ENERGY TRANSITION: THE IMPORTANCE OF ENERGY STORAGE SYSTEMS TOWARDS A MORE SUSTAINABLE WORLD

TRANZIȚIA ENERGETICĂ: IMPORTANȚA SISTEMELOR DE STOCARE A ENERGIEI PENTRU O LUME MAI SUSTENABILĂ

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Abstract: *This paper underscores the importance of energy storage systems in facilitating the global energy transition towards a more sustainable future. As renewable energy sources gain prominence, energy storage becomes crucial for their integration and optimization. The paper explores various types of energy storage systems and their role in the energy transition, highlighting benefits such as renewable integration, grid stability and cost reduction. Technological advancements, economic viability, policy frameworks and environmental considerations are also noted. The paper concludes by emphasizing the need for further research, development, investment in energy storage and regulatory support to achieve carbon neutrality by 2050.*

Keywords: energy transition, energy storage systems, sustainability, renewable energy integration.

Rezumat: *Acest articol subliniază importanța sistemelor de stocare a energiei în facilitarea tranziției energetice globale către un viitor mai sustenabil. Pe măsură ce sursele de energie regenerabilă câștigă proeminență, stocarea energiei devine crucială pentru integrarea și optimizarea acestora. Documentul explorează diferite tipuri de sisteme de stocare a energiei și rolul acestora în tranziția energetică, evidențiind beneficii precum integrarea surselor regenerabile, stabilitatea rețelei și reducerea costurilor. De asemenea, sunt luate în considerare și progresele tehnologice, viabilitatea economică, politicile publice și considerațiile de mediu. Potrivit concluziilor, sunt necesare continuarea cercetării, dezvoltării, investițiilor în stocarea energiei, precum și a sprijinului legislativ pentru atingerea neutralității climatice până în 2050.*

Cuvinte cheie: tranziție energetică, sisteme de stocare a energiei, sustenabilitate, integrarea energiei regenerabile.

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1. Introduction

Energy is an essential resource in our everyday life, for people and for economic operators, but also a resource with a strong strategic dimension, highlighted in particular by the difficult security and geopolitical context, as the war started in Ukraine in 2022 showed and also by the recovery efforts following the COVID-19 pandemic. In recent years, the significant rise in electricity prices has triggered a domino effect: in a deeply interconnected economic and social system, this has led to a general jump in inflation as well as in the prices of all consumer goods.

The demand for power has increased rapidly over the past decade due to economic growth, population expansion and the industrialization of developing countries worldwide. Managing this demand can be difficult and often results in high levels of pollution and Greenhouse Gas emissions (GHG), creating serious health and environmental concerns and elevating indirect costs on society. Industries such as power generation, manufacturing and transportation often rely on non-renewable resources, thus stressing the energy grid and accelerating pollution within the atmosphere. To combat this issue, there has been a shift to employ renewable technology as a superior method of energy generation, from natural resources, such as hydro, wind and solar. Renewables are well suited to meet diverse energy demands and various industries by providing sustainable, clean and efficient energy, free of harmful pollution or GHG.

Electricity is a commodity that cannot be stored, in principle, being produced in close correlation with consumption. But new technologies are driving innovation in the energy sector, making renewable energy more accessible and affordable than ever before, while also impacting energy costs in a positive way for society and industry. Some of these technologies, such as energy storage systems, will play an important role in the future and they are already starting contributing to the energy transition today. In short, energy storage represents the storage of a quantity of energy produced at a certain point in time for later use. Because energy can take many forms, storing it involves transforming it from different difficult-to-manage states into more practical or economically advantageous ones.

Therefore, as example, when using renewable energy, intermittent power outages are frequent and this happens when the amount of energy produced and the amount of energy consumed are not equal. But by storing surplus electricity produced by renewable resources during periods of low demand and delivering it during times of high demand, energy storage reduces these intermittent power outages, also helping to balance the electricity grid's load and reducing dependence on nonrenewable resources. [12]

This paper provides a starting point for conducting in-depth investigations into various aspects of energy storage systems and presents an inductive research, which aims to investigate how energy can be used in a more useful and sustainable way for society, the energy system and industry. In theory, this approach can help to uncover new insights into the ways that storage systems are affecting the energy industry and may inform future policy decisions or investment strategies. At the same time, a comparative analysis of different energy storage technologies was made and the objective is to assess the strengths and limitations of different types of storage systems and provide insights into their optimal utilization, while also exploring their role in the energy transition process. Thus, in order to promote the energy transition and create a more sustainable world, this article emphasizes the importance of energy storage systems and how storage helps the current energy system to become more efficient and less polluting.

2. Overview of energy transition

Energy transition is the process by which the global energy sector is switching from energy production and consumption systems based on fossil fuels (i.e. oil, natural gas and coal) to technologies based on renewable energy sources (RES). It thus represents a significant structural change in the system because, in order to meet the goal of reducing emissions, as called for in the Paris Agreement [13], the entire energy value chain needs to change: from production, transport, distribution to consumption, and even storage.

In this regard, sustainability is a concept that is becoming more and more important given the global situation of climate change and the need to find solutions in order to deal with it. There are currently more than 300 definitions of this concept, but the main idea of sustainability is that it refers to three dimensions: the economic, the environmental and the social dimension, which must be taken into account when using resources [29]. These three aspects of sustainability are also part of the EU's Energy packages [30], which establishes a framework for a new, sustainable energy policy at the level of the EU, and are also presented as dimensions of the energy trilemma [31].

The use of renewable energy sources would be the ideal way to cut back on the consumption of fossil fuel-derived power as a result of global warming, which is another topic linked to energy transition. According to literature, GHG are the primary contributor to global warming. [1] In this regard, the European Union (EU) started multiple programs to establish a new path in research and technologies, among other things with the scope of decreasing global warming, in order to fulfill all of these demands and avoid it.

