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[Edgars Kudurs](#)*, [Dagnija Blumberga](#), [Kristiāna Dolge](#), [Erlanda Atvare](#)

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Article

Ranking of Electricity Accumulation Possibilities: Multicriteria Analysis

Erlanda Atvare, Edgars Kudurs *, Kristiāna Dolge and Dagnija Blumberga

Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia

* Correspondence: edgars.kudurs@rtu.lv

Abstract: The pace in the implementation of renewable electricity storage in Europe is disappointingly slow. Several factors influence this and there is a need to speed up the rate and increase the volumes in order to promote a 100% transition to renewable energy resources, expand the practice of using renewable energy, and contribute to the improvement of the quality of life of consumers. An important factor is significantly reducing impact on the environment and climate change. Electricity from renewable energy sources such as solar and wind has a seasonal nature that cannot provide the necessary electricity consumption and cover peak loads. The so-called "energy resource crisis" is also a very topical problem at the moment, which reinforces the global need to increase the share of renewable energy resources in the overall balance of primary energy resources. Practical wider integration of renewable electricity storage is what can help stimulate this. The availability of renewable electricity is constantly increasing, and the level of technological innovation is rapidly developing. Therefore, it is valuable to analyze, look for connections and for the ways to accumulate electricity in order to promote its availability from private homes to the national scale and more broadly on the European scale. Therefore, this article analyses and compares the different options for renewable electricity storage, from small batteries to large storage systems, arriving at the best solution according to needs, using analysis methods such as multicriteria decision analysis (MCDA) and TOPSIS. After comparing nine criteria, such as the amount of investment required, existing power density, efficiency, duration of operation and others in two groups (small and large accumulation systems), it was concluded that lithium-ion batteries are currently the best solution among batteries, while pumped hydro storage is the best solution among large accumulation systems.

Keywords: energy, decision-making analysis, innovations, TOPSIS, renewable, storage

1. Introduction

The last decades have seen a purposeful transition in the European energy sector from centralized fossil use to renewable energy source systems. Taking into account the 2030 and 2050 goals set by the European Union in the climate and energy sector, one of the contributions is the commitment to increase the share of energy resources in the total balance of primary energy resources, reduce greenhouse gas emissions and promote energy efficiency [1]. To be able to achieve and stimulate these goals, an integral factor is not only the use of renewable electricity to replace fossil fuel resources, but also the targeted integration of renewable electricity accumulation. Energy storage is a critical enabler of energy transition. The principle is based on the accumulation of excess energy at times when the demand is lower and the efficiency of energy production is higher, but the discharge, i.e. transfer of energy back for consumption, at times when the production volumes are too small is affected by the seasonality of renewable electricity.

There are countless benefits to using renewable electricity, especially when it comes to solar and wind power. The most important aspect is the sustainability of the resource, making it possible to reduce the impact of the energy sector on climate change. No less important are the economic

benefits, which can be further increased by directly storing energy. Accumulation of electricity can meet the needs of consumers, which differ both in terms of volumes and loads characteristic of consumption, which are uneven over the course of the year. The benefits of accumulation are to cover the so-called peak hours and to eliminate the impact of seasonality. By accumulating renewable energy, it not only makes it possible to ensure self-consumption, but also gives renewable energy a higher value by selling electricity at a higher price. On a larger scale, it is also an opportunity to postpone expensive investments in transmission and distribution infrastructure, ensuring higher efficiency of existing networks [2].

There is a need to promote the sustainable development of Europe by showing the competitiveness, benefits, and latest solutions for energy storage. Therefore, this article reviews and compares ten different storage technologies that, after extensive research, have shown potential effects that provide high efficiency, and the ability to compete in the market and in practice. Accumulation systems differ both in their degree of complexity and in the number of constructive elements, as well as in terms of cost, environmental impact, efficiency and other factors. The types of energy storage chosen for analysis and mutual comparison are illustrated in Figure 1.

