

Comparison of the Suitability between the Piston Solid Gravitational Energy Storage and Rechargeable Battery Energy Storage for Applications in the Industrial Process of Electricity Storage

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Abstract. Contemporarily, the electricity deficiency is a problem that should be faced and discussed for most countries. To solve this problem, the electricity should be used wisely. In this paper, the suitability between the Piston Solid Gravitational Energy (PSGES) and Rechargeable Battery Energy Storage (RBES) for applications in the electricity storage for both scenarios is compared. First, the development conditions, quantitative metrics including energy efficiency, energy density, response time of discharging, energy losses during the storage, duration of the storage, and levelized cost of the energy are discussed for each system. Then, quantitative metrics between these 2 systems are compared. The comparison results shows that the RBES used sodium-sulfur (NaS) has the highest competency compared with the rest systems. It has flexible discharge time, fast response time, high energy density and power density, relatively low levelized cost of the energy, and high efficiency. Thus, the RBES used NaS is the optimal solution for both scenarios.

Keywords: Energy storage, Electricity storage, Renewable energy.

1. Introduction

The energy deficiency is a very server problem all over the world. Many countries and regions have encountered the energy crisis and shortage, such as Pakistan, Libya, and Europe [1-3]. To solve the energy crisis, there are three possible solutions including: increasing the generation rate of the energy, reducing the usage of the energy, and storing and releasing the energy flexibly in different period. The last solution is achieved via energy storage system. This solution is more sustainable and environmental-friendly compared with the solution that generate more energy. This solution is not suffering as the reduction of the usage of the energy, especially in extreme temperature such as winter and summer.

There are lots of energy storage systems in the world. In this paper, the Solid Gravitational Energy Storage, especially Piston Solid Gravitational Energy Storage (PSGES) and Rechargeable Battery Energy Storage (RBES), especially Li-ion, Lead-acid, and sodium-sulfur technologies will be discussed in detail. These two kinds of energy storage systems will be compared to figure out a better solution to store the extra electricity and discharge the electricity for a large amount quickly or discharge for a long time continuously and stably.

This paper aims to provide an overview of the PSGES and 3 kinds of RBESs, quantitative analysis of these systems, and comparison among these systems. Choose the best solution as the system for storing electricity or energy based on the data. Different types of quantitative metrics will be analyzed for these 4 types of storage systems, including energy efficiency, energy density, power density, energy losses during the storage, discharge time, response time, and levelized cost of the energy. To select the best solution, the Pugh method is applied. Each quantitative matrix will be evaluated and scored. The system which gets the highest score will be considered as the best solution. This paper could provide the brief advantages and disadvantages for these 4 kinds of energy storage systems and provide quick selection for companies or teams that need energy storage system.

2. Basic Technical Characteristics of the PSGES

2.1. Working Mechanism of the PSGES

For the PSGES, the energy is transformed and stored as the gravitational energy in the solid mass. The PSGES mainly consists of a gravity piston, pump, turbine, liquid medium, sealed container, and motor. The mechanism of the PSGES is intuitive. The energy, such as electricity will be stored by driving the pump-turbine to compress the liquid to lift the piston to transform the energy to the gravitational energy. When the piston reaches a certain height, seals will release to ensure the piston will not drop due to the gravity and lose gravitational energy.

2.2. The State of Development of the PSGES

As shown in Fig. 1 (a), The research trend of the SGES began around 2016 and 2017. The number of the related papers increased compared to previous years. The number of related patents increased around 2020 and 2021. At the same time, the number of related papers increased drastically compared to 2020 [5]. Based on the pie chart presented in Fig 1, the PSGSE, MMSGES, and TSGES are three most popular types of SGESs [4].

