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Comparative analysis of the efficiency of various energy storages

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Abstract—**The use of renewable energy creates the need to solve the problem of its discontinuity. Previous experience has shown that energy storage devices are best suited for this. They can be attributed to new technologies, since the operation of some energy storage devices is based on the latest achievements of modern science and technology. Energy storages is now at the beginning of its development, as renewable energy is still used to a limited extent. But which of the ubiquitous different types of energy storages is most likely to be the most efficient for the future industrial energy supply? The aim of the research was to obtain an answer to the above question. For this, seven types of energy storages, the use of which is spreading in the world, are analyzed in a comparative manner in terms of the most important parameters. The comparison was made using mathematical methods of data analysis, based on data collected from the relevant literature, and allows a fairly objective answer to the question under study.**

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.

I. 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 [1–4].

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 [5–16].

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 [5–16].

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. To do this, the most objective comparative analysis was carried out, the result of which was supposed to form an answer to the question posed.

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.

II. METHODOLOGY

Such methods of scientific research as comparison, abstraction, axiomatic, analysis, synthesis, formalization and induction were used during the research.

Seven parameters were selected for the research, which are most important for the characteristics of energy storages 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 [5-24].

Considering inflation, unit cost data were used only for the last 6 years.

If the parameter value changes, the average value is taken for calculations:

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

Some values in the literature are expressed as the plural form of the unit of measurement (like seconds, minutes, etc.), without specifying a number. To get the numbers needed 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, "minutes" – half an hour (30 minutes), etc.

Each type of energy storage was evaluated by a final coefficient based on 3 general principles: 1) 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; 2) no preference is given to any parameter, the significance of each parameter is taken equal for the final assessment; 3) a good parameter value 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 drive (total 7 x 7 = 49 coefficients). To do this, first, within each parameter, the sum of all 7 coefficients that correspond to seven different types of drives was taken equal to 100, and the sum of all 49 coefficients for all seven parameters was 700.

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

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

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:

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

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

$$RIC = 1 / IC. \qquad (4)$$

At the third step, the coefficient was calculated:

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

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

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

III. RESEARCH RESULTS

More than a hundred different literatures were studied to collect data. Forty seven of them: [5-51] were particularly useful, and all data were taken from these sources. Various values of energy storage parameters available in the mentioned literature were taken and recorded in groups. As a result, 49 sets of values were formed, each of which corresponded to a certain parameter of a certain type of energy storage. Then, according to (1), the average for each set of values was calculated. Based on the obtained averages, Table 1 was compiled.

TABLE I. CALCULATED AVERAGES FOR PARAMETER VALUES OF ENERGY STORAGES

Parameter	**Averages for Parameter Values of Energy Storages**						
	Electrochemical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravitational***	***Compressed 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 1. 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 (2). The 5 coefficients obtained from these calculations for each type of energy storage (total 7 x 5 = 35) were entered in Table 2.

Since it is better to have smaller numerical values for response time and unit cost, the coefficients corresponding to them were calculated in three steps using (3), (4) and (5).

At the first step, intermediate coefficients corresponding to the values of the parameters were calculated using (3).

At the second step, the reciprocals of the intermediate coefficients were calculated using (4).

At the third step, calculations were made using (5) and the obtained 2 more coefficients for each type of energy storage (14 in total) were entered in Table 2.

Finally, according to (6), the final coefficients were calculated based on the terms in each column.

TABLE II. COEFFICIENTS BY PARAMETERS AND FINALS FOR EVALUATING ENERGY STORAGES

Parameter	**Coefficients Obtained as a Result of Evaluating Parameter Values**						
	Electrochemical	***Electro capacitive***	***Thermal***	***Flywheel***	***Gravitational***	***Compressed air***	***Cryogenic***
Output power	2.12	0.0025	4.25	0.17	59.47	25.49	8.50
Capacity	0.26	1.3e-6	12.17	0.0052	83.90	3.15	0.52
Efficiency	14.63	18.70	10.77	18.50	16.26	12.40	8.74
Response time	1.58	95.94	0.10	0.53	0.79	0.53	0.53
Discharge time at rated 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
Unit cost	1.28	0.51	41.71	0.66	11.92	36.20	7.72
Final coefficients	44.33	123.97	106.42	31.09	212.67	118.10	63.43

IV. CONCLUSION

Thus, the results of the research confirmed the proposed hypothesis. The gravitational energy storage showed the best result 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.

