the estimated storage capacity was 984 kWh with 90% efficiency. Meanwhile, Slocum et al. [59] presented larger scale systems (some GWh) with 65%–70% efficiency.

Gravity power module (GPM) technology consists of a piston, a water container, and a return pipe connected to a turbine pump [60,61]. The system operates in a closed circuit while charging as off-peak electricity is used to drive the engine that transfers water through the return pipe by lifting the piston on the shaft. While in discharge mode the piston drops, forcing water back through the return pipe and the turbine that drives the generator, turning the potential energy into electrical energy. The amount of energy stored by this technology varies with piston size and shaft height. Gravity power's goal is to provide power in the 40 MW to 1.6 GW range [60].

GPM and ARES (advanced rail energy storage) are storage technologies suitable for large scale applications. They are also suitable for long term storage as they have a low self-discharge rate. Besides, when compared to other gravity storage systems, the GPM has the highest power density, and also has a high lifetime and efficiency, as shown in Table 1.

The GPM has been studied in many aspects, such as sizing studies by Berrada et al. [27], Loudiyi and Berrada [61] and Berrada et al. [62]. Studies on economic and risk analysis were conducted by Berrada et al. [63–65] and Oldenmenger [66]; GPM viability when combined with another storage system was also studied by Berrada et al. [67].

Berrada et al. [63] concluded that the PHES and GPM levelized costs of energy storage (LCOE) were 120 €/MWh and 123 €/MWh, respectively. Also, another work by the same authors on sizing indicated that the storage unloading time was about 368 s. It also concluded that critical system parameters include flow rate and pressure. On the other hand, the results show that the efficiency of the system depends on the sealing material used in the system [62].

These research studies confirm the possibility that GPM has a capital cost per kWh equal to or slightly higher than PHES when fully matured as they are based on a similar concept. Also, if the GPM

reaches 75%–80% round-trip efficiency, it may be an excellent alternative to PHES in locations without favorable topography.

Hydraulic hydro storage (HHS) and ground-breaking energy storage (GBES) are similar to GPM, but both are constructed by excavating an area to form a natural piston. The excavated part is connected to a return pipe and sealed; therefore, its operation is the same as the GPM. In addition to the layout difference, HHS and GBES differ in their storage scale ranging from 1 to 20 GWh and have power ratings ranging from 20 MW to 2.75 GW [68–70].

Advanced rail energy storage (ARES) is a rail-based traction drive system that uses surplus renewable energy or grid electricity to move a mass to a higher altitude by rail. The blocks descend when the system is being unloaded, each block weighs about 45–64 t, and a 16 km route is performed [71]. The pilot project has a 78%–80% efficiency, no self-discharging storage loss, a lifetime of 40 years, and is located in Tehachapi, California. ARES LLC is building the first commercial project in Nevada: a 50 MW power system, 12.5 MWh power capacity, with a 9.3 km path and a 780 t transport mass [72]. ARES has topographic limitations as an area with an altitude difference is required for its installation. However, it is an alternative for large-scale applications [72,73].

The storage technology termed Gravitricity is based on vertically raising and lowering a heavy mass along an axis in the ground [74,75]. The pistons have a mass of up to 3000 t, and the axles go up to 1500 m deep; these axes can be from existing mines or built axles [74]. The mass is lifted with a cable system, similar to the lifting systems used in mines and cranes. Efficiency is about 80%–90%, with a response time of about 0.5 h, a lifetime over 50 years, and discharge time up to 2 h, as Table 1.

When compared to other gravity energy storage technologies, the use of overhead weights requires minimal land use and can make use of existing excavations. Besides, this storage can be combined with compressed air, by sealing the shaft; space can be used simultaneously as a compressed air pressure vessel, increasing the amount of energy stored by up to three times [74]. Gravitricity received funding in 2018 to build a prototype of 250 kWh performed in South Africa [76,77].

Deep sea energy storage (MGH) is similar to Gravitricity and eliminates the need for shaft infrastructure because it uses a floating sea platform to move masses [78]. StratoSolar [79] proposes the MGH with a photovoltaic power generation system floating on 20-km-high platforms.