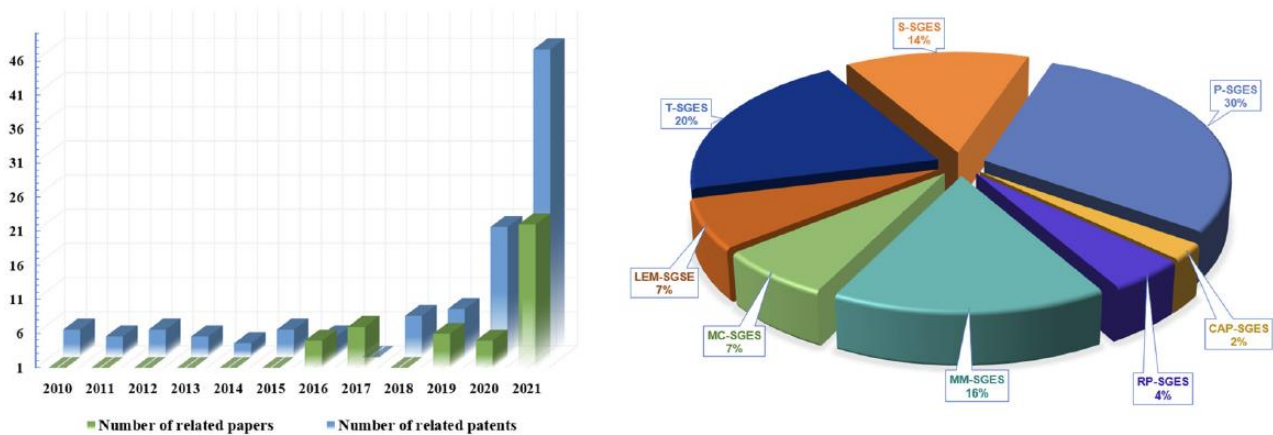


Figure 1. Research Trends of the SGES [4]

The development of the PSGES was first beginning with the modelling, material selection, and sizing and economic analysis of the PSGES in 2016 [5, 6]. In 2017, the system design, economic performance, dynamic modelling, design considerations, and technical design of the PSGES were developed and proved [7,8]. One of implementations of the PSGES was conducted by Heindl Energy [9]. They applied photovoltaic units to generate electricity and store the electricity in the PSGES by driving the pump-turbine to lift the piston up to store the gravitational energy.

3. Quantitative Analysis of the PSGES

In this section, the quantitative analysis, or quantitative metrics of the PSGES will be presented. The data includes the energy losses during the storage, energy efficiency, energy density, power density, levelized cost of the energy, discharge time, and lifetime. The data will be summarized with the data of the RBES in comparison part.

3.1. Energy Losses during the Storage

The energy losses during the storage could roughly be divided into three types: mechanical losses, electrical losses, and heat losses. The mechanical losses could be divided into hydraulic losses and efficiency of the pump-turbine and the motor. The electrical losses are mainly the losses during the transportation of the electricity in the cable. The heat losses are the losses caused by the heat generated during the transportation, caused by the Joule's Law and the resistance of the cable. As the PSGES,

which is mainly involved liquid medium, the hydraulic losses are the main energy losses. Thus, the energy losses during the storage will focus on the hydraulic losses.

Table 1 presents 6 different cases with different designs and the hydraulic losses percentage to the total energy losses. The dimension of the design increases from C1 to C5. The dimension of the design of C5 and C6 are the same but decrease half of the return pipe length from C5 to C6. The hydraulic friction energy losses increases when the size of the design increases. However, the percentage of the hydraulic losses tends to decrease. This indicates that if it is possible, the PSGES should be designed as large as possible.

Table 1. The Percentage and amount of hydraulic friction loss [10]

Hydraulic Friction Energy Loss	C1	C2	C3	C4	C5	C6
Watt-hour (Wh)	0.0395	10.156	66.140	238.28	2571.02	1490.88
%	1.65%	0.49%	0.40%	0.0397%	0.011%	0.0064%

3.2. Energy Efficiency

The energy efficiency means that the total energy stored into the energy storage system divided by the total energy generated or input. For PSGES, the energy efficiency could roughly be calculated by gravitational energy of the piston divided by the energy produced.

$$\eta = \frac{E_{Gravitational}}{E_{Produced}} \quad (1)$$

The calculation of the energy efficiency is not the point in this paper. Only the data of the energy efficiency are provided for comparison. The energy efficiency of the PSGES is around 75% to 80% [11].