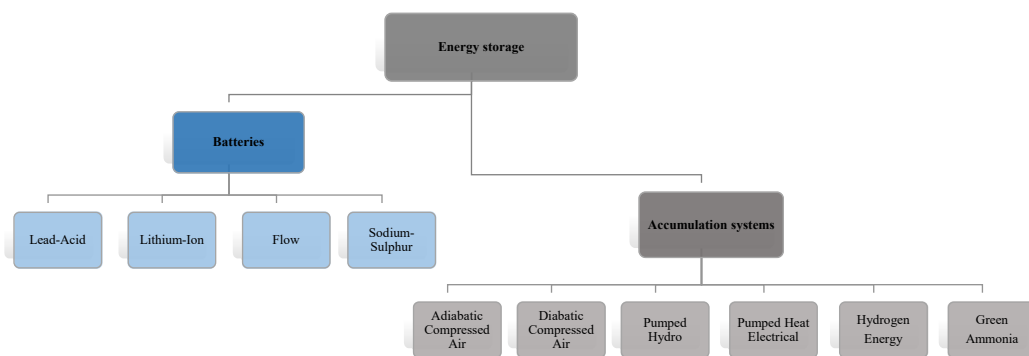


Figure 1. Electricity storage technologies

Electricity storage technologies were divided into two groups, batteries and accumulation systems. The first group compared batteries intended for storing smaller amounts of energy in small households. The second group includes large electricity storage systems, which are expected to be integrated into power plants on a national scale. Below is a brief overview of the literature analysis for each of the types of accumulation.

1.1. Lead-Acid Battery

The most common batteries for energy storage are lead-acid batteries used as backup energy sources. They are based on electrochemical charge/discharge reactions that occur between the positive electrode containing lead dioxide and the negative electrode containing porous lead. These electrodes are immersed in an aqueous sulfuric acid electrolyte that participates in charge/discharge reactions. In recent years, new types of lead-acid batteries have been invented. One such battery is the valve-regulated lead-acid battery which is sealed and does not need to be topped up with water, and thus the maintenance cost of this type of battery is cheaper. Gel-type lead-acid batteries, which are filled with gel instead of liquid, reduce the possibility of leakage [3]. Taking into account the challenge of the modern world, even these batteries, continue to be improved and currently efforts are being made to improve the performance of lead-acid batteries and extend their life cycle. One of the examples most often cited in recent articles is to improve the discharge capacity of lead-acid batteries, for example, through the use of graphene oxide [4].

1.2. Lithium-Ion Battery

The energy storage technology of lithium-ion batteries seems to be particularly well-known, given that they are used in more than 50% of the market for small, portable electrical devices, especially mobile phones, because they can provide twice the operating time of a conventional battery. Thus the response time is much smaller, they charge faster, can last longer and have the highest efficiency [5]. Lithium-ion batteries are based on electrochemical charge/discharge reactions that occur between a positive electrode containing lithium metal oxide and a negative electrode composed of carbon material. In recent years, the large-scale integration of lithium-ion batteries has been accelerating, particularly driven by the development of automotive and energy storage innovations. It is possible to conclude that lithium-ion batteries can unequivocally be considered the main, potentially the most widely used storage technology of the future. Technological development further increases energy density, operation and cycle times. Also, the cost of the system will continue to decrease, which is currently the largest part of the capital expenditure of lead-acid, flow, or sodium-sulphur batteries. This can be improved by increasing industrial capacity and promoting mass production. Already, lithium-ion batteries are used for self-consumption in residential and commercial buildings, which are distributed for emergency support and frequency regulation, respectively, as well as for the integration of large renewable energy equipment into power systems [6]. Recycling processes and equipment are also being introduced, which ensure the recycling efficiency is already well over 50% [7].

1.3. Flow Battery

Flow batteries are based on tanks in which the electrolyte is stored. This technology is capable of providing a large amount of energy (more than 10 MWh) for balancing electricity in the power grid. These batteries work similarly to lead-acid batteries, but the electrolyte is stored in external tanks that vary in size depending on the amount of energy to be stored [8]. However, current technologies for flow batteries are still expensive and have a relatively low energy density, which limits their use in large-scale applications. Therefore, solutions are being sought to solve this problem and organic flow batteries are offered as one of the options, which use organic molecules and are considered one of the most promising technologies due to their low cost and high performance [9].

1.4. Sodium-Sulphur Battery

The sodium-sulphur battery system is an energy storage system based on electrochemical charge and discharge reactions that occur between a positive electrode (cathode), usually made of molten sulphur (S), and a negative electrode (anode), usually made of molten sodium (Na). The electrodes are separated by a solid ceramic, sodium beta alumina, which also serves as an electrolyte. Sodium-sulphur batteries operate at high temperatures and are safe against external and climatic conditions. Most of the installed sodium-sulphur battery production base is in Japan and the US, and the first European projects were installed in Reunion Island (France), Germany and the United Kingdom. The strategic importance of sodium-sulphur technology remains to cover peak hours or other energy-intensive applications. More specifically, in Japan, sodium-sulphur batteries are widely used in the provision of public services, with a total of approximately 300 MW of stored energy. They are also used in the stabilization of wind farms and solar energy production equipment, peak power and weather changes [10].