The works of Botha and Kamper [40] and Morstyn et al. [80] present the sizing and modeling of Gravitricity storage systems. Botha and Kamper [40] provide the modeling of a gravitational energy storage (GES) system in abandoned mines and analyze two lifting methods, the conventional and electric machines. GES has energy density between 0.2 and 3.1 Wh/L, power density between 0.3 and 30 W/L, energy rating 10^7 Wh, power rating $2 \cdot 10^7$ W, discharge time 0.5 h, 50 year lifetime, and 85% round-trip efficiency.

The work of Botha and Kamper [40] indicates that storage capacity is limited by both the system height and the piston mass that is hoisted, meaning that it does not have high energy storage like other gravitational energy-based storage systems. The low energy density combined with low discharge time and high power density indicates that GES is best suited for high power and distributed generation services.

Morstyn et al. [80] have also designed a gravity energy storage system using suspended weights for the development of abandoned mines. In their case study, 340 mine wells could be converted into gravity storage units with capacities higher than 1 MWh, providing 0.804 GWh of energy storage. This system is based on the assumption that the suspended weights are limited to 3000 metric tons and are constructed using iron ore.

3. Small Scale Energy Storage: Modeling the System

This section presents the proposal of a gravitational storage system and its sizing. This system is based on the same principle of working as Gravitricity [75], as a solution for improving quality and energy saving. However, unlike the studies found in the literature and presented in Section 2, this

paper aims at small-scale end-use, i.e., small industry and residential use, without the requirement of a mine as seen in the works of Botha and Kamper [40] and Morstyn et al. [80].

The system stores renewable energy in the form of gravitational potential energy and the storage is performed by suspending weights. The system is loaded by lifting a piston and discharged during a high demand period when the piston is released for descending.

Figure 2 shows the design of the gravity energy storage system consisting primarily of a piston, gears, wire ropes, motor/generator, inverter, and the photovoltaic power generation system. Meanwhile, Figure 3 represents the overall flowchart of system processes.

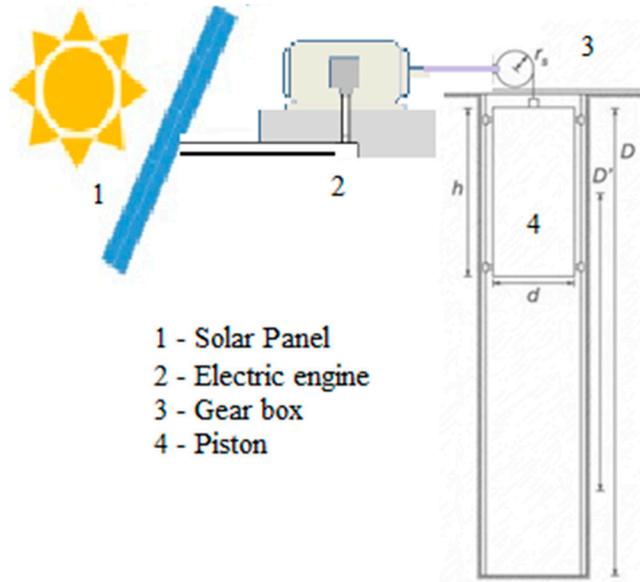


Figure 2. Small scale gravity energy storage system using piston.

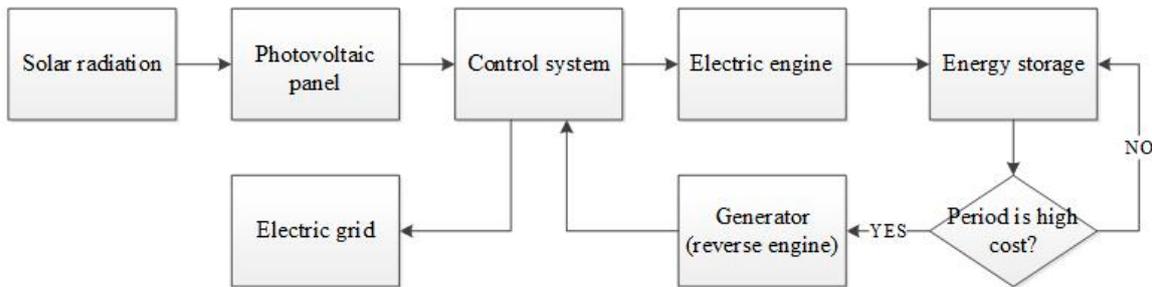


Figure 3. Simplified flowchart of the energy storage system.