Changing the way electricity is produced and consumed is therefore part of this process, as part of the energy value chain, and one of the impacts is the use of storage systems. Given the global and especially European targets for reducing greenhouse gasses and increasing the share of renewables in the energy mix to 40% - a target set for 2030 [14] - energy storage has an extremely important role to play in the transition to a decarbonised energy system.

The most pressing and significant of the many interesting and different difficulties we currently confront is how to comprehend and influence the coming technological revolution, which will unavoidably reshape humanity. Rapid technical advancements in the fields of energy storage, fuel efficiency and renewable energy not only increase the profitability of investments in these sectors, which enhance Gross domestic product (GDP) development, but they also help to mitigate climate change, one of the biggest global concerns of our day.

There are many inventions still in their infancy, but as they build upon and magnify one another in a fusion of technologies from the physical, digital and biological worlds, they are already nearing an inflection point in their evolution. It is also the case of energy storage, which, according to studies, [2] is part of the fourth industrial revolution and will help change the world as we know it.

However, the progress of wind and photovoltaic power systems (which are symbols for sustainable development, green growth and energy transition) in the past several years became debatable, as they have contributed relatively little so far, even though they are moving forward swiftly. These types of assets have the advantages of being renewable and producing no pollution when in use, but their biggest issue is their sporadic and irregular output, which depends on elements we have no control over, such as wind for wind turbines and sunlight for solar panels. Unlike other energy production methods, their production its difficult to manage (from the point of view of forecasting as accurately as possible the times of production and operation of power generation units), therefore installing a storage system would make the electricity production more stable and also help the energy system.

3. Importance of energy storage systems

Energy storage systems refer to technologies and devices that store energy for later use. [15] They are intended to collect and store surplus electricity created during periods of low demand or high renewable energy output and to release it when demand or renewable energy generation is high.

The main reason for storing energy is the time lag between energy production and the need for energy consumption. In general, the basic rule for transmission and distribution networks is that what goes in must equal what comes out from the grid. Today, if one electricity production source suddenly produces less, either consumption should be lowered (which is not always possible) or another source must step in to make up the difference. The same concept applies if a power source generates more on its own (i.e., the surplus must be used or temporarily stored) and, as a result, these scenarios clearly demonstrate why energy storage is a must for the system. Due to their various forms of storing energy, these systems serve an important role in balancing energy supply and demand, enhancing grid stability and facilitating the integration of intermittent RES into the electrical grid. Moreover, they can reduce the costs with the electricity system balance.

As mentioned, energy storage has an extremely important role to play in the transition from fossil fuels to renewable energy sources, for several reasons. Firstly, RES such as wind and solar are intermittent in nature (producing power only when the sun shines or the wind blows) and the storage systems can help to store excess energy generated during peak periods for usage during periods of low generation. Secondly, energy storage systems can provide assured power capacity for difficult conditions of wind and sun, increasing grid stability. Thirdly, energy storage systems can provide energy to remote areas where grid extension may not be economical and new grid and storage technologies in energy will speed up the transition towards more decentralized sources. Moreover, they can also help to reduce greenhouse gas emissions by allowing for the optimal use of RES and reducing the need for conventional power plants.

Based on these arguments, in terms of the benefits of energy storage, three areas of activity can be identified for which storage is important and have a positive impact (Table 1): for suppliers, for consumers/users and for energy producers.

Table 1. **Benefits of storage systems by activity area [16]**

Suppliers	Consumers/users	Energy producers
● improve operating efficiency and reduce fuel costs; ● ensure maintenance of the quality of supply; ● synchronize generation and consumption for isolated networks; ● can be used as an emergency power supply.	● brings money savings if the energy market has variable prices over time; ● offer power in case of emergencies; ● can be used to power electric vehicles and household or mobile appliances.	● ensure time-shifting to one's own advantage by selling energy when the price is high (valid for the variable price market); ● helps for the integration of Renewable Energy Sources both locally and at energy system level.

There are already several examples of systems that have been implemented around the world that emphasize the importance of energy storage. These examples highlight the relevance of energy storage systems in balancing energy supply and demand, ensuring power capacity in challenging wind and solar conditions, boosting grid stability and supplying electricity to remote places. They also demonstrate that, due to the intermittent nature of renewable energy technologies, energy storage devices can be a feasible technological and economic option. Some examples of energy storage projects around the world are:

1. Three Gorges Dam in China - one of the largest energy storage projects in the world, it is a hydro power plant with a capacity of 22,500 MW that was completed in 2003 and cost USD 37 billion; [17]

2. South Australia's Hornsdale Power Reserve - one of the world's largest lithium-ion battery energy storage projects that has played a crucial role in stabilizing the grid and addressing grid instability issues in the region while supporting renewable energy integration; [18]

3. Andasol Solar Power Station in Spain - one of the largest solar energy storage projects in the world, it is a thermal storage system, completed in 2009, with a capacity of 1,030.5 MW that uses molten salt; [19]

4. Huntorf in Germany - one of the oldest and most successful energy storage projects in the world, it is a compressed air energy storage system with a capacity of 321 MW, completed in 1978. [20]

However, energy storage is frequently a challenging task. For instance, when a spring is compressed, the energy that was supplied to it is stored for the duration of the compression. In fact, the spring wants nothing more than to unwind, as energy dislikes being concentrated or stored, and it will naturally attempt to disperse. Energy storage is frequently risky: a gasoline or gas tank may blow up and release energy; a mass held aloft could fall; a woodpile could catch fire; a dam could cave in; an inflated balloon could burst, etc. Additionally, because energy cannot be infinite and is obtained by multiplying power by time, both storing and releasing energy need time. For instance, even if batteries could store a lot of energy in a short amount of time, the difficulty would then come from the power grid, which would find it challenging to meet the necessary power requirements. As a result, this is (still) a serious barrier to the growth of electric cars.