When planning the use of energy storages on an industrial scale in a variety of areas, it will be advisable to give preference to gravitational devices.

REFERENCES

[1] M. Roser, *Why did renewables become so cheap so fast?* [Online]. Available: https://ourworldindata.org/cheap-renewables-growth. [Accessed: Octember 15, 2023].

[2] “What is renewable energy?” [Online]. Available: https://www.un.org/en/climatechange/what-is-renewable-energy. [Accessed: Octember 15, 2023].

[3] “Advantages and Disadvantages of Renewable Energy.” [Online]. Available: https://www.conserve-energy-future.com/advantages-and-disadvantages-of-renewable-energy.php. [Accessed: Octember 15, 2023].

[4] H.K. Lakeh, “What Are the Advantages and Disadvantages of Renewable Energy?” [Online]. Available: https://www.greenmatch.co.uk/blog/2021/09/advantages-and-disadvantages-of-renewable-energy. [Accessed: Octember 15, 2023].

[5] “Electricity and Energy Storage.” [Online]. Available: https://world-nuclear.org/information-library/current-and-future-generation/electricity-and-energy-storage.aspx#:~:text=Storage%20systems%20for%20electricity%20include,of%20energy%20they%20can%20store. [Accessed: Octember 15, 2023].

[6] L. Yao, B. Yang, H. Cui, J. Zhuang, J. Ye, and J. Xue, “Challenges and progresses of energy storage technology and its application in power systems,” Journal of Modern Power Systems and Clean Energy, vol. 4, 2016, pp. 519–528.

[7] J.I. San Martín, I. Zamora, J.J. San Martín, V. Aperribay, P. Eguía, *Energy Storage Technologies for Electric Applications*. [Online]. Available: http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html. [Accessed: Octember 15, 2023].

[8] “Electric Energy Storage,” [Online]. Available: https://www.c2es.org/content/electric-energy-storage/. [Accessed: Octember 15, 2023].

[9] S. Perkins, *Explainer: How batteries and capacitors differ*. [Online]. Available: https://www.snexplores.org/article/explainer-batteries-capacitors. [Accessed: Octember 15, 2023].

[10] “Energy storage for electricity generation.” [Online]. Available: https://www.eia.gov/energyexplained/electricity/energy-storage-for-electricity-generation.php. [Accessed: Octember 15, 2023].

[11] “Energy Storage: How It Works and Its Role in an Equitable Clean Energy Future.” [Online]. Available: https://www.ucsusa.org/resources/how-energy-storage-works. [Accessed: Octember 15, 2023].

[12] “Electricity Storage.” [Online]. Available: https://www.epa.gov/energy/electricity-storage. [Accessed: Octember 15, 2023].

[13] J.S. Jones, *The different types of energy storage and their opportunities*. [Online]. Available: https://www.smart-energy.com/storage/the-different-types-of-energy-storage-and-their-opportunities/. [Accessed: Octember 15, 2023].

[14] R.J. Campbell, *Electricity Storage: Applications, Issues, and Technologies*. [Online]. Available: https://www.everycrsreport.com/reports/R45980.html. [Accessed: Octember 15, 2023].

[15] “Energy Storage: How It Works at Home and on the Grid.” [Online]. Available: https://justenergy.com/blog/energy-storage-how-it-works-home-and-grid/. [Accessed: Octember 15, 2023].

[16] “Packing some power.” [Online]. Available: https://www.economist.com/technology-quarterly/2012/03/03/packing-some-power?frsc=dg%7Ca. [Accessed: Octember 15, 2023].