3.3. Energy Density and Power Density

The energy density is the total energy storage of the system divided by the volume or the mass of the storage system. High energy density indicates that the small size of the system could contain a large amount of energy. To get the value of the power density, the energy should be divided by the time. All 2 equations are presented below [11]:

$$E = \rho \pi \left(\frac{d_p}{2} \right)^2 l_p g h \quad (2)$$

$$Energy\ Density = \frac{E}{V} = \frac{\rho \pi \left(\frac{d_p}{2} \right)^2 l_p g h}{\pi \left(\frac{d_s}{2} \right)^2 l_s} \quad (3)$$

$$Power\ Density = \frac{Energy\ Density}{time} = \frac{Energy\ Density}{3.6 \cdot 10^3 \cdot t} \quad (4)$$

ρ : density of the liquid medium, kilogram per cubic meter kg/m^3
 d_p : diameter of the piston, meter, m
 l_p : height of the piston, meter, m
 g : gravitational constant, newton per kilogram, N/kg
 h : high of the shaft or the container, meter, m
 V : volume of the shaft, cubic meter, m^3
 d_s : diameter of the shaft, meter, m
 l_s : height of the shaft, meter, m
 t : discharging time of the PSGES, hour, h

The energy density and the power density of the Gravitational Energy Storage (GES) are 0.2-3.1 kWh/m³ and 0.03-30 kW/m³ [8]. These data could also be applied to the PSGES because the PSGES is one kind of the GES.

3.4. Levelized Cost of Energy (LCOE)

Several aspects, including the Operation & Maintenance cost, life cycles, system efficiency, and lifetime expected energy output, consist of the LCOE, which is calculated by dividing the costs during the whole lifetime over the total energy production during the lifetime [7]. In other words, lower LCOE implies that less money should be paid for the same amount of the energy produced. This means the system is profitable.

Fig 2. and Fig 3. show that the Gravity Storage have low LCOEs compared to the other energy storage system. This means that the PSGES contains higher potential to earn profit.

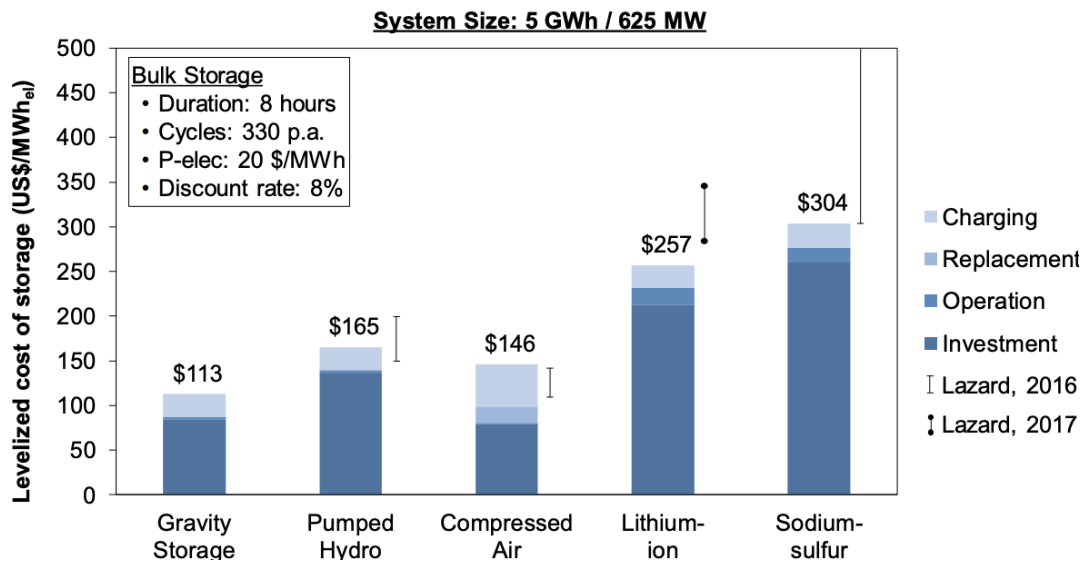


Figure 2. Levelized Cost of Energy for 5 different Storage System in 5 GWh / 625 MW [12]