4. Technological advances in energy storage systems

One of the most popular and adaptable energy storage technologies are the batteries, as they can store electricity and may be repeatedly charged and discharged. Particularly lithium-ion batteries have gained popularity in the past decade because of their high energy density, efficiency and decreasing prices. The market for batteries was valued at USD 25 billion in 2019 and it was growing. Also, according to different predictions, the battery market will be worth USD 116 billion annually by 2030, excluding investments in the supply chain [33]. However, there are various energy storage systems available, each with unique properties and applicability for diverse applications.

When evaluating energy storage systems, it is essential to take into account the energy per mass characteristics along with other elements like efficiency, cost, cycle life and environmental impact when assessing energy storage systems. The best energy storage technology depends on the particular needs of the application and the trade-offs between system weight and energy storage capacity. The amount of energy that can be stored within a given mass or weight of a storage medium is referred to as the energy per mass issue and is an important factor to take into account when comparing various types of energy storage systems. In order to evaluate a storage technology's suitability for a given application, it is essential to understand the energy per mass characteristics of that technology [33]. Energy storage technologies are classified according to the form of energy used (electrochemical, chemical, mechanical, electrical or thermal) and contain multiple types of technologies [16].

Table 2. **Energy storage types of technologies**

Electrochemical storage systems	The earliest rechargeable energy sources are in the form of an electrochemical cell in which, by means of electrochemical reduction/oxidation (redox) reactions, storage takes place in the form of chemical reaction energy. This energy is then converted into electrical energy by closing the external circuit of the battery. In this way, relatively large amounts of energy can be stored. Battery energy storage systems (BESS) and Lithium-ion batteries (LIBs) use electrochemical reactions to store power for later use. To meet the ever-increasing demands for environmental and energy sustainability, this type of battery is one of the most used worldwide due to their adaptability, scalability and decreasing costs, compared to other technologies. [3] These types of storing are important in a variety of applications, from grid-scale energy storage to household and business energy management due to their high energy density which make LIBs suitable for portable electronic devices and electric vehicles as well. They also provide a significant amount of energy per unit mass. While LIBs have gained significant popularity in recent years due to their higher energy density, longer cycle life and improved performance characteristics, lead-acid batteries also have a place in the energy storage landscape, especially for applications where cost, availability and specific requirements favor their use. Lead-acid batteries are particularly suited for applications where cost-effectiveness and reliability are prioritized over high energy density and fast charging/discharging capabilities and are used for residential, commercial and industrial settings [33].
Chemical storage systems	There are two types of chemical storage systems, both of which are well-known and even used in industry: synthetic natural gas (SNG) storage systems and hydrogen storage systems. As with hydrogen, the SNG produced can be stored under pressure in underground tanks or transported directly through the gas grid. The production of SNG is preferably done in places where both carbon dioxide and electricity (which is mostly in excess) are available. However, there is a need for intermediate, local storage of gas, as the chemical process is a continuous process. In the case of hydrogen storage systems, it’s important to note first that hydrogen does not exist in nature in a free state, but has to be produced and the cost of producing hydrogen currently exceeds the cost of the energy that can be generated. Two types of plants with practical use of hydrogen are currently known: stand-alone (mainly mobile) plants and energy plants. A typical hydrogen storage system consists of an electrolyser (an electrochemical converter that electrically splits water into hydrogen and oxygen), a hydrogen storage tank and fuel cells. The electrolysis process is an endothermic process, i.e. heat is required

	during the reaction, after which the hydrogen obtained is stored under pressure in gas cylinders or tanks. For economic and practical reasons, oxygen is not stored but released into the atmosphere. Depending on how the electricity that powers the electrolyser is produced, the hydrogen produced can be classified as: renewable hydrogen (produced with renewable energy, biogas or biomass); hydrogen produced by fossil fuel (natural gas or coal gasification); low carbon hydrogen (using fossil fuels and capture of the resulting carbon or electricity from renewable sources); hydrogen from derived synthetic fuels. [4] However, depending on the storage technique used and the system's design, hydrogen storage, which is frequently used for fuel cells, offers a high energy to mass ratio. It is important to note that hydrogen storage frequently calls for additional infrastructure and presents issues with storage and safety.
Mechanical storage systems	There are three types of mechanical storage systems, respectively through pumped storage hydropower (PSH), compressed-air energy storage (CAES) recovery and flywheel energy storage systems (FESS). The first type, PSH, is a method of storing and generating electricity to provide the energy needed during periods of high consumption by moving water between two reservoirs at different altitudes. During periods of low consumption, pumps pump water from the lower reservoir to the upper reservoir for further use (e.g. in Romania, the Tarnița Lăpuștești pumped hydroelectric power plant project is one of the examples applying this system, but it is still at the stage of construction intention [21]). Due to the significant potential energy stored in the elevated water and the mass of the water, which offers a significant energy storage capacity, this technology has a high energy per mass. In the case of CAES, it is based on the principle that a compressed gas contains more energy than an uncompressed gas. Such a plant has one or more low- or high-pressure compressors that convert electricity into compressed air at a high pressure and then store it inside sealed underground spaces or pipe and vessel systems above ground. When this energy is needed, the air is heated using natural gas and decompressed in air turbines, allowing the operation of a generator to produce electricity. Comparing CAES systems to other technologies, they may have less energy per mass, but their large-scale storage capabilities make up for it. The amount of compressed air and the pressure at which it is stored, among other things, have an impact on the energy storage capability of CAES [33]. The FESS represents systems for storing kinetic energy in spinning masses with minimal frictional losses. The rotational energy is stored in an accelerated rotor, a massive, rotating cylinder, and the main components of a flywheel are the rotating cylinder (comprising a rim attached to the shaft) in a compartment, the bearings and the

