Applied problems of information systems operation

UDC 004.942 doi: https://doi.org/10.20998/2522-9052.2023.3.13

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COMPARATIVE ANALYSIS OF THE EFFICIENCY OF VARIOUS ENERGY STORAGES

Abstract. **Research relevance** This article presents a mathematical solution to the issue of a comparative analysis of various types of energy storage devices and determining the most efficient type of energy storage device for use on an industrial scale. **The subject** of the study in the article is the most important parameters of seven types of energy storages, the use of which is spreading in the world. **The purpose** of the work is to obtain an answer to the following question: which of the ubiquitous different types of energy storages is most likely to be the most efficient for the future industrial energy supply? The following **tasks** are solved in the article: 1) generalization of the collected data; 2) analysis (evaluation) of data using mathematical methods of data analysis. The following research **methods** are used: comparison, abstraction, axiomatic, analysis, synthesis, formalization and induction. The following **results** were obtained: among the analyzed energy storages, the best result was shown by a mechanical potential (gravitational) energy storage. **Conclusions:** If it is planned to use energy storages on an industrial scale in various fields, it should be recognized as expedient to give preference to gravitational devices.

Keywords: energy storage; gravitational energy storage; electrochemical energy storage; capacitor energy storage; thermal energy storage; flywheel energy storage; compressed air energy storage; cryogenic energy storage.

Introduction

Recently, the transition to renewable energy has been widely discussed around the world, but the difficulties that will follow this transition are often ignored. However, the possibility of using renewable energy will depend on the elimination of the aforementioned difficulties.

Renewable energy has a number of advantages over traditional energy, but it also has serious disadvantages. In most cases, it can only be provided intermittently. These breaks can be regular and predictable, as in the energy of the Sun, sea tides, or irregular and unpredictable, as in the energy of the wind, sea waves. The intermittency of renewable energy is one of its main disadvantages [1–8].

Even now, when traditional energy sources are universally preferred, power outages occur and this is a problem. But in the future, with the transition to the use of renewable energy, interruptions in its supply will become common and frequent, and the problem will increase dramatically. This will have a serious negative impact on energy consumers.

The results of previous analyzes show that the use of energy storage means is the most optimal solution to the problem under consideration. At the same time, a certain amount of supplied energy with its excess (for example, at night or during hours of less consumption) can be accumulated and stored. When energy decreases (for example, during peak hours) or it is off, previously accumulated energy can be used. This means that renewable energy sources require the use of energy storages along with them [9–20].

Energy storages is currently being deployed mainly at the level of commercial and demonstration projects in some countries that are starting a gradual transition to renewable energy. They are of different types and differ sharply from each other in terms of the principle of operation, device, technical capabilities and financial costs. Along with all this, there is no doubt that the need for the use of energy storages will arise and increase as the transition to the widespread use of renewable energy around the world [9-20].

But a natural question arises: what type of energy storage among many different types will be the most effective for future uninterrupted power supply on an industrial scale? Getting a definitive answer to this question was the aim of the study.

This problem was partially considered in [11, 14].

However, in [11] gravitational and cryogenic energy storages were not considered, the comparison was built in a primitive way and for each parameter separately, and only 5 parameters were used. In [14], flywheel, compressed air and cryogenic energy storages were not considered, the parameters of various storages were collected in one table, but no comparison was made. Therefore, the task of determining the efficiency of each considered energy storage device for subsequent objective comparative analysis and identification of the most efficient type of energy storage device is topical.

In the research, based on the collected theoretical material, the effectiveness of seven types of energy storage devices that are gaining distribution in the world has been studied and analyzed in terms of technical and economic aspects. These are electrochemical, electro capacitive, thermal, mechanical kinetic (flywheel), mechanical potential (gravitational), compressed air and cryogenic energy storages. To simplify the task a little, the influence of the terrain, atmospheric pressure, temperature, humidity, wind and other natural phenomena on the operation of these energy storages is not taken into account.

Based on the results of previous analyzes, it is assume that a mechanical potential (gravitational) energy storage will be more effective than other storages. The research should confirm or refute this assumption.

Methodology

Such methods of scientific research as comparison, abstraction, axiomatic, analysis, synthesis, formalization and induction were used during the research. The research was conducted in two stages: 1) data collection 2) evaluation.

1. Data collection.

As many different materials as possible were used to ensure the greatest possible objectivity.