1.5. Adiabatic Compressed Air Energy Storage

An adiabatic compressed air energy storage system is based on compressing air and storing it in underground craters. The available electricity is used to compress the air to a pressure of up to 100 bars and store it at a depth of about 100 meters. The heat produced during the compression cycle is stored using thermal energy storage, while the air is forced into underground cavities. When the stored energy is needed, compressed air is used while recovering the heat from storage. This process runs automatically when there is a surplus of energy, and fuel is not used for energy recovery, which

is one of the main factors for raising the level of efficiency, as well as for the process to run without CO₂ emissions. Although research into this type of energy storage system has been on-going since 2003, it is not yet commercially available and only implemented in the demonstration process. A particular challenge is the cost, which means that the first installations will be particularly expensive due to the need for ultra-advanced turbo machines and innovative high-temperature storage structures. A second challenge is the need for high-temperature piping technologies, as air temperatures can rise above 600 °C during compression. It is important to mention that regions where geological salt formations naturally form can be used to store compressed air, are the most suitable places for power plants of this type of compressed air technology [11].

1.6. Diabatic Compressed Air Energy Storage

The geological locations, as mentioned in adiabatic compressed air technology, are also suitable for diabatic compressed air technology. The working principle is also very similar to that of adiabatic compression and diabatic compression also uses air compression and storage in craters. These are usually the aforementioned salt craters, depleted gas cavities, aquifers, or layers of hard rock. However, the air released from the adiabatic system here is heated by burning natural gas or fuel. Therefore, this type of energy storage technology is not pure, but rather a hybrid system consisting of a natural gas-powered, open-loop turbine and an electric storage system. Since the beginning of the 1980s, there are only two such systems in the world - in the US and Germany. Although natural gas is used in this case, after a certain period of operation the technology shows 97% production reliability and 99% compression [12].

1.7. Pumped Hydro Storage

Accumulation of electrical energy is also possible in the reservoirs of hydro stations, considering that the principle of water potential energy is used for the accumulation of electrical energy. In such a system, during periods of low demand and high availability of electricity, water is pumped and stored in upper reservoirs. By releasing energy in accordance with demand, the electricity is obtained in a shorter reaction time. The difference between peak loads and off-peak periods is balanced, ensuring grid stabilization. Weighing several criteria, the use of water storage is the most mature electricity storage system, when taking into consideration the installed power, capacity, the ability to provide additional frequency and voltage control to the power grid. The ability of such an accumulation system to adapt and switch to different operating modes is also important, providing particularly efficient pumping power even at low capacities when asynchronous motor generators are engaged. It is predicted that the use of water storage for electricity storage, as a concept, will be the main driving factor to help countries achieve their goals in reducing GHG emissions [13].

1.8. Pumped Heat Electrical Storage

Analogous to pumped hydro storage, accumulation can also be provided using thermoaccumulation. In this case, instead of pumping water uphill, heat is pumped from one storage, where the temperature is around -160°C, to another heat storage (+500°C) using a reversible heat pump. Electricity is generated by driving the heat engine, while heat is stored using wood chips. Although this type of storage system is in the development stage, the long service life of the systems has been proven, even with regular stopping and starting. Efforts are being made to ensure the feasibility of high-efficiency devices suitable for operation in argon and at high temperatures. Also, there is a need for more economically justified solutions for integrating such systems, because in specific situations this type of accumulation could be the solution, for example, in decommissioning nuclear reactors. The system can be adjusted [14].

1.9. Hydrogen Energy Storage

Gain potential is placed on hydrogen energy storage technology systems, considering the possibilities of using the technical solution as an independent energy supply system in energy-

isolated areas. The use of hydrogen has several applications besides the energy sector. It can be used both as an admixture for liquefied gas after the methanization process and as a fuel effect in vehicles, it is also possible to turn it into methanol, a resource that can be used in industry. In the system, electricity is stored by electrolyzing water to produce hydrogen and oxygen, whereby oxygen is released and hydrogen is stored. However, to transfer electricity to the grid, hydrogen is re-electrified by combining hydrogen with oxygen. An important aspect is that heat and water are released as a by-product, which is a usable resource. Currently installed projects in Europe use alkaline electrolyzers directly, ranging in size from a few kW to several hundred MW, with a short response time, effectively following load changes affected by wind farm output. It is also expected that hydrogen will be transferred for mobility purposes and wholesale through the gas network [15]. In addition, it should be mentioned that hydrogen energy storage technologies are being further developed for example, as hydrogen-biomethane, and hydrogen-methane storage systems, increasing the quality of syngas and biogas, however, this will not be discussed in more detail.