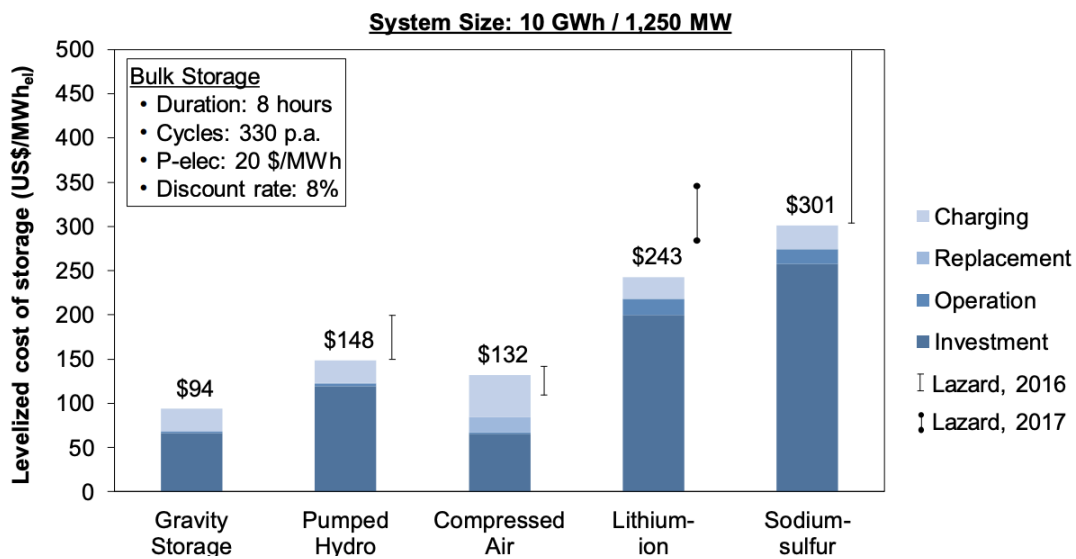


Figure 3. Levelized Cost of Energy for 5 different Storage System in 10 GWh / 1250 MW [12]

3.5. Discharge Time, Lifetime, and Response Time

The discharge time means the time used for fully discharge the gravitational energy that contains in the piston or the PSGES. The lifetime means how long the energy storage system could be used until it is considered as dysfunctional. For the PSGES, the discharge time is around 1-4 hours, and

the lifetime is over 40 years [11]. The response time is the time used between the startup of the system and the start of producing energy. One kind of the SGES's response time is around 0.5 seconds [11]. This system is based on the shaft and the vertical movement of the mass. Because no specific data shows the response time of the PSGES, the response time of the PSGES is assumed around 0.5 seconds.

4. Basic Technical Characteristics of the RBESs

4.1. Background Information of the RBESs

For the RBES, the design majorly consists of 2 different electrodes and 1 electrolyte. Differences among each type of RBESs are materials of 2 electrodes and the electrolyte. There are more than 15 types of RBESs existing in the world, including Lead-acid, Li-ion, Hydrogen, and Flow Batteries [13]. In this part, only Li-ion, Lead-acid, and sodium-sulfur (NaS) will be discussed.

The electrodes are made by different materials that can induce the redox reaction due to the different electrochemical potential during the discharge state [14]. The electrochemical energy could be released as the electricity through cables that connected to the negative and the positive electrodes. The electrochemical reaction is reversible so the energy storage system could be charged.

4.2. State of Development of the RBES

In 2016, the RBES was detailly reviewed and discussed about its technologies and applications [13]. In 2017, the sizing of the RBES was discussed and focusing on the microgrids technology [13]. In 2018, the detailed introduction of the Lead-acid batteries was provided [13]. Besides, the review of the sizing of the RBES, smart charging and discharging, and some power issues were presented [13]. From 2019 to 2021, the RBES technology had gradually become mature and mainly been discussed about the criteria of designing the RBES, sizing methods, and the comparison with other energy storage systems [13].