	transmission device (stator-mounted motor/generator). Energy is maintained in the flywheel by keeping the rotating body at a constant speed. Increasing this would result in more energy being stored. The flywheel is supplied with electricity by a transmission tool and if the rotational speed of the flywheel is reduced. At the same time, the high-speed flywheel rotation gives them characteristics of high energy per mass. The mass of the flywheel affects its ability to store energy and improvements in materials and design have made it possible for modern flywheel systems to have higher energy densities [33].
Electrical storage systems	First type of electrical storage system is the electric double layer capacitor (EDLC). It is an energy storage system based on electrostatic effects that occur between two carbon electrodes with high specific surface areas per volume (e.g. activated carbons). Compared to lead-acid batteries, EDLC have a lower energy density, but can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capacity). Lead-acid batteries, on the other hand, have lower energy density but are more cost-effective and often used in stationary applications, such as backup power systems [36]. Another type of electrical storage system is the energy stored in superconductors. In the case of superconducting magnetic energy storage (SMES), energy may be kept in a magnetic field created by the flow of current through the superconducting coil which is kept below the critical temperature. A typical system consists of a superconducting coil, an AC-DC-AC converter and an artificial cooling system, which can reach 95% efficiency. However, because of the requirements of maintaining a low temperature, the high cost of the superconducting coil and environmental problems brought on by the strong magnetic field, the technology is used for short-term storage. [32] As conventional power plants are replaced by renewable energy plants (wind, solar, geothermal, biomass), there is a move to provide ancillary services and functionality, such as voltage and frequency regulation, to mitigate their variability in the power supply. One solution to these requirements is the MMC multi-level modular converter static compensator (STATCOM) [5] with a battery energy storage system (BESS), by which it has been made possible to inject or absorb active or reactive power into and from the electricity grid independently.
Thermal storage systems	This type of storage can be done by using molten salt. A means of storing energy by thermal systems can be done by melting salt, the energy required for this process being produced by solar power plants using radiation concentration technology in a solar tower or trough. Salt (potassium, sodium or calcium nitrate) usually melts at 131 °C and is then heated by solar collectors to 566 °C. It can then be stored for up to a week in tanks and, if needed, the energy stored in it is used to produce superheated steam which then drives a conventional turbine. The

	efficiency of this storage process is up to 99% compared to using solar radiation directly to produce steam. There are two types of thermal storage systems: latent heat storage (these technologies have the advantage of storing more energy, and the materials that can be used are very diverse, ranging from salts and polymers to metal alloys) and thermo-chemical storage (involving reversible endothermic and exothermic chemical reactions).

According to the European Commission [7], each technology's cost might give an indication of how competitive it is in specific applications, such as longer or shorter-term use. A technology is more competitive in long-term energy storage applications if it has a high cost per unit of electricity but a low cost per unit of energy. Also, technologies with high cost per power but low energy costs are more competitive for storing energy temporarily. Thus, in Figure 1 below it can be seen that battery technology (BESS/LIBs) is currently the most cost and benefit efficient.

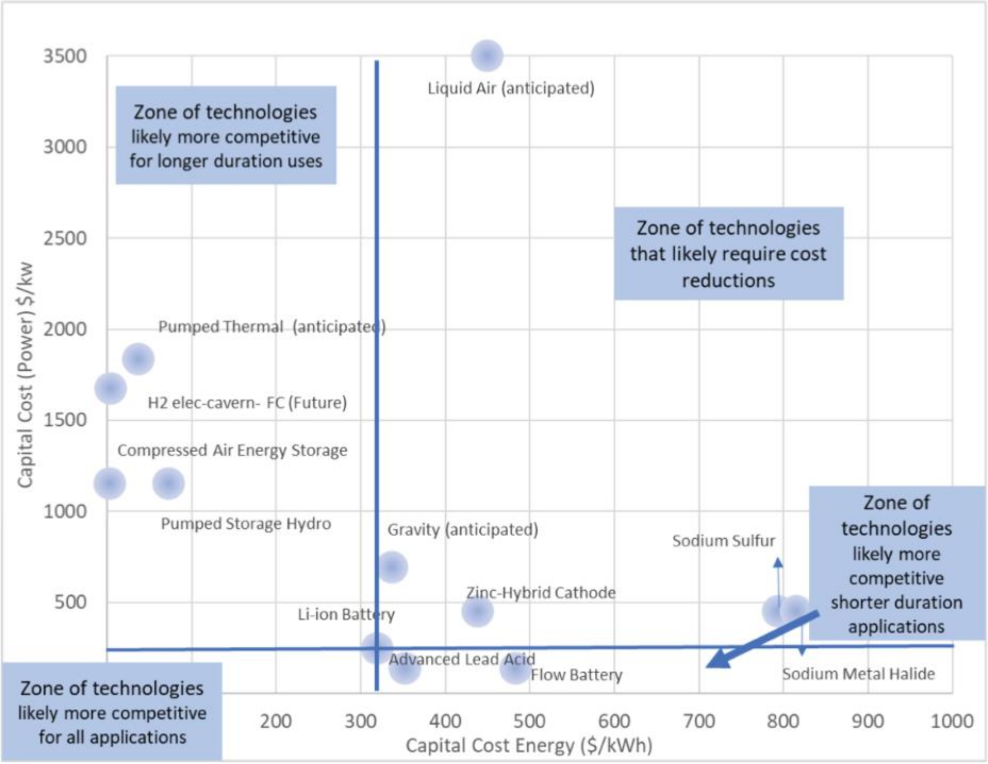

Figure 1. Capital cost of power and energy for different technologies [7]

According to energy industry companies, grid intelligence, renewable energy and an energy storage solution could work together to create a dependable, cost-effective and environmentally responsible energy supply. [12] In this regard, blazing the path for clean, reliable and cost-effective energy storage is electrolysis technology, applying water and unbalanced excess power to produce hydrogen. This can be distributed or stored for future use. Essentially, time shifting the energy supply to best align with cyclic and sometimes unpredictable power demands, the use of hydrogen for energy storage helps augment, transmit and distribute energy assets as needed.