Seven parameters were selected for the research, which are most important for the characteristics of energy storage devices and are most often found in the literature. These are output power, capacity, efficiency, response time, discharge time at rated power, service life and unit cost [9-28].

Since in various literature the values of some parameters are expressed in different units of measurement, for each of the following three parameters, a conversion was made to the specified unit of measurement:

- output power – watt
- capacity – watt-hour
- unit cost – US dollar/kilowatt-hour

For the other four parameters, there was no such need.

Taking into account the presence of inflation, only data for the last 6 years was used to collect data on unit cost.

If the parameter value changes in a certain range, the average value of the range was taken for calculations:

$$\text{Average} = (\text{Least value} + \text{Largest value}) / 2 \quad (1)$$

Some values in the literature are expressed as the plural form of the unit of measurement (like seconds, minutes, etc.), without specifying a specific number. In order to obtain the numeric values necessary for evaluation, the plural form is converted to a numeric form. For this, the principle was applied: the plural form of the unit of measurement was taken as half of the unit of measurement one step more. For example, "seconds" were taken as half a minute – 30 seconds. All such transformations performed during the research are presented in Table 1.

Table 1 – **Converting the plural form of a unit of measure to values expressed in numbers**

Plural form of unit of measurement	Unit of measure one step up	The resulting value
milliseconds	a second	0.5 seconds
seconds	a minute	30 seconds
minutes	an hour	30 minutes
hours	a day	12 hours
days	a week	3.5 days

2. Evaluation.

Each type of energy storage has been rated by some factor for ease of comparison. It is called the final coefficient and is determined on the basis of 3 general principles that apply to all types of energy storages:

- the final coefficient of a particular type of energy storage is formed by the sum of the coefficients corresponding to the values for each parameter;
- no parameter is given preference in the evaluation, the significance of each parameter is taken equal for the final assessment;
- a good value of the parameter gets a proportionally larger one, and a bad value gets a smaller coefficient.

To implement the above principles, it is required to determine the coefficients corresponding to the values for each parameter for each type of storage (total 7 x 7 = 49 coefficients). To do this, first, within each individual parameter, the mathematical sum of all 7 coefficients that correspond to seven different types of storages was taken equal to 100, and the sum of all 49 coefficients for all seven parameters is 700. Such application of coefficients is necessary for the possibility of final evaluation based on the values of completely different parameters. The results of previous analyzes show that the above mathematical approach is able to provide the necessary objectivity in finding the answer to the question posed.

If it is better for a parameter to have a larger numerical value, then the coefficient (C) was calculated as follows:

$$C = TV \times 100 / \text{Sum } TV \quad (2)$$

Here TV is the type value and Sum TV is the sum of values of all types. If it is better for a parameter to have a smaller numerical value, then inverse proportionality was applied and the coefficient was calculated in three steps.

At the first step, the intermediate coefficient (IC) was calculated:

$$IC = TV \times 100 / \text{Sum } TV \quad (3)$$

At the second step, the reciprocal of the intermediate coefficient (RIC) was calculated:

$$RIC = 1 / IC \quad (4)$$

At the third step, the coefficient was calculated:

$$C = RIC \times (100 / \text{Sum } RIC) \quad (5)$$

Here Sum RIC is the sum of RIC of all types. After that, the final coefficient (FC) was calculated by summing all the coefficients:

$$FC = C1 + ... + C7 \quad (6)$$

To simplify the calculation of the coefficients, the numbers in Tables 4, 5, 6, 7 and 8 are rounded to the nearest hundredth. If in the fractional part of the number after the decimal point the first digit is zero, rounding was done to thousandths, and if the first two digits are zeros, then to ten thousandths.

Research results

More than a hundred different literature covering relevant areas were studied to collect data. Fifty-one of them: [9–59] were particularly useful, and all data was taken from these sources. Discrimination between different sources was excluded: any information taken from any source was accepted on an equal basis with others.

The various values of the considered parameters of each type of the studied energy storage available in the mentioned literature were taken and recorded in separate groups. As a result, 49 sets of values were formed, each of which corresponded to a certain parameter under consideration.

For example, the set of values for the output power of thermal energy storages consisted of 28 elements. The smallest of these elements is 5 kW and the largest is 500 MW. Efficiency values for compressed air energy storages were taken from 19 sources. The smallest of them is 35%, and the largest is 86%. In three cases, all values in the set were the same. The collected values are listed in Table 2, but not all are recorded in the corresponding cell, but only the smallest and largest values from each set (in the above examples, these are 5 kW and 500 MW, also 35% and 86%), with a "-" sign between them.