1.10. Green Ammonia Storage Technology

Another large-scale energy storage method is green ammonia storage technology. It is closely related to the hydrogen energy storage technology described above. The essence of the method is the conversion of biomass into ammonia. This concept combines renewable energy production, biomass chemical loop ammonia production and direct ammonia fuel cells [16]. One of the most promising ways to obtain "green" ammonia is by using hydrogen from the electrolysis of water and nitrogen separated from the air. Then, using "green" electricity, hydrogen and nitrogen create a reaction at high temperatures and pressure to produce ammonia. Linking ammonia production with "green" hydrogen could create many new opportunities for more rational energy storage and accumulation. At the same time, it can also be used as a raw material for industrial production and a solution in the transport sector. The innovative technology of ammonia fuel cells is already being used in several transport ships in European waters. Although the technological solutions are still in the process of developing innovations in close connection with "green" hydrogen, "green" ammonia marks a new era not only in the world and European energy, but also in the national economy[17].

Overall, when evaluating the different accumulation possibilities, it is important to note that the suitability for a specific region is particularly influenced by geographical compatibility, the independent infrastructure, as well as the corresponding climate zone and other factors. The purpose of this study is to find the most successful solution, considering the overall results of different factors, based on the innovation of the technological solution, without including a specific geographical location, infrastructure adequacy, climatic conditions, or other similar factors. Therefore, the analysis provides a general overview of the field of accumulation, at the relevant stage of development.

2. Materials and Methods

In this study, TOPSIS, multi-criteria analysis (MCDA) was used to determine the best solution among electricity storage technologies.

Multi-criteria decision analysis (MCDA) is a multi-step process consisting of a set of methods to structure and formalize decision-making processes in a transparent and consistent manner [18]. The MCDA methodology can be considered as a non-linear recursive process consisting of four steps:

- structuring the decision problem;
- preference formulation and modelling;
- compilation of alternative assessments (preferences);
- making recommendations.

In the evaluation of MCDA alternatives, it is important to define the criteria that affect the problem. The most popular MCDA criteria are [19]:

- economic criteria - quality, flexibility, price, lead time, relationships, costs, technical capabilities, logistics costs, reverse logistics, rejection rate;

- environmental criteria - environmental management system, resource consumption, eco-design, recycling, environmental impact control, wastewater, energy consumption, reuse, air emissions, environmental code of conduct;
- social criteria - Stakeholder Involvement, Staff Training, Social Management Commitments, Health and Safety, Stakeholder Relations, Social Code of Conduct, Donations to Sustainable Projects, Stakeholder Rights, Safety Practices, Annual Accident Rate.

MCDA is used to make decisions and analyze the relevance of goals from a variety of information and data - qualitative and quantitative, data from the physical and social sciences, and from policy and ethics to evaluate solutions to problems. Different MCDA methods can be used to solve problems and they can be sorted by several parameters and their model type [20].

Full name of the TOPSIS method - Order selection method based on similarities with ideal solutions. This follows from the concept of the ideal point shifted, from which the compromise solution has the shortest distance. The main advantages of TOPSIS are the identification of an infinite number of criteria and alternatives with a relatively simple calculation method. Also, no special software or specific programming techniques are required to use this method.

The results of TOPSIS provide an alternative comparison in a useful and easy-to-understand format. Alternatives must be selected for evaluation, which are evaluated according to four criteria: technological, economic, environmental and social. The first step using the TOPSIS method is the normalization of the decision matrix, followed by the calculation of the best and worst solution of the normalized decision matrix. The best solution corresponds to the theoretical variant of the preferred level of each criterion, while the worst solution corresponds to the theoretical variant of the least desirable level of each criterion. Finally, the distance of each alternative is calculated, which further allows to obtain the proximity coefficient of the ranking alternatives. Alternatives rank from best to worst [21]. The equations of the TOPSIS method used in this study are described below.

Normalized matrix value can be derived by multiplication of normalized value and weight which is done by following Equation (1).

$$v_{ai} = w_i \times r_{ia} , \quad (1)$$

where

v_{ai} = weighted value;

w_i = weight, $w_1 + w_2 + \dots + w_m = 1$, $w_i = 1 \dots m$;

r_{ia} = normalized criterion value.

Distance for each ideal and non-ideal alternative can be calculated by the sum of the squares of weighted criterion values. The calculation can be done by following Eq. (2, 3).

$$d_a^+ = \sqrt{\sum_{j=1}^n (v_i^+ - v_{ai})^2} \quad (2)$$

where

d_a^+ = distance for each action to the ideal solution;

v_i^+ = ideal solution;

v_{ai} = weighted value.

$$d_a^- = \sqrt{\sum_{j=1}^n (v_i^- - v_{ai})^2} \quad (3)$$

where

d_a^- = distance for each action to the non-ideal solution;

v_i^- = non-ideal solution;

v_{ai} = weighted value.