In addition to the classic pumped storage, which has been promoted for over 50 years, hydrogen technology has become particularly attractive. [6] In this regard, there are already products available on the market which use this technology. Electrolyzers have a wide dynamic operating range and coupled with renewable resources, such as wind, solar and hydro, to store energy in the form of hydrogen for future use, with fast dynamic response times, high-pressure and favorable efficiencies, this sustainable technology is sometimes considered the backbone of energy-storage solutions.

When it comes to battery technology, an important aspect is the lifespan of them and how they are used depending on various factors. The number of charge-discharge cycles a battery can go through before experiencing a significant decline in performance is referred to as its life-cycle and it is a crucial factor to take into account when evaluating the suitability and economic viability of energy storage systems. The life-cycle of a battery is typically defined as the number of cycles or years of service a battery can provide before its capacity drops below a specific threshold, called state of charge (SoC), often around 80% of its initial capacity. [34] Also, in years, analysis shows that ordinary batteries used for energy storage last between 10 and 20 years, depending on the conditions of use, and after this period they must be dismantled and scrapped [35] or repurposed for smaller purposes - such as prosumers.

Several factors affect the life-cycle of the electrochemical storage systems, among them the depth of discharge (DoD), charging and discharging rates, operating temperature and battery chemistry. Elevated temperatures can hasten chemical reactions inside the battery, hastening their degradation and shortening their lifespan. So, battery life is generally better extended at cooler operating temperatures.

When it comes to DoD, batteries that experience deeper discharges per cycle typically have a shorter life span than those that are subjected to shallower discharges. In addition, faster charging and discharging rates can put more strain on batteries, also shortening their life span. Different DoD were plotted on the horizontal axis below and the number of cycles were entered on the vertical axis in some experiments done so far on Lithium Ion and Lead Acid batteries (Figure 2) [35].

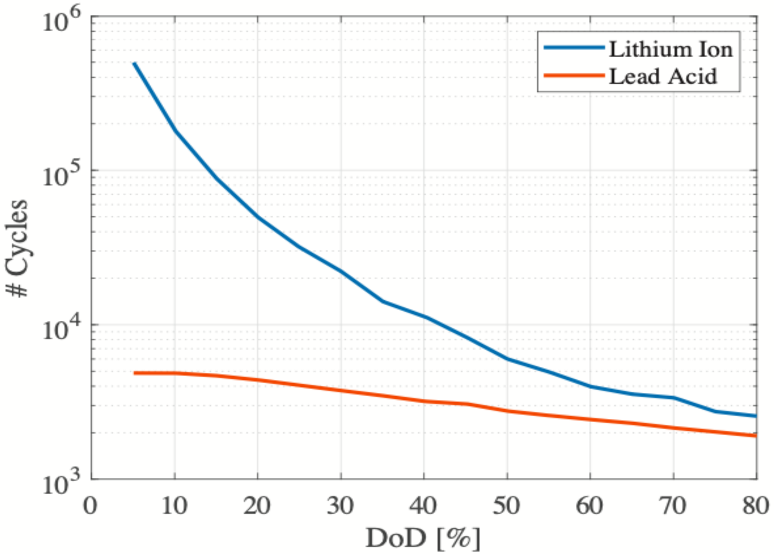

Figure 2. Number of charging cycles of a lithium ion battery and a lead-acid battery at different depths of discharge (DoD) [36]

An electrochemical cell's capacity was measured after it was repeatedly charged and discharged for the various DoDs. If this was less than 80% of the initial capacity, the number of cycles was entered in the diagram. Therefore, in Figure 2, it can be seen that electrochemistry affects how many cycles there are and the lead acid battery has a much lower cycle capacity. Along with the absolute number, the shape of the number of cycles will vary depending on the DoD as well. With lead-acid we have a linear shape, while the Lithium-ion battery shows a non-linear shape in the logarithmic representation.

This also introduces the concept of capacity loss of batteries at various states of charges, which refers to the reduction in their total energy storage capacity over time, particularly at different states of charge (SoC) - a term expressed as a percentage of its maximum capacity. This loss thus represents the decrease in the battery's ability to store and deliver energy compared to its initial capacity and it is typically non-linear and tends to be more significant at higher and lower SoC values. In this regard, Peukert's Law [37] explains how the discharge rate affects battery capacity and, according to it, increased internal resistance and electrochemical reactions may result in a reduction in the effective capacity of batteries. So, the number of charge-discharge cycles a battery undergoes impacts its capacity loss. Higher cycle counts generally correlate with increased capacity degradation.

Moreover, as mentioned, temperature plays a crucial role in the performance and life-cycle of batteries. In general, the recommended temperature range for optimal battery performance and longevity is specified by manufacturers. The exposure to high temperatures can accelerate the degradation processes within batteries, leading to increased capacity loss and reduced life-cycle: temperatures above 40-45°C can accelerate the degradation processes within lithium-ion batteries, leading to increased capacity loss and reduced life-cycle; above 60°C (140°F) can cause thermal runaway in lithium-ion batteries, leading to safety hazards such as the risk of fire or explosion; while sustained high temperatures above 50-55°C can accelerate the corrosion of electrodes and reduce battery life for lead-acid batteries. In the opposite direction, too low temperatures can affect battery performance, such as increased internal resistance, reduced capacity and potential limitations in charging and discharging rates: temperatures below freezing (0°C) can cause the electrolyte in lithium-ion batteries to freeze, leading to irreparable damage; while cold temperatures below -20°C can significantly increase the internal resistance of batteries, limiting their charging and discharging rates and reducing overall performance [33]. Therefore thermal management systems in energy storage applications to regulate battery temperature and ensure optimal performance are extremely important, but this raises the question of whether the batteries also need more electricity to keep them at a low temperature during the summer or at high temperatures during the winter. This would actually also increase the demand for electricity in the system, which is not necessarily helpful when public policy calls for reduced consumption.