In Figure 2, h is the height of the suspended weight, d is the piston diameter, D is the shaft depth, D' is the usable depth for energy storage, and r_s is the radius of the traction sheave. Additional details of the connections and guidance system are provided in the patent filed by Gravitricity [75].

Figure 3 presents the sequence of operation of the proposed system in which, in the sunny period, the photovoltaic panel receives solar radiation, the electrons when affected by this radiation move, and generate an electric current in the panel cells. Electric current, along with voltage, generates power at the photovoltaic cell terminals. An inverter transforms direct current into alternating current for use in the grid.

The electrical energy derived from these processes is used in an electric engine, which transforms the electrical energy into mechanical energy that acts on lifting a piston using a pulley system, which aims to facilitate the ascent. As the mass rises, the potential energy increases. When the piston reaches the top, the energy is then stored as mechanical potential energy, and this step is referred to as the system loading mode.

The discharge mode happens when the demand for energy increases; in sunless periods, such as night, which usually have a higher cost of electricity from the network, this mass is released to the descent. In this way, the motor acts in reverse, acting as an electric generator.

3.1. System Sizing

This section scales the gravitational energy storage system and the photovoltaic system. The focus is on developing equations describing energy storage capacity, energy densities, and power density.

For the photovoltaic system, modeling the maximum rated power (P_P) was calculated according to Equation (1):

$$P_P = n \cdot W_P, \tag{1}$$

where n is the number of modules, and W_P is the maximum power of each module (W).

The calculation for the average energy (W_h) generated by the photovoltaic system is shown in Equation (2):

$$E_P = \frac{S_r \cdot P_P}{I_{STC}} \cdot \eta, \tag{2}$$

where S_r is the solar radiation available for a given location depending on weather conditions and the time of year; η is the efficiency of the cell; I_{STC} is the irradiance at STC (1000 W/m^2).

Storage system sizing was calculated from the following equations. The system's energy storage capacity is given by Equation (3):

$$E_{ES} = \eta_{ES} \cdot g \cdot m \cdot D', \tag{3}$$

where E_{ES} is given in J , η_{ES} is the round trip efficiency of the system, m is the mass of weight (kg), g is the acceleration of gravity (9.8 m/s^2) and D' is the usable depth shaft to store energy (m). The conversion between Joule (J) and Watt-hour (Wh) is done as in Equation (4):

$$1 \text{ Wh} = 3600 \text{ J}. \tag{4}$$

Thus, the stored energy can be written in Wh with Equation (5):

$$E_{ES} = 2.78 \cdot 10^{-4} \cdot (\eta_{ES} \cdot g \cdot m \cdot D'). \tag{5}$$

The volume of weight, V , is given by the height h of the cylinder and the diameter d , according to Equation (6). It has been considered that the system uses a cylindrical piston, therefore:

$$V = \frac{\pi \cdot d^2 \cdot h}{4}. \tag{6}$$

For the piston made of a material with density ρ (kg/m^3), the mass of weight, m , is expressed as Equation (7):

$$m = \rho \cdot V. \tag{7}$$

The usable depth of the shaft to lift the weight is represented by Equation (8), where D is the depth of the shaft:

$$D' = D - h = D - \frac{4 \cdot m}{\pi \cdot d^2 \cdot \rho}. \tag{8}$$

Thus, the total energy storage capacity (Wh) can also be expressed by Equations (9) and (10):

$$E_{ES} = 2.78 \cdot 10^{-4} \cdot \left[\eta_{ES} \cdot \left(m \cdot g \cdot D - \frac{4 \cdot m^2 \cdot g}{\pi \cdot d^2 \cdot \rho} \right) \right], \tag{9}$$

$$E_{ES} = 2.78 \cdot 10^{-4} \cdot \eta_{ES} \cdot \rho \cdot \pi \cdot \left(\frac{d}{2} \right)^2 \cdot h \cdot g \cdot D. \tag{10}$$

As the piston height increases and its diameter is kept constant, the mass increases. However, it reduces the usable depth of the shaft, creating a trade-off for energy capacity. Thus, the piston height should be as low as possible to increase storage capacity.