5. Quantitative Analysis of the RBES

In this section, the quantitative analysis, or quantitative metrics of the PSGES will be presented. The data includes the energy losses during the storage, energy efficiency, energy density, power density, levelized cost of the energy, discharge time, and lifetime. The data will be summarized with the data of the PSGES in comparison part.

5.1. Energy Losses during the Storage

The energy loss for the RBES is similar as the PSGES. They both have the cable conduction loss. Besides, they will also self-discharge after the system is fully charged and dormant. However, the self-discharge of the PSGES is not obvious because the piston is usually kept stable by the seal to prevent the gravitational movement. The self-discharge rate of the RBES is low, and the PSGES is very low [15].

The conduction loss has the same mechanism of the PSGES. It could be calculated based on the Joule's Law because the conductor has the property of the resistant.

To calculate the energy losses during the storage, only require deducting 1 by the energy efficiency. The evaluation of the energy losses during the storage for the RBES is insufficient to draw the conclusion. It must be calculated based on the energy efficiency data.

5.2. Energy Efficiency, Energy Density, and Power Density

Definitions of these three quantitative metrics are the same as definitions in PSGES's. Only data will be provided in this section. The discussion mainly focuses on three technologies, including lithium-ion, Lead-acid, and Sulfur-sodium batteries. The data are provided in Table 2.

Table 2. Energy efficiency, energy density, and power density of Lithium-ion, Lead-acid, and NaS technologies [13]

Technology	Energy efficiency (%)	Energy density (Watt-hour/Liter)	Power density (Watt-hour/Liter)
Li-ion	75-90	100-265	250-693
Lead-acid	70-90	35-40	80-90
NaS	89	150-300	10000

5.3. Levelized Cost of Energy

The LCOE of the Li-ion RBES and the NaS RBES are presented in the LCOE section in the PSGES part. The LCOE of the Li-ion and NaS are 243-257 and 301-304 USD/MWh [12]. Based on the other resource, the LCOE of the Li-ion and Lead-acid are 0.32 euro/kilowatt-hour and 0.34 euro/kilowatt-hour [16]. This paper was received on 23 November 2020 [16]. The medium conversion rate from EUR to USD was 1.1854 [17]. Thus, the LCOE of the Li-ion and Lead-acid were 367.5 and 403 USD/MWh.

5.4. Discharge Time, Lifetime, and Response Time

The discharge time of the RBES has a very wide range. It could provide energy from only a few seconds to 4 hours [18]. For the short service time, they usually aim to response for the unpredicted and random variations in demand and generation. For the long service time, the major purpose is to be a resource of the electricity during the peak electricity-demand period.

Table 3. Lifetime and Response time of Li-ion, Lead-acid, and NaS technologies

Type of the RBESs	Lifetime (years) [19]	Response Time [20]
Li-ion	14-16	ms
Lead-acid	15	ms
NaS	12-20	ms

6. Comparison between the PSGES and the RBES

In this session, the data of the PSGES and the RBES are summarized. Besides, the qualification for selecting the energy storage system for storing extra electricity in low-demand period and discharge in high-demand period will be analyzed based on the data and specific criteria. All data are listed in Table 4.

Table 4. Summary of the quantitative metrics of the PSGES and the RBES

Metrics	PSGES	RBES (Li-ion)	RBES (Lead-acid)	RBES (NaS)
Energy Efficiency, %	75%-80%	75%-90%	70%-90%	89%
Energy Density	0.2-3.1 kWh/m ³	100-265 Wh/L	35-40 Wh/L	150-300 W/L
Power Density	0.03-30 kW/m ³	250-693 W/L	80-90 W/L	10000 W/L
LCOE, USD/MWh	94-113	243-257 (Heindl Energy) or 367.5	403	301-304
Discharge Time	1h-4h	a few seconds-4h		
Lifetime, year	40 years	14-16 years	15 years	12-20 years
Response time	Around 0.5 s	ms	ms	ms