5. Economic, environmental and policy considerations

Each energy storage technology has its own set of benefits, limitations and cost issues. The intended application, necessary storage capacity and duration, round-trip efficiency, scalability and cost-effectiveness all influence technology selection. Thus, ongoing research and development activities aim to increase these technologies' performance, efficiency and cost-effectiveness, hence broadening the alternatives for energy storage.

According to the findings of the various scenarios examined, the building-based gravity module system is more economically feasible and has a greater capacity for energy storage than the building-based pumped hydro system. [8] In addition, among the possibilities considered, network storage is currently the most profitable technology that can be used at the moment. Even with tiny battery sizes, the physical battery cycle rate will stay low, according to research on viability of energy storage systems [9].

The costs connected with energy storage systems include the investment cost for the acquisition and installation of renewable energy conversion equipment, the charging cost and the energy price, which is the difference between charging and discharging. 88% of the total cost is represented by the cost of the compressor as well as the cost of the storage tank. With the rising range of the storage system, the cost of the system's automation is decreasing. Furthermore, studies show that the primary step that storage technologies must overcome is achieving economic feasibility and that future progress in research and development of new storage technologies is needed, in order to help lower prices [10].

Therefore, from an economic standpoint, energy storage devices may be more cost effective than grid extension for remote residential sites. Furthermore, energy storage can aid in demand management by lowering electricity prices, reducing investments in generating, transmission and distribution networks and boosting system dependability. As a result, this amplifies the argument that significant future advancement in energy storage technology research and development is likely to help cut prices and enhance competitiveness, making it an appealing alternative for businesses and investors.

In Europe, recently, the European Commission has recommended to include nuclear power and natural gas in a limited group of energy sources alongside renewables in order to promote nuclear power use in the short term and minimize green transition issues generally. However, the need for flexibility in the energy system will increase significantly in all Member States in the coming years, reaching 24% of the overall EU demand in 2030 and 30% by 2050. According to studies, the EU will need greater energy storage capacity by the years 2030 and 2050, but the level of investments is insufficient at present. The European Commission projects that between EUR 100 and EUR 300 billion would be needed in financing to support important advancements in energy storage systems up to 2050 therefore, in this regard, several EU subsidies and national state aid are currently available for storage. In March 2023, the Commission published a series of proposals [22] for

Member States, outlining specific actions that would help those countries adopt energy storage in their domestic markets.

While achieving zero emissions and reducing reliance on fossil fuels are top priorities across Europe, the EU is a long way from producing the majority of its power from renewable sources. Only 35% of the power produced at the moment originates from these sources. Therefore, to increase this percentage, the Green Deal [23] and the NextGenerationEU [24] recovery plan both propose allocating EUR 1 trillion to green development. The effects on the energy industry may be significant, however system stability will be challenged by the additional intermittent renewable production capacity, necessitating infrastructure modernization and new strategies to balance the power generation [25].

According to specialists, if the EU achieves its net-zero emissions target, it will gain a significant economic advantage, but a lengthy period of high energy costs might have a negative impact on the economy and prevent even more crucial investments in new production capacity, making the shift to greener energy generation hard.

Making energy storage a feasible solution from an economic perspective is one of the challenges to achieve the transition, among the need for better electricity production forecasts (for renewable assets), as the storage necessity appears when in any period this production is not enough to satisfy the consumers' demand. It is recognized that renewable sources connected directly to the grid have a significant impact due to their fluctuating nature, increasing the difficulty in stabilizing the network and playing an important role in predictions that follow to be done.

Therefore, as noted, disadvantages of energy storage systems include their cost, technical limitations and the need for new designs to operate at higher pressures and temperatures. Some storage technologies, such as batteries and ultracapacitors, have low discharge times with high power ratings, while others, such as compressed air energy storage (CAES), have storage vessel barriers.

In terms of risks associated with energy storage systems, they include the potential for accidents, such as fires or explosions, and the environmental impact of the materials used in the storage systems. Additionally, the use of energy storage systems may require changes to regulations and policies to ensure their safe and effective integration into the grid.

An example of the impact on the grid that renewable energy sources, particularly solar power, are already having on the system and that regulations need to take into account is the “Duck Curve” concept [26], which symbolizes the challenges of integrating renewable energy into the grid without using energy storage systems. Initially coined by the California Independent System Operator (CAISO), it illustrates the daily electricity demand and supply patterns in California. Its unique form is that of a duck, with the head and neck standing in for the daily net load, or the discrepancy between power consumption and generation. This curve is important because, as solar panels proliferate across California, the curve's belly - symbolizing midday surplus energy - has been steadily growing (Figure 3). This phenomena presents a problem since it may lead to a surplus of electricity during the day and a sharp increase in demand as dusk approaches. For an energy system to be reliable and stable, this imbalance must be managed.