Closeness coefficient (Ca) shows the distance to the non-ideal solution, which is determined by Equation (4).

$$Ca = \frac{d_a^-}{d_a^+ + d_a^-} , \quad (4)$$

where

$d_a^+ + d_a^-$ = sum of the distance to the non-ideal solution;
 d_a^- = distance to the non-ideal solution [21].

After conducting a literature review, it was concluded that in order to obtain more accurate results, it is necessary to compare energy storage technologies in two groups. Evaluating the scalability and technical parameters of the technologies, it was determined that in one group, lead-acid, lithium-ion, flow, and sodium-sulphur batteries will be compared, while in the other group, the literature-reviewed storage systems, adiabatic compressed air energy storage systems, diabatic compressed air energy storage systems, pumped hydroelectric storage, pumped heat electrical storage technologies, hydrogen energy storage, and green ammonia storage technologies will be compared. Nine comparison criteria were defined for the batteries, while eight were defined for the storage systems, without evaluating power density. Technological, economic, environmental, and social aspects were covered in the determination of the criteria. The created matrices, defined criteria, and assigned values are visible in Tables 1 and 2.

Table 1. Overview of Selected Criteria for Batteries

		A1	A2	A3	A4
		Lead-Acid	Lithium-Ion	Flow	Sodium-Sulphur
		Battery	Battery	Battery	Battery
C1	Investments, EUR/kWh	150	450	250	375
C2	Power density, W/kg	75	260	130	150
C3	Cycles, count	1750	5000	4500	4500
C4	Duration of operation, years	10	17,5	30	17,5
C5	Reaction time, s	0,003	0,003	0,003	0,003
C6	Efficiency, %	80	94	72,5	75
C7	Climate impact factor, kgCO ₂ eq/kWh	0,2	0,175	0,183	0,67
C8	Technological readiness (1-5)	3	4	2	3
C9	Social factor (1-5)	2	3	1	2
		[3,22]	[6,23]	[24,25]	[10,26]

Most of the numerical values in the matrix were obtained after literature analysis, assuming the average values within the given range. Meanwhile, criteria for technological readiness and social factors were determined based on information found in literature analysis as well as the opinions of four experts specialized in environmental science or electrical engineering. In this case, criteria were determined on a five-point scale, assigning values from the lowest (1) to the highest (5). Accordingly, the social factor of energy storage technologies was evaluated based on their impact on sustainable development, considering promoting and hindering factors, as well as the dimension of participation and examples of good practices for integrating energy storage into practice. The more positively the technology was evaluated in terms of its impact on sustainable development and commercialization potential, the higher the value assigned. Meanwhile, technological readiness was evaluated based on the technical maturity of the battery, or its proximity to broader commercialization. Accordingly, the more developed the technology and the broader its availability in the market, the higher the rating was given. Battery investments were compared as peculiar battery investment costs per kWh. The power density criterion determines the battery's ability to release power at a specific moment. Storage devices with higher power density can operate larger load devices. Meanwhile, the cycle count is related to the lifespan and efficiency, as this parameter describes the number of charge/discharge cycles that the battery can provide before performance degradation [27]. The response time parameter characterizes the time required for the system to provide energy at full nominal power. Although this parameter is the same for the observed batteries, it is more important for comparing energy storage systems [28]. Similarly, the climate impact factor was also proposed as a criterion, which in this case describes the intensity of emissions generated if renewable energy is stored.

Table 2. Overview of Selected Criteria for Accumulation Systems

		A5 Adiabatic Compressed Air	A6 Diabatic Compressed Air	A7 Pumped Hydro	A8 Pumped Heat Electric al	A9 Hydrogen Energy	A10 Green Ammonia
C1	Investments, EUR/kWh	1600	800	3400	350	750	2900
C2	Cycles, count	10000000	10000000	10000 000	15000	10000000	10000000
C3	Duration of operation, years	30	30	80	25	17,5	30
C4	Reaction time, s	180	180	0,003	2	60	1
C5	Efficiency, %	70	55	77,5	72,5	30	52,5
C6	Climate impact factor, kgCO ₂ eq/kW h	0,15	0,185	0,165	0,175	0,1137	0,003
C7	Technologic al readiness (1-5)	2	3	4,5	1	2	1
C8	Social factor (1-5)	2	2	3	2	5	5
		[11,29,30]	[12,31]	[29,32]	[14,29]	[15,33]	[17,34,35]

The energy storage system matrix was also based on the criteria, assumptions, and sources described in the battery matrix. However, the power density criterion was not evaluated here. Considering the different components of the systems, it is not possible to compare this parameter separately. Similarly, the economic aspect in this matrix was determined as capital expenditure per kW, taking into account that they are mostly perceived as long-term expenses.