[17] “Pumped Hydroelectric Energy Storage.” [Online]. Available: http://www.eseslab.com/ESsensePages/PHS-page. [Accessed: Octember 15, 2023].

[18] “Compressed Air Energy Storage.” [Online]. Available: http://www.eseslab.com/ESsensePages/CAES-page. [Accessed: Octember 15, 2023].

[19] “Batteries.” [Online]. Available: http://www.eseslab.com/ESsensePages/Batt-page. [Accessed: Octember 15, 2023].

[20] “Flywheels.” [Online]. Available: http://www.eseslab.com/ESsensePages/ Flywheels-page. [Accessed: Octember 15, 2023].

[21] “Supercapacitors.” [Online]. Available: http://www.eseslab.com/ESsensePages/ Supercaps-page. [Accessed: Octember 15, 2023].

[22] “Cryogenic Energy Storage.” [Online]. Available: http://www.eseslab.com/ESsense Pages/Cryo-page. [Accessed: Octember 15, 2023].

[23] “Thermal Energy Storage.” [Online]. Available: http://www.eseslab.com/ESsense Pages/TES-page. [Accessed: Octember 15, 2023].

[24] B.G. Ibrahimov, E.G. Hashimov, A.M. Talibov, and A.H. Hasanov, “Research and analysis indicators fiber-optic communication lines using spectral technologies,” Advanced information systems, vol. 6(1), 2022, pp. 61–64. doi: https://doi.org/10.20998/2522-9052.2022.1.10

[25] A.C. Ruoso, N.R. Caetano, and L.A.O. Rocha, “Storage Gravitational Energy for Small Scale Industrial and Residential Applications,” Inventions, vol. 4(4), 2019, pp. 1–13; https://doi.org/10.3390/inventions4040064

[26] J.A. Jeevarajan, T. Joshi, M. Parhizi, T. Rauhala, and D. Juarez-Robles, “Battery Hazards for Large Energy Storage Systems,” ACS Energy Lett., vol. 7, 2022, 2725–2733.

[27] “Engineer-Poet: The Ergosphere: Zinc: Miracle metal?” [Online]. Available: http://ergosphere.blogspot.com/2005/06/zinc-miracle-metal.html. [Accessed: Octember 15, 2023].

[28] V. Talawar, *Different Types Of Energy Storage Devices To Store Electricity*. [Online]. Available: https://cselectricalandelectronics.com/different-types-of-energy-storage-devices-to-store-electricity/. [Accessed: Octember 15, 2023].

[29] D.V. Crotzer, *Energy Storage Myths: #1 Arbitrage*. [Online]. Available: https://www.energystorageconsultants.com/energy-storage-arbitrage/. [Accessed: Octember 15, 2023].

[30] P. Hutchins, *U.S. Utility-Scale Battery Storage Power Capacity to Grow Substantially by 2023*. [Online]. Available: https://www.ajot.com/news/us-utility-scale-battery-storage-power-capacity-to-grow-substantially-by-2023. [Accessed: Octember 15, 2023].

[31] “Compressed Air Energy Storage.” URL: https://caes.pnnl.gov/. [Accessed: Octember 15, 2023].

[32] M. Dooner, *Thermal energy storage*. [Online]. Available: https://estoolbox.org/index.php/en/background-2/8-samples/8-tes-introduction. [Accessed: Octember 15, 2023].

[33] “Energy Sorage Association Homepage.” [Online]. Available: http://energystorageassociationarchive.org/. [Accessed: Octember 15, 2023].

[34] C. Dalvi, *Cryogenic Energy Storage*. [Online]. Available: http://large.stanford.edu/courses/2012/ph240/dalvi2/. [Accessed: Octember 15, 2023].

[35] “Building the future of renewables using gravitational energy storage.” [Online]. Available: https://greengravity.com/technology/. [Accessed: Octember 15, 2023].