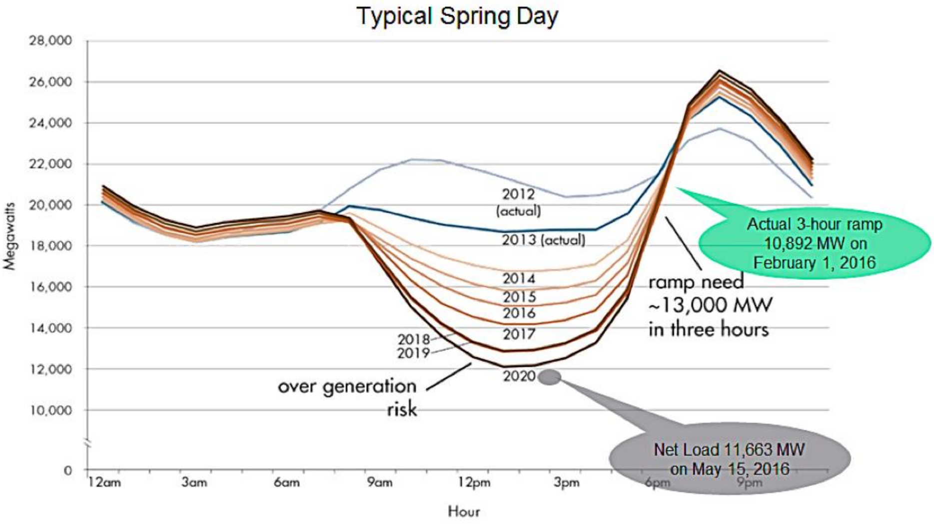

Figure 3. The duck curve shows steep ramping needs and overgeneration risk [26]

Another example of the impact of renewables and the present “Duck curve” can be found in most countries where renewables, and in particular photovoltaics, have strongly penetrated the energy system - including in Romania (Figure 4).

This emphasizes the critical need for energy storage options, demand response initiatives and further grid integration of renewable energy. Thus, by effectively managing the “Duck Curve” is one way of accelerating the transition to a more resilient and sustainable energy future.

On the other hand, the increasing demand for batteries, driven by the growing adoption of electric vehicles and renewable energy systems, brings attention to the battery manufacturing supply chains and material sourcing practices. Understanding the environmental effects of battery manufacturing, including the extraction of raw materials, processing and waste disposal, is critical and it can even bring delay in the energy transition process.

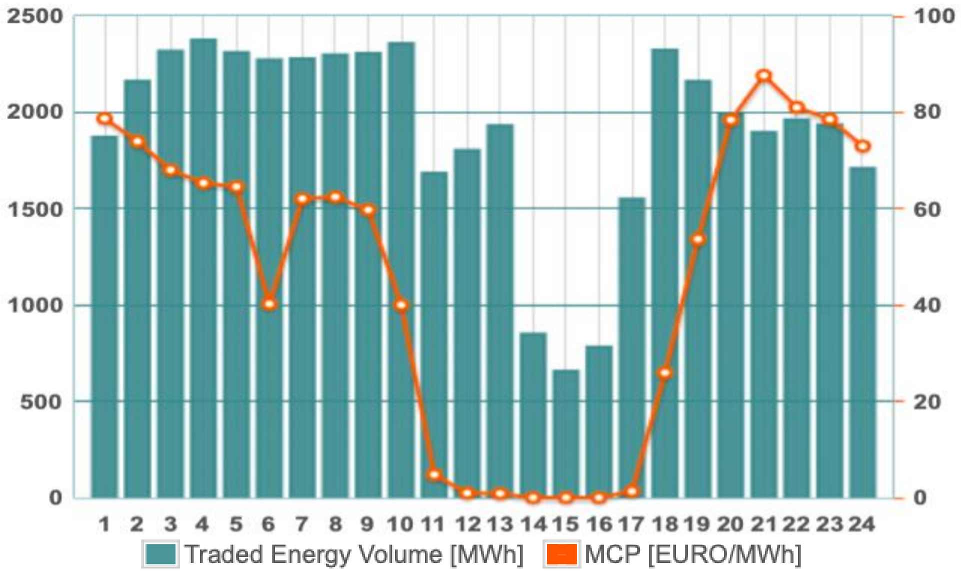

Figure 4. Price curve in the Day-Ahead Market of Romania for the day of delivery May 21, 2023 [27]

The extraction of several raw materials, including lithium, cobalt, nickel, graphite and rare earth elements is necessary for the manufacture of batteries. But the environmental effects of extraction methods, such as mining, can be significant and include habitat destruction, deforestation, soil erosion and water pollution. Additionally, the extraction of some minerals, such as cobalt, has been linked to social and labor problems, such as child labor in some places and unsafe working conditions. Despite the raw materials' high technical potential, some of them are not the best choice when sustainability and environmental concerns are taken into account, as well as China's onerous raw material import dependence at global level. Alternative chemistries have been investigated in the last ten years, despite the fact that batteries remain the most extensive storage system for commercial use [38]. The majority of the raw materials are found in a small number of locations worldwide, including South Africa, Northwestern China, Eastern Russia, Chile, Bolivia and Argentina.

At the same time, it is crucial to guarantee ethical behavior and responsible sourcing throughout the battery supply chain. Finding and addressing environmental problems and violations of labor rights may be difficult in the absence of transparency and traceability, therefore creating systems to track the source of raw materials and confirming ethical mining and processing methods can help reduce negative effects on the environment and society. In addition, battery end-of-life management and recycling are crucial for reducing environmental damage, as the release of toxic substances into the environment can result from improper disposal. The ability to recover valuable materials from batteries is made possible by ever-improving battery recycling technologies, which also lessens the need for additional resource extraction. Closing the loop and lowering the environmental impact of batteries requires enhancing battery recycling infrastructure and putting in place efficient collection and recycling programs.

According to the International Energy Agency (IEA), China is expected to dominate demand for Electric Vehicles' (EV) batteries up to 2025. It is also noticeable that in the last three years the global passenger sales increased significantly when compared with 2020 and it is observed that an exponential increase suggests continuation over the next few years, with China still dominating the global EV market, but sales are rising quickly elsewhere too.