Thus, certain ranges of values of the parameters under consideration were created for the studied energy storages (46 ranges in total), and specific values appeared in three cells not in the form of a range.

The values of two parameters: response time and discharge time at rated power in the literature in some cases are indicated as a plural form of the unit of time, for example, "milliseconds", "seconds", "minutes", "hours", "days". In some cases, these values are given in numbers.

To enable evaluation, all values in the plural form of the unit of time were converted to numerical values in the order specified in Table 1.

Then, according to the formula (1), the average value of the range was calculated for each parameter, the value of which is expressed as a range. Table 3 was compiled on the basis of the average values obtained, as well as the three specific values available.

Table 2 – **Parameter values collected from the literature for each type of energy storage [9-59]**

Parameter	**Parameter values for each type of energy storage**						
	Electrochemical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compre-ssed air***	***Cryogenic***
Output power	5 kW -250 MW	0.8-300 kW	5 kW - 500 MW	2 kW -20 MW	250 kW - 7 GW	9 kW -3 GW	100 kW - 1 GW
Capacity	0.7 kWh - 250 MWh	0.2-1 kWh	18 MWh - 11.6 GWh	3 kWh - 5 MWh	2 MWh - 80 GWh	7 kWh - 3 GWh	2.5-500 GWh
Efficiency, %	45-98	85-99	25-80	85-97	70-90	35-86	15-70
Response time	seconds	milli-seconds	1-15 minutes	1-2minutes	1 second - 2 minutes	1-2 minutes	1-2minutes
Discharge time at rated power	minutes - days	seconds - minutes	hours - days	seconds - hours	hours - days	hours - days	hours - days
Service life, years	3-20	10-20	30	10-20	20-50	20-50	20-40
Unit cost, $/kWh	40-4000	100-10000	3-120	800-7000	1-430	2-140	140-530

Table 3 – **Calculated average values of energy storage parameters**

Parameter	**Average values of energy storage parameters**						
	Electrochemical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compres-sed air***	***Cryogenic***
Output power	125 MW	150 kW	250 MW	10 MW	3.5 GW	1.5 GW	0.5 GW
Capacity	125 MWh	0.6 kWh	5.8 GWh	2.5 MWh	40 GWh	1.5 GWh	250 MWh
Efficiency, %	72	92	53	91	80	61	43
Response time	30 seconds	0.5 seconds	8 minutes	1.5 minutes	1 minute	1.5 minutes	1.5 minutes
Discharge time at rated power	42 hours	15 minutes	48 hours	6 hours	48 hours	48 hours	48 hours
Service life, years	12	15	30	15	35	35	30
Unit cost, $/kWh	2020	5050	62	3900	216	71	335

Evaluation began after the full formation of Table 3.

Since other formulas were used in the case where the lower numerical value is considered the best, the corresponding parameters were evaluated separately.

Since it is better to have large numerical values for output power, capacity, efficiency, discharge time at rated power and service life, the coefficients corresponding to them were calculated by formula (2).

The 5 coefficients obtained from these calculations for each type of energy storage (total 7 x 5 = 35) are listed in Table 4.

Since it is better to have smaller numerical values for response time and unit cost, the coefficients corresponding to them were calculated using formulas (3), (4) and (5). At the first step, intermediate coefficients corresponding to the values of the parameters were calculated using formula (3).

The results were entered in Table 5.

Table 4 – **Calculated coefficients corresponding to parameters for which it is better to have large numerical values**

Parameter	Coefficients obtained as a result of evaluating parameter values						
	Electroch emical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compre-ssed air***	***Cryo-genic***
Output power	2.12	0.0025	4.25	0.17	59.47	25.49	8.50
Capacity	0.26	1.26 e-6	12.17	0.0052	83.90	3.15	0.52
Efficiency	14.63	18.70	10.77	18.5	16.26	12.40	8.74
Discharge time at ra-ted power	17.48	0.10	19.98	2.50	19.98	19.98	19.98
Service life	6.98	8.72	17.44	8.72	20.35	20.35	17.44

Table 5 – **Intermediate coefficients corresponding to parameters for which it is better to have smaller numerical values**

Parameter	Intermediate coefficients corresponding to parameter values						
	Electroche mical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compres-sed air***	***Cryo-genic***
Response time	3.57	0.059	57.11	10.71	7.14	10.71	10.71
Unit cost	17.33	43.33	0.53	33.46	1.85	0.61	2.87

At the second step, the reciprocals of the intermediate coefficients were calculated using formula (4) and the results were entered in Table 6. At the third step, calculations were made using formula (5) and the obtained 2 more coefficients for each type of energy storage (14 in total) were entered in Table 7.