Based on the data, the PSGES has the smallest highest energy efficiency compared with all 3 types of RBES. The PSGES has no competency with the RBES in the energy density and power density. The LCOE of the PSGES is lower. Lower LCOE means that the same amount of energy could be produced in a lower price or investment. The discharge time of the RBES is more flexible than the PSGES. The discharge time could be just a few seconds and long enough to 4 hours. The lifetime of the PSGES is much longer than the RBES. This mainly depends on the maintenance difficulty of the

RBES. It is dangerous to disassemble the RBES to replace and maintain the cathode and anode because substances inside have the potential to combust spontaneously. However, the PSGES could be maintained by replacing some obsolete parts. No chemical hazards are involved during maintenance procedures. The response time of the RBES is not certain but the time are based on the millisecond. It is relatively smaller than the 0.5 seconds of the PSGES.

7. Selection of the Energy Storage System

The selection of the energy storage system could be based 2 different operational conditions: steady output of the energy for a long time (>2h) to provide energy during the peak period and large output of the energy for a short time to response the unpredicted and random variation of the demand and generation.

There are several criteria for selecting the system for 2 different operational conditions. Criteria of selecting the system are based on the value of the data provided in the Table 4. The detailed score criteria are provided below.

For these 2 kinds of energy storage system, the selection could be proceeded based on the Pugh method. Because there are 4 types of technologies are presented, 4 scores are assigned for judgement: 4 (outstanding), 3 (good), 2 (eligible), and 1(weak). Each technology will be evaluated based on the criteria presented above and assigned a specific score. The technology that has the highest score will be selected for the best solution for the energy storge system.

Table 5 shows that the score for each technology for long-time energy production during the peak period. Based on the score, the RBES based on the sodium-sulfur technology is the best solution for the long-time energy production during the peak period. If the NaS technology is not available, the Li-ion RBES is also a good choice. The PSGES is not recommended because of the geological dependency. It requires large area for installation and operation. The PSGES could be a good choice for the place with wide plain area. The Lead-acid RBES is not recommended and has the lowest score because the energy density, power density, lifetime, and LCOE are too mediocre. The LCOE is too high that this project is not profitable.

Table 6 shows that the score for each technology for the short-time production of energy. Based on the score, the NaS RBES is still the best option for short-time energy production to tackle the unpredicted and random variation of demand and generation. The PSGES is not recommended because the discharge time is too long. The other 2 RBES technologies have relatively low LCOE, energy density, and power density. Thus, the RBES has the highest competency.

Table 5. Metrics for selecting energy storage system for long-time energy production during the peak period.

Criteria	PSGES	RBES (Li-ion)	RBES (Lead-acid)	RBES (NaS)
Discharge time	4	4	4	4
Response time	4	4	4	4
Energy density	1	3	2	4
Power density	1	3	2	4
Lifetime	4	2	2	2
LCOE	4	2	1	2
Energy efficiency	3	4	4	4
Total	21	22	19	24

Table 6. Metrics for selecting energy storage system for short-time energy production.

Criteria	PSGES	RBES (Li-ion)	RBES (Lead-acid)	RBES (NaS)
Discharge time	1	4	4	4
Response time	4	4	4	4
Energy density	1	3	2	4
Power density	1	3	2	4
Lifetime	4	2	2	2
LCOE	4	2	1	2
Energy efficiency	3	4	4	4
Total	18	22	19	24

8. Conclusion

Based on the comparison among the PSGES, RBES (Li-ion), RBES (Lead-acid), and RBES (NaS), the RBES using NaS technology has the highest competency. It is outstanding in the flexible discharge time, fast response time, high power density, energy density, and energy efficiency. Thus, the RBES using NaS technology could be considered the best option for both long-time energy output during the peak period and the instantaneous energy output for the unpredicted and random circumstances. This paper and summary provide a brief comparison between the PSGES and the RBES. This could help the designer or planner have a quick understanding of choosing the energy storage system and the detailed technology. However, the research did not consider some factors, including but not limiting to the geological, anthropological, and environmental factors. These factors require further discussions and research based on different region and geological characteristics.

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