China represents currently the largest share of automotive battery demand, with almost 200 GWh of battery demand in 2021, an increase of 140% with respect to 2020 (Figure 5). A question that will remain open is what will happen in the future, 10 years from now, when these batteries will lose their efficiency. Will the countries of the world take care to reuse them and reintroduce them into the economy? How will states that even now have problems with transparency of information and official data, such as China, be monitored?

The supply chains for EV batteries have a number of intricate steps. Using advanced materials synthesis to create cathode and anode materials after the extraction of the required mineral ores and refinement to create chemicals of sufficient purity. The supply chains for other battery parts like electrolytes and separators are also very complicated, as the battery pack is then integrated into the EV and cells are manufactured and housed in modules within it. LIB life-cycle environmental impact assessments fall into a number of categories for analysis.

A concept known as the "circular economy" is frequently connected to the idea that the more material that is kept in use, the better. It has been suggested that the activities adhering to the circular economy criteria should be evaluated in light of economic, environmental and social sustainability because the simple circulation of materials does not necessarily imply a higher degree of sustainability [29].

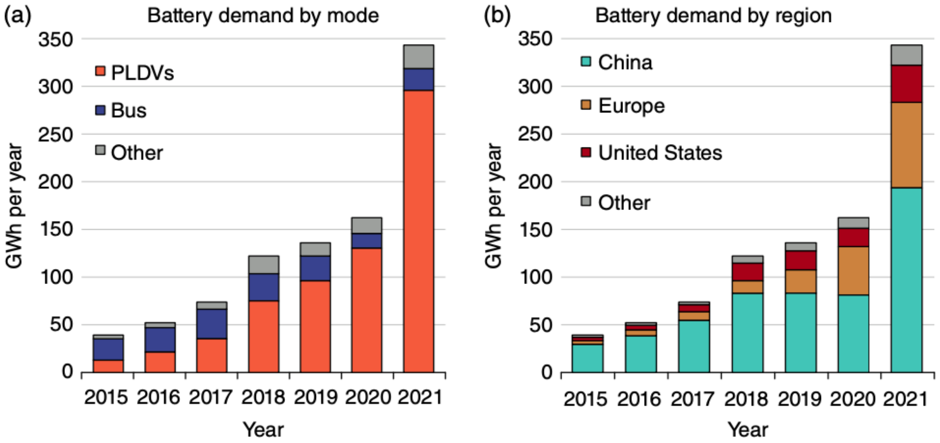

Figure 5. Battery demand by (a) vehicle type and (b) region (PLDVs = passenger light-duty vehicles) [39]

In the case of battery technologies, increased use of battery technology is at the forefront of strategies to store renewable energy and reduce carbon emissions from transportation. However, the manufacture of batteries leaves a sizable carbon footprint. For instance, the development of a fully electric vehicle has a higher carbon footprint than a vehicle powered by an internal combustion engine. But the overall CO2 footprint of an electric vehicle is lower over the course of its lifetime due to lower direct and indirect emissions and, moreover, modern battery recycling methods can make up 60% to 65% of the production emissions [40]. Therefore, circularity in the battery chain should be taken into account in the context of the end market and weighed against cross-industry benefits for transportation and power generation, just like with a number of other products and technologies.

6. Conclusions

The need for flexibility in the energy system will increase significantly worldwide in the coming years and a way in which this can be achieved is through the use of energy storage systems. As other authors mentioned, there is no “just black and white”, therefore we need to focus on diversification and all types of energy storage technologies [11]. For example, there are some opponents, supporting fossil fuels, that say that this is “stupid” to produce electricity via RES, convert it for example into green hydrogen and after again to convert it into electricity because of some energy losses, but this is a clear way to 2030/2050 Zero Carbon Society [28] and the other option is to stay on fossil fuels, coal and other similar sources.

In order to combat climate change and provide a safe and stable energy supply, it is crucial that the world makes the transition to a more sustainable energy future. Energy storage systems will play an increasingly important role in facilitating the integration of renewable energy sources and maximizing their advantages as they gain popularity. The facilitation of the integration of renewable energy, improvement of grid stability and reliability, reduction of electricity prices and decrease of peak demand are the most relevant benefits of energy storage systems. The potential of storage is also shown by the fact that a lot of innovations and developments in these technologies are currently being done worldwide to make these systems more accessible in the future. Incentives and legislative frameworks that encourage the use of energy storage and its integration into energy markets are also investigated in many countries and a paradigm shift is needed today.

Locally, it is essential for each country to update the investment plans related to their domestic energy infrastructure and to correlate them with the strategies at national level. It is also important that legislative measures for the energy sector are preceded by an effective public consultation process, in order to take into account the investment needs of the entire energy value chain, from production to the final consumer, and to include energy storage systems as solutions to increase electricity networks’ efficiency, reduce imbalances and to help, from a commercial point of view, to stabilize electricity prices to the benefit of all actors in the energy sector.

At the same time, to address the environmental issues related to battery, production, research and development efforts must continue. This entails investigating substitute materials with less detrimental effects on the environment, enhancing extraction and processing methods and developing recycling technologies. It is possible to develop more environmentally friendly battery technologies and lessen environmental problems associated with the supply chain and material sourcing by investing in research and innovation. Also, a commitment to circular thinking and sustainability by design will produce significant new insights and cost- and efficiency-reducing levers while new ideas for more environmentally friendly methods and the steps required for a sustainable future will emerge as a result of the growing use of renewable energy sources and energy storage technologies.

The current paper may therefore serve as a springboard for further research into many aspects of energy storage systems. Energy storage technologies play a significant role in creating a more sustainable society. At the same time, additional analysis should be done in the areas of research, policy development and implementation. In addition, as noted, ongoing research and development activities are needed to increase these technologies' performance, efficiency and cost-effectiveness, hence broadening the alternatives for energy storage.

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