Using the TOPSIS method, all criteria were given equal weights of 0.111 when evaluating the battery criteria and 0.125 when analyzing the storage system criteria. This assumption was made to avoid errors in the weighting process, since in this case, when analyzing storage technologies, it is not possible to distinguish between the importance of criteria.

After the TOPSIS analysis, a sensitivity analysis was carried out to evaluate the changes in the obtained results depending on the criteria or the determination of the weight changes from the influencing factors.

Sensitivity analysis is a research method that determines how different sources of uncertainty in mathematical models contribute to the overall uncertainty of the model. This technique is used within certain limits that depend on one or more input variables. Sensitivity analysis is often applied in the business world and economics. It is usually used by financial analysts and economists, also known as "what-if" analysis [36].

To determine the impact of alternative allocations on the TOPSIS method results, equal significance of alternatives is determined. Initially, the weights are set to $w=1/n$ (where n is the number of influencing parameters). The weight that is subject to changes is determined by Equation (5).

$$w_{k1} = \beta_k \times w_{k=1,2,3,\dots,n} \quad (5)$$

where

w_{k1} – the weight that is subject to changes

β_k – coefficient of uniform variation, which sums up to 1

w_k – weight changes

The distribution of other weights is altered based on weight changes according to formula (6).

$$w_{k21} = w_{k31} = \frac{(1 - w_{k11})}{n - 1}, \quad (6)$$

where

w_{kxx} – the weight that is subject to changes

n – number of influential parameters [37].

The initial weights of alternatives are replaced with the newly obtained weights in the TOPSIS matrix, and the approach is repeated with the results of all the set criteria. In this work, sensitivity analysis was performed for each criterion by changing weight values from 0.1 to 0.9.

3. Results

After performing a multi-criteria decision analysis using the TOPSIS method and setting an equal weighted weight of 0.111, the obtained results for alternative batteries are visible in Figure 2.

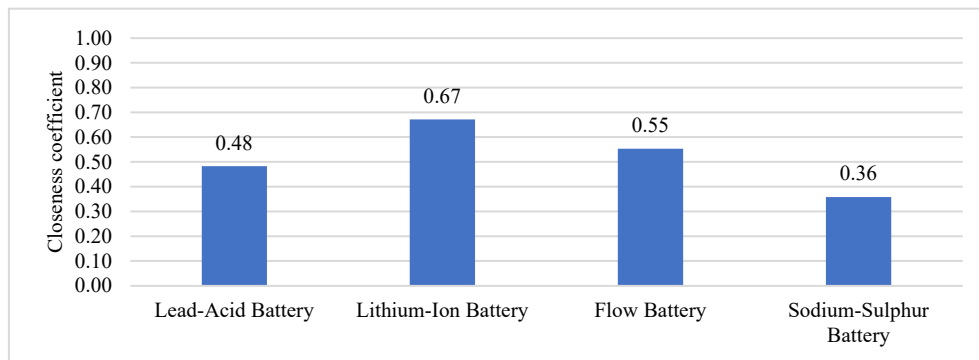


Figure 2. Battery TOPSIS MCDA analysis results

It was determined that among the four analysed types of batteries, lithium-ion batteries are the closest to the ideal option, with a proximity coefficient of 0.67. Although the investment in a lithium-ion battery (EUR/kWh) is the highest among the compared batteries, this parameter is outweighed by its high-power density, which is about twice as high as the other alternatives, as well as the significantly high efficiency and number of charge/discharge cycles, which are considered primary aspects for achieving such results. It is important to note that the social factor and technological readiness of lithium-ion batteries are also rated the highest. Therefore, lithium-ion batteries are considered the most potential solution for energy storage. Next, with a proximity coefficient of 0.55, flow batteries are ranked. The main advantages of these batteries are their long lifespans and high number of charge/discharge cycles, providing high power density while maintaining relatively low investment costs. Accordingly, lead-acid (0.48) and sodium-sulphur (0.36) batteries have received lower evaluations. Such results are mainly influenced by their relatively low power density and operational lifespan. Additionally, the impact of these batteries on climate change (kgCO₂eq/kg) is higher than that of the other two batteries. However, even the battery types with lower ratings are not considered uncompetitive in the energy storage technology market. Under specific parameters, which may differ primarily depending on technological needs and individual views, flow batteries, lead-acid batteries, and sodium-sulphur batteries, by further developing their innovation potential, can provide effective energy storage, promoting a global transition to the use of renewable resources.

