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Energy storage and conversion technologies: Current trends, environmental impacts, and future Directions

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Abstract

Energy systems are constantly evolving due to advancements in technology, changing demand, costs, environmental impacts, and the availability of alternative energy sources. Traditionally, energy generation relied heavily on fossil fuels; however, there is a shift towards modern technologies that emphasize renewable resources such as wind and solar energy. As population growth, economic development, and increased per capita energy consumption fuel rising energy demands, consumers are facing higher energy prices. Traditional energy sources are struggling to keep up with this increasing demand, driven by the growing use of devices like computers and mobile phones. Various energy storage solutions, including thermoelectric storage (TES), compressed air energy storage (CAES), flow batteries, superconducting pumped hydro storage (PHS), and hybrid energy storage (HES), have been explored. The extraction of raw materials for these energy storage systems can have diverse effects on human health, while different energy storage technologies can also impact climate change in various ways. The social implications of integrated energy storage facilities in different regions are under investigation. This comprehensive review could provide valuable insights for various stakeholders in the energy industry. By enabling flexible generation and stable electricity supply, energy storage can help meet consumer expectations.

Keywords: Fuel cell vehicles, hybrid energy storage, mechanical energy storage, climate change, human toxicity, social index

Introduction

Energy storage is a method used to regulate energy supply and demand by preserving energy for future use [1]. A battery or accumulator is a device that stores energy in various forms, including latent heat, electrical potential, gravitational potential, radiation, chemical energy, and heat. As production and demand for energy continue to grow, energy storage methods and devices have become more advanced. Traditionally, these devices included capacitors, dry cells, batteries, and magnets. When planning and selecting suitable energy storage technologies for integration into a region's grid systems, it is important to consider the economic and environmental impacts of these technologies, including CO2 emissions [2]. Energy storage will be increasingly important in the future, as patterns of high production and consumption continue over days, weeks, or even months. As production and demand have risen, energy storage technologies and devices have also become more advanced. In the past, devices such as capacitors, dry cells, batteries, and magnets were commonly used for energy storage.

Types of Technologies for Energy Storage

1. Storage of Electrochemical Energy

Petrol-powered vehicles are expected to continue facing competition from electrochemical energy storage devices. Recent advancements in battery technology have opened up promising opportunities for the production of electric vehicles (EVs) that can effectively compete in the market. However, the thermodynamic and kinetic limitations of the electrochemical reactions involved in batteries do not entirely meet the demands of the variable energy consumption patterns in vehicles.

1.1. Lithium-ion batteries

The performance and safety of lithium-ion batteries are significantly influenced by factors such as temperature, voltage range, and charge rate. Exceeding the recommended thresholds for these parameters can lead to a substantial decline in battery performance and pose safety risks. Additionally, accurately predicting the Remaining Useful Life (RUL) of the battery during its service life and assessing its capacity are vital for ensuring reliable operation. One aspect of battery depletion is the dynamic electrochemical processes, which can be thought of as a form of "inorganic life." When batteries are fully charged, they can store a large amount of potential energy because their electrodes are in a state that diverges from thermodynamic equilibrium. A battery is considered "dead" when it is completely depleted [3]. To safely operate electric motors and other equipment without generating excessive heat, it is crucial to carefully regulate the electrical energy released through an external electrical circuit.

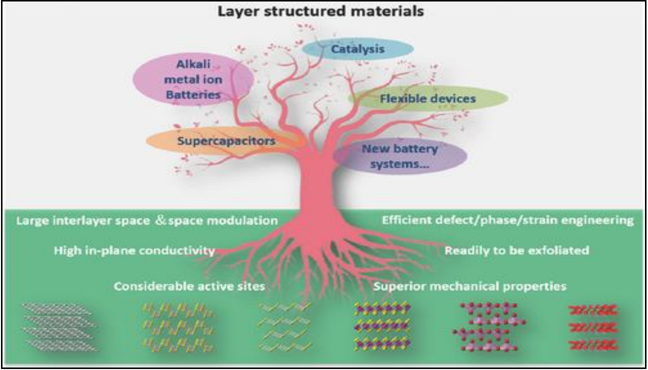

Fig 1: Layer Structured Materials for Advanced Energy Storage and Conversion

Lithium has the highest oxidation potential, measuring 3 V above the standard hydrogen potential, and it is the third lightest element in the universe. Lithium batteries offer excellent prospects for developing high-energy, high-density, efficient, long-lasting, and high-power batteries. This is particularly relevant given the growing demands of the future electrified transportation industry.