[36] S.K. Moore, *Gravity energy storage will show its potential in 2021*. [Online]. Available: https://spectrum.ieee.org/gravity-energy-storage-will-show-its-potential-in-2021. [Accessed: Octember 15, 2023].

[37] A. Lane, *Can gravity batteries solve our energy storage problems?* [Online]. Available: https://www.bbc.com/future/article/20220511-can-gravity-batteries-solve-our-energy-storage-problems. [Accessed: Octember 15, 2023].

[38] D.Z. Morris, *Energy-Storing Train Gets Nevada Approval*. [Online]. Available: https://fortune.com/2016/05/22/energy-storing-train-nevada/. [Accessed: Octember 15, 2023].

[39] A. Rathi, *Stacking concrete blocks is a surprisingly efficient way to store energy*. [Online]. Available: https://qz.com/1355672/stacking-concrete-blocks-is-a-surprisingly-efficient-way-to-store-energy. [Accessed: Octember 15, 2023].

[40] U. Eberle, R. von Helmolt, “Sustainable transportation based on electric vehicle concepts: A brief overview,” Energy Environ. Sci., vol. 3, 2010, pp. 689–699.

[41] B.G. Ibrahimov, E.G. Hashimov, “Analysis and Selection Performance Indicators Multiservice Communication Networks Based on the Concept NGN and FN,” 2021: Fifth International Scientific and Technical Conference "Computer and informatıon systems and technologıes" (CIST, April, 2021), Kharkiv: Computer and information systems and technologies, pp. 96–98. DOI: https://doi.org/10.30837/csitic52021232904

[42] D. Roberts, *Using electricity at different times of day could save us billions of dollars*. [Online]. Available: https://www.vox.com/energy-and-environment/2019/8/7/20754430/renewable-energy-clean-electricity-grid-load-flexibility. [Accessed: Octember 15, 2023].

[43] D. Timmons, *Opinion: We now have the technology to create a grid of cheap fully renewable electricity*. [Online]. Available: https://www.marketwatch.com/story/we-now-have-the-technology-to-create-a-grid-of-cheap-fully-renewable-electricity-2019-08-22. [Accessed: Octember 15, 2023].

[44] P. Maloney, *Minnesota study finds it cheaper to curtail solar than to add storage*. [Online]. Available: https://www.utilitydive.com/news/minnesota-study-finds-it-cheaper-to-curtail-solar-than-to-add-storage/546467/. [Accessed: Octember 15, 2023].

[45] J. Eyer, “Electric utility transmission and distribution upgrade deferral benefits from modular electricity storage,” Albuquerque: Sandia National Laboratories, 2009.

[46] “Pumped Storage.” [Online]. Available: https://www.hydro.org/waterpower/ pumped-storage/. [Accessed: Octember 15, 2023].

[47] R. Walton, *$1B Montana pumped storage hydro project secures funding*. [Online]. Available: https://www.utilitydive.com/news/1b-montana-pumped-hydro-project-secures-funding/558833/. [Accessed: Octember 15, 2023].

[48] A. Lee, *Global renewables group tests concrete flywheel energy storage*. [Online]. Available: https://www.rechargenews.com/transition/global-renewables-group-tests-concrete-flywheel-energy-storage/2-1-605228. [Accessed: Octember 15, 2023].

[49] R. Gupta, N. K. Sharma, P. Tiwari, A. Gupta, N. Nigam and A. Gupta, Application of energy storage devices in power systems, International Journal of Engineering, Science and Technology, vol. 3(1), 2011, pp. 289–297.

[50] N. Kularatna, and K. Gunawardane, “Capacitors as energy storage devices: Simple basics to current commercial families,” Energy Storage Devices for Renewable Energy-Based Systems (Second Edition), Rechargeable Batteries and Supercapacitors, 2021, pp. 181–197.

[51] “Wayback Machine.” [Online]. Available: https://web.archive.org/web/20140801113053/http://www.colorado.edu/engineering/energystorage/files/MSThesis_JGLevine_final.pdf. [Accessed: Octember 15, 2023].