As for the wire ropes of the system, it was assumed that the length of the rod (l_r) is the same as the height at which the piston travels (usable depth), i.e., $l_r = D'$. Also, the piston diameter (d) is approximately the same as the shaft diameter, i.e., $d \approx d_{\text{shaft}}$. Thus, the system energy density (Wh/m^3) can be calculated according to Equation (11):

$$\rho_{\text{ES}} = \frac{E_{\text{ES}}}{V_{\text{eixo}}} = 2.78 \cdot 10^{-4} \cdot \rho \cdot g \cdot h. \quad (11)$$

Meanwhile, Equation (12) presents the calculation of power density (W/m^3):

$$\rho_{\text{P}} = \frac{\rho \cdot h \cdot g}{3.6 \cdot 10^3 \cdot t_d}, \quad (12)$$

where t_d is the storage system unload time in hours. Both energy density and power density depend on piston height (h) and piston material density (ρ). This property is true for any shape as long as the shape of the shaft and piston are the same.

4. Storage System Characteristics and Applications

This section uses the system modeling of Section 3.1 to analyze storage capacity and energy and power densities that are calculated using different piston materials illustrating the system performance.

The electric motor/generator considered was the model W22 Magnet IR5 Ultra Premium, manufactured by the company WEG. This motor is a synchronous type with high-performance permanent magnets and has 97% efficiency.

As seen in Table 1 and some studies discussed, this type of storage has a lifetime of 50 years or more, a response time of less than one second. Round-trip efficiency for the gravity energy storage system is considered as 90% according to the Gravitricity system.

The average energy of the photovoltaic system (EP) was estimated at 3 kWh, to meet the demand of a residence. Also, it was considered that the system could be loaded and unloaded once a day. Two materials were selected for the piston: iron, and concrete, with densities of 7850 and 3150 kg/m^3 , respectively [63,80]. Berrada et al. [63] and Botha and Kamper [40], presented that iron showed better relative density and cost ratio when compared to other options.

The use of concrete or iron has been suggested because they are common materials, which are widely available in the construction of industrial and residential buildings, which are the focus of this article. Thus, these materials can be obtained from wastes or tailings of the construction itself.

With a shaft depth of 12 m, a piston height of 5 m, a diameter of 4 m and a mass and approximately 375 metric tons, 11,000 Wh of energy can be stored. The amount of 11,000 Wh corresponds to the energy required for single household use. Energy and power density are relatively high compared to those shown in Table 1. A block made of iron yields the energy density of approximately 107 Wh/m^3 and power density of 214 W/m^3 . While with a concrete block the energy density is 43 Wh/m^3 and the power density is 86 W/m^3 . The discharge time of 0.5 h was considered for the calculations. However, total potential energy storage capacity is affected by the mass block and density variations.

Figure 4 shows the effect of varying mass on energy storage potential, and Figure 5 shows the behavior of the amount of energy stored as density increases. These variations were calculated using constant values for the block diameter, height, and shaft height, except these values 4 m, 5 m, 12 m, respectively.

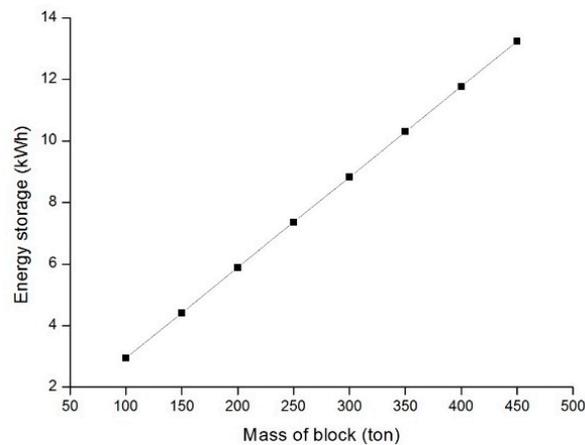


Figure 4. The effect on energy storage potential as a function of the amount of mass of the block.