1.2. Redox flow batteries (RFBs)

Flow batteries offer the advantage of being independently scalable for both energy capacity and power output, as they store energy in liquid electrolytes. Although their energy density is lower than that of lithium-ion batteries, vanadium redox flow batteries are well-suited for large-scale storage applications due to their stability and long cycle life. In these systems, energy is stored in external tanks using two soluble redox species instead of relying on two solid electrodes within the cell. Flow-through systems provide several benefits, including reduced internal resistance and straightforward cell stack topologies, along with the ability to independently vary energy and power ratings [4]. The benefits of redox flow batteries (RFBs) make them an attractive option for large stationary energy storage systems with capacities ranging from 1 kWh to 10 MWh. There are several types of RFBs, including vanadium RFBs, polysulfide bromide RFBs, and uranium RFBs. Additionally, lithium-metal-based RFBs and zinc-bromine RFBs feature a solid metal electrode on the anode side and a flowing electrolyte on the cathode side. Vanadium RFBs were first successfully developed at the University of New South Wales in the 1980s [5], using vanadium ions in various oxidation states on both sides of the cells.

1.3. Solid-state batteries

Electrical battery utilizes a solid electrolyte, moving away from the conventional liquid or gel polymer electrolytes. This innovative design enhances ionic conduction between the electrodes. As a result, solid-state batteries are theoretically capable of achieving a much higher energy density compared to traditional lithium-ion or lithium polymer batteries, making them a promising advancement in battery technology [6]. Metallic lithium is used for the anode, while oxides or sulfides are used for the cathode in solid-state batteries, significantly increasing their energy density.

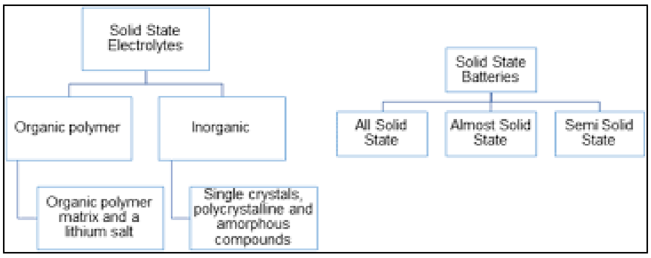

Fig 2: varieties of solid-state batteries and electrolytes.

This setup allows for the effective separation of components, as only lithium ions can pass through the solid electrolyte. As a result, solid-state batteries can address several issues associated with the currently used liquid electrolyte lithium-ion batteries, such as flammability, low voltage, the creation of unstable solid-electrolyte interfaces, poor cycling performance, and reduced strength. Furthermore, solid-state batteries are entirely solid. Inorganic solids, including single crystals, polycrystalline, and amorphous compounds, and organic polymers like polyethylene oxide mixed with lithium ions, are the two primary categories of solid-state electrolytes [7]. Unlike organic polymers, which often possess strong interfacial properties but lack both mechanical strength and ionic conductivity, inorganic solid electrolytes demonstrate minimal interfacial characteristics while offering high mechanical strength. There are three types of solid-state batteries (SSBs) available: semi-solid-state batteries (Semi-SSBs), nearly solid-state batteries (Almost SSBs), and all-solid-state batteries (All-SSBs). Semi-SSBs contain approximately 10% electrolytes by weight; Nearly SSBs contain less than 5%, while All-SSBs consist entirely of solid electrolytes.

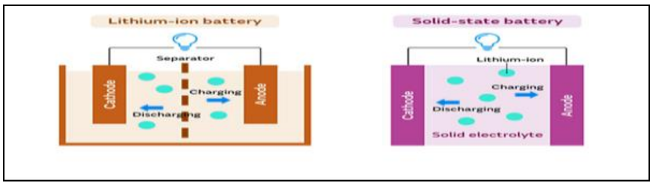

Fig 3: The distinction between a solid-state battery and a lithium-ion battery

Ceramic electrolytes in solid-state batteries require high pressure to maintain contact with the electrodes [8]. Ceramic separators in solid-state batteries are susceptible to breaking under mechanical force.