Similarly, after performing a multicriteria decision analysis using the TOPSIS method and setting an equal weighted value of 0.125, the results obtained for the alternatives of energy storage systems are visible in Figure 3.

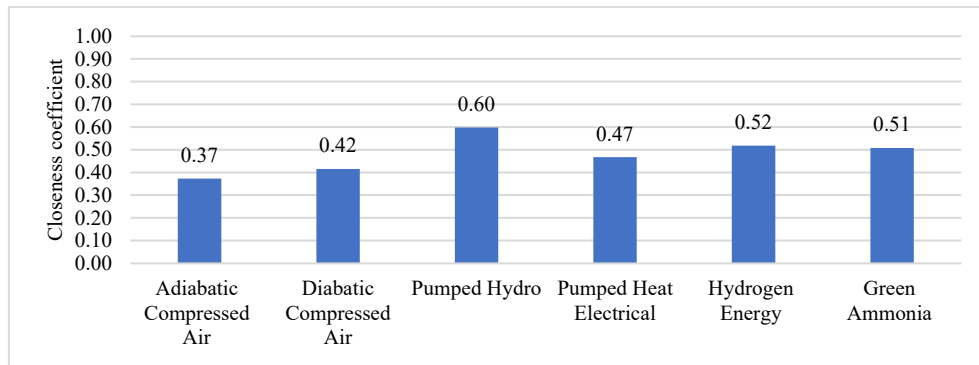


Figure 3. Accumulation systems TOPSIS MCDA analysis results

Among the compared six energy storage systems, it was found that the hydroelectric pumped storage station is the closest solution to the ideal renewable energy storage technology, reaching a proximity coefficient of 0.60. This result was mainly obtained because it is the most matured storage system among those considered, as electricity storage is also possible in hydroelectric reservoirs, so large capital expenditures are not necessary. The operational lifetime is also significantly longer, reaching up to 80 years, and the efficiency is the highest at 77.5%. The hydrogen energy (0.54) and green ammonia (0.51) storage technologies are ranked lower. According to literature analysis, these two technologies for energy storage were also evaluated as the most promising and with a higher added value outside the energy sector. However, capital expenditures for these storage systems are significantly higher, and the technological solutions are still in the innovation development process. With a proximity coefficient of 0.45, the electric thermal energy storage technology is ranked lower because, although the capital expenditures EUR/kWh are the lowest among the compared storage systems, technological readiness is still at the demonstration level, hence the social factor is evaluated the lowest. The farthest from the ideal solution are the diabatic compressed air energy storage system (0.42) and the adiabatic compressed air energy storage system (0.38), considering the technological limitations of operation, geographic restrictions, and the fact that compressed air energy storage system infrastructure is suitable for mountainous areas where underground craters are also found. The reaction time for both technologies is also significantly longer. However, among the compared alternative storage system options, each one is considered a competitive storage technology in the nearer or farther future, providing efficient energy storage. Also, different storage technology concepts can be adapted to specific geographic regions and infrastructure challenges.

To verify the results, a sensitivity analysis was performed for battery alternatives using all the criteria mentioned before. The sensitivity analysis was not performed for the accumulation systems, because the criteria overlap and a wider analysis would reduce the transparency of the results. The obtained results are shown in Figure 4.