Table 6 – **Reciprocals of intermediate coefficients from Table 5**

Parameter	Reciprocals of intermediate coefficients						
	Electroche mical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compres-sed air***	***Cryogenic***
Response time	0.28	16.95	0.018	0.093	0.14	0.093	0.093
Unit cost	0.058	0.023	1.89	0.030	0.54	1.64	0.35

Table 7 – **Coefficients corresponding to parameters for which it is better to have smaller numerical values**

Parameter	Coefficients obtained as a result of evaluating parameter values						
	Electroche mical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravitatio nal***	***Compresse d air***	***Cryogenic***
Response time	1.58	95.94	0.10	0.53	0.79	0.53	0.53
Unit cost	1.28	0.51	41.71	0.66	11.92	36.20	7.72

Finally, using formula (6), the final coefficients were calculated based on the terms taken from Table 4 and Table 7, and the results were entered in Table 8.

Table 8 – **Final coefficients for evaluating different types of energy storages**

Parameter	Final coefficients						
	Electroche mical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravita-tional***	***Compres-sed air***	***Cryogenic***
Final grade	44.33	123.97	106.42	31.09	212.67	118.10	63.43

Aspects (opportunities) of practical application

Some types of gravity storage devices may have certain limitations. For example, a pumped hydro storage device depends on the presence of large reservoirs located at different heights.

The main advantages of gravitational energy storage are as follows: huge output power, huge capacity, long service life, low operating costs.

The main disadvantage of gravitational energy storage is sometimes called the large scale of construction. But this statement is disputable, if we take into account the output power and capacity, which are provided by gravitational storage devices.

The discussion of the results

Thus, the results of the research confirmed the proposed hypothesis. Among the analyzed energy storages, the best result was shown by a mechanical potential (gravitational) energy storage with a final coefficient of 212.67. This is 2.13 times better than the arithmetic mean of 100 for all types of energy storages analyzed.

As evidence of the objectivity and advantages of such a result, the fact that the use of gravitational force is still the most common way to accumulate energy on a huge scale can serve as evidence. In addition, in recent years there are more and more new ways of using gravity to store energy. And this shows that the potential of this approach to energy storage is far from being exhausted.

Conclusions

The results of the work done show that for the accumulation of energy in large quantities, the use of gravitational force is clearly better than other options. It's cheaper, easier and more durable.

If it is planned to use energy storages on an industrial scale in various fields, it should be recognized as expedient to give preference to gravitational devices.

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Received (Надійшла) 12.05.2023
Accepted for publication (Прийнята до друку) 16.08.2023

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Порівняльний аналіз ефективності різних типів накопичувачів енергії

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Анотація. Актуальність дослідження. У статті наведено математичне вирішення питання порівняльного аналізу різних типів накопичувачів енергії та визначення найбільш ефективного типу накопичувача енергії для використання у промислових масштабах. **Предметом дослідження** у статті є найважливіші параметри семи типів накопичувачів енергії, використання яких розглядається у світі. **Мета роботи** – отримати відповідь на таке запитання: який із поширених різних типів накопичувачів енергії, швидше за все, буде найефективнішим для майбутнього промислового енергопостачання? У статті вирішуються такі **завдання**: 1) узагальнення зібраних даних; 2) аналіз (оцінка) даних із використанням математичних методів аналізу даних. Використовуються такі **методи дослідження**: порівняння, абстракція, аксіоматика, аналіз, синтез, формалізація та індукція. Були отримані такі **результати**: серед проаналізованих накопичувачів енергії найкращий результат показав механічний (гравітаційний) накопичувач енергії. **Висновок.** Якщо планується використовувати накопичувачі енергії в промислових масштабах у різних сферах, слід визнати за доцільне віддати перевагу гравітаційним пристроям.

Ключові слова: зберігання енергії; накопичувачі гравітаційної енергії; електрохімічний накопичувач енергії; конденсаторний накопичувач енергії; акумулювання теплової енергії; накопичувач енергії маховика; акумулювання енергії стисненого повітря; кріогенний накопичувач енергії.