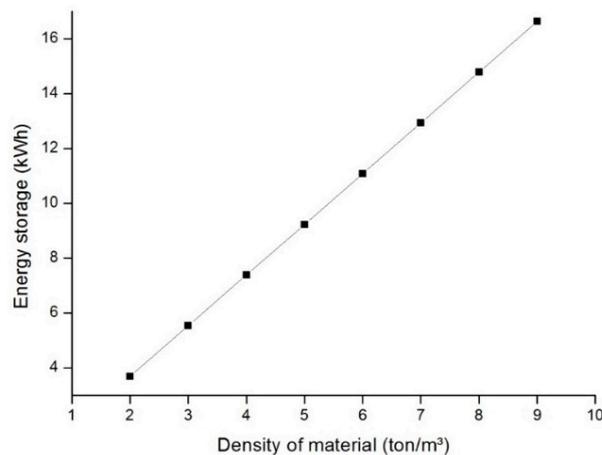


Figure 5. The behavior of the amount of energy stored as a function of the density of the material of the block.

As the mass of the material or the density of the block increases, the density also increases in a linear behavior. Thus, material density is an essential factor when shaft depth and diameter are small. In this scenario, when the density increases, the mass also increases and, consequently, the energy capacity grows, even if there is a restriction of diameter size and depth. Therefore, this parameter is significant for small-scale applications.

In another scenario, with no size restriction but with mass restriction, with increasing diameter and shaft depth, there are also gains with storage capacity. Although the mass is restricted, the piston travels higher, storing more energy. In this situation, there is room availability, so the capacity to store energy is considered on a large scale. Therefore, for small-scale storage, the ability to store energy is more sensitive to the change in piston material density. While in large-scale storage, shaft depth and piston diameter size are the most representative factors for capacity and storage.

As the application itself already limits the system considered in this work, the system implementation will not reach the maximum point. Therefore, we only explore the behavior of the piston height as a function of storage capacity.

The main benefit of the system is related to the scale of a household, which when equipped with this storage system coupled with the photovoltaic generation, reduces the amount of energy used from the grid and thus increases its self-sufficiency. The installation of this system is practical and comfortable, can be done together with the design of any establishment (residential, commercial, or industrial). Thus, the system is an electromechanical and waterless form of energy storage, with no

geographical/topographic limitations, such as a mine or water reservoir. Besides, the storage system does not require a connection to the grid.

5. Conclusions

This paper presented a new gravity-based energy storage system as a new technology for small-scale use. Also, the operating principle and limitations of the different technologies of mechanical energy storage were presented, especially those that use gravitational energy. Moreover, these technologies were compared technically, and their applications analyzed.

The proposed system is an electromechanical form which requires minimal land use and does not use water for its operation, with less stringent geographical requirements than traditional stockpiles. In addition, it has advantages in terms of installation, since it can be installed in buildings and off-grid. This new system has the potential to have high storage density, unloading time on the order of minutes, a lifetime of 50 years, and efficiency of around 90%, which would optimize power supply and utilization, as well as increase energy self-sufficiency.

The gravitational storage system that uses a piston is a viable and promising storage technology. However, research and studies on feasibility, modeling, sizing, and sensitivity analysis are required to gain a more detailed understanding of the challenge involved in the maturity and practical development of this proposal. This future work will allow one to accurately compare their features and costs with other existing energy storage options.

Author Contributions: A.C.R.: literature review, construction and editing of the manuscript, acquisition of results; N.R.C.: literature review, methodology development, analytical modeling; L.A.O.R.: discussion of results, grammar, spelling and equation review.

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Conflicts of Interest: The authors declare no conflict of interest.

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