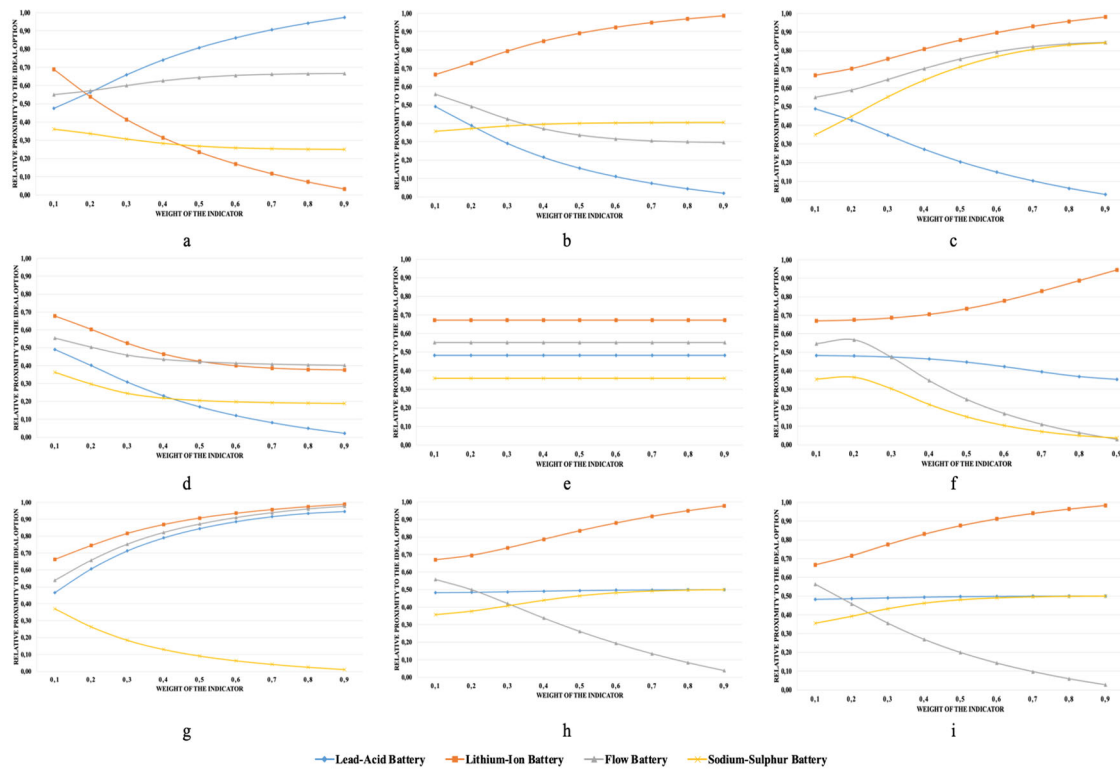


Figure 4. TOPSIS sensitivity analysis for battery alternatives changing the weight of indicators as follows: a -necessary investments for the installation and maintenance of the accumulation; b -storage power density; c -number of charge/discharge cycles; d -lifetime of the technology; e -system response time; f -efficiency of the storage system; g -environmental impact; h - technological readiness of the system for commercialization; i -social factor, direct benefit to society.

Considering the results of the sensitivity analysis, it is possible to determine the specific impact of each criterion on the selected technological solutions for the accumulation of renewable electricity, making it possible to determine the most important factors that change the results of the TOPSIS analysis. The main conclusions that arise from the analysis of batteries are as follows: lithium-ion batteries are negatively affected by the amount of required investment (a), also according to the input data, it can be concluded that the investment EUR/kWh at this moment of development is approximately two times higher than the other types of accumulation in this group and also by lifetime of the technology, however, this is outweighed by the fact that in practically all other criteria, lithium-ion batteries show the best indicators, accordingly justifying its emergence in the forefront of the other batteries. It should be noted that lead-acid and sodium-sulfur batteries are almost not affected by technological readiness (h), as their innovative progress is average, as is the social factor, direct benefit to society (i), while the reaction time (e) does not particularly affect all types of batteries, as it is almost identical for all types. And the last visible influencing factor is the environmental impact factor (g) for sodium-sulfur batteries, which is also significantly higher in the collected data.

4. Discussion

Accumulation of renewable electricity is the main driving force for the development of a sustainable, climate-neutral and competitive energy sector. Therefore, taking into account current global challenges, the study of these technological solutions plays a particularly important role. There is a need to analyse and inform people about the technological possibilities of existing alternatives, promoting wider awareness and understanding of the best solutions.

After conducting the relevant analyses, reviewing the literature sources, the most innovative solutions, weighing the influencing criteria and summarizing the results, it has been possible to achieve the goal of this research, to determine the potentially best renewable electricity storage

alternatives and to provide a general overview of the current stage of technological development in this field. Using the TOPSIS MCDA method, it was found that lithium-ion batteries are the best alternative in the battery group, considering their efficiency, sustainability, technological readiness, although the amount of investment is currently the largest for this type. In the accumulation systems group, the pumped hydro storage was the closest to the ideal solution for the moment, however, weighing all the factors, it was concluded that the technologies with more potential were hydrogen and green ammonia. The sensitivity analysis applied for battery types gave insight into the main factor inhibiting the commercialization of technologies - the high cost of installation and individual components, and total necessary investments.

It can be concluded that the research has provided insight into the renewable electricity technology sector, evaluating the positive and negative factors of different accumulation systems, as well as future development opportunities, by weighing the best solutions. Of course, it would be necessary to carry out more in-depth research, developing a wider range of criteria, as well as analysing other renewable electricity storage options. This provides valuable information to promote the integration of energy-efficient storage technologies in electricity storage and transmission systems, helping to introduce wider use of renewable electricity both in individual households and in power plants on a national scale.

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