2. Thermal energy storage

Thermal energy storage (TES) devices help reduce fuel combustion, benefiting both the economy and the environment. Almost all human activities generate heat, and when viewed on a larger scale, the amount of heat produced—from cooking in our kitchens to driving our cars—is significant and often wasted. However, there may be opportunities to creatively utilize this waste heat. By returning the hot or cold material to its original state, the energy stored as heat can be recovered and used again to power heat engine devices that generate electricity.

2.1. Sensible heat storage system

Heat energy is stored in sensible heat thermal energy storage materials based on their specific heat capacity (Cp). This process absorbs heat energy and raises the temperature of the materials without changing their phase. The ability of these materials to retain heat is affected by their specific heat, density, volume, and temperature fluctuations. Materials used for sensible heat storage include various types of thermal energy storage substances**.**

Materials for sensible heat storage

Water

In active systems, water serves as both a heat transfer fluid (HTF) and a thermal energy storage (TES) medium, thanks to its ease of circulation. Water has several advantages, including high specific heat, low cost, wide availability, and non-toxicity. It can exist in three states: liquid, ice, and steam. Ice is used for the storage of cold goods, while the liquid phase can store heat energy at temperatures below 100°C [9]. The best medium for storing thermal energy is water. High-temperature heat energy is stored in the steam phase. In concentrating solar power (CSP) plants that use the direct steam generation (DSG) method, steam accumulators are employed as thermal energy storage (TES) systems. To contain saturated steam, high-pressure, insulated steel tanks are used [10]. Liquid water is a potential medium for thermotherapy heat storage. Buoyancy, caused by the density difference from heating the liquid, creates a desired temperature gradient throughout the storage.

Concrete blocks.

Concrete blocks are an effective option for storing heat, primarily due to several advantages they offer. These advantages include low cost, ease of construction, strong mechanical properties, non-flammability, and non-toxicity. Because of their high mechanical strength, concrete does not require a container, further reducing costs. Concrete is composed of three main ingredients: cement, gravel, and sand. Gravel provides the mineral makeup based on the type of rock, while sand is primarily made up of quartz, with around 90% of it being silica (SiO_2). The binder used in concrete is cement. Before being utilized in concrete mixtures, Portland cement consists mainly of the following ingredients: calcium oxide (CaO, 63%), silica (SiO_2, 19%), and aluminum oxide (Al_2O_3, 6%), among others. During the curing process, cement undergoes hydration, which leads to the formation of various cement phases, including calcium silicate hydrate, calcium alumina silicate hydrate, and portlandite. As the temperature rises during the heat absorption process, several transformations occur within the concrete block. This includes dehydration (105°C - 440°C, C-S-H phase), dehydroxylation (440°C - 580°C, Portlandite phase), decarbonation (560°C - 1000°C), and phase changes (e.g., quartz transitions from α to β at 571°C), among other changes [11]. These changes result in calcium oxide residue that easily rehydrates by absorbing moisture from the air while cooling. Consequently, the solidified paste swells and fractures due to small volume variations and repeated temperature cycles.

Devices for latent heat storage

The latent heat of storage materials allows them to retain heat during a continuous temperature change, often through a phase transition. Typically, this involves a transition from solid to liquid. However, solid-to-solid phase transitions can also be used. While solid-to-solid phase shifts have a lower specific latent heat, they offer advantages such as minimal leakage and no need for encapsulation. On the other hand, the phase transition from liquid to gas has the highest latent heat during the phase change [12]. The formula

$Q = mL$ represents the thermal energy that latent heat stores. Where L is the specific latent heat ($kJ.kg^{1}$) and m is the mass (kg).

Materials that store thermal energy for latent heat storage

Organic.

The solid-liquid phase change temperature of many organic materials typically falls within the range of 180 to 300 degrees Celsius, which is considered suitable for human thermal comfort. Organic compounds that are non-toxic, non-corrosive, and chemically stable can be easily found in nature. As a result, organic thermal energy storage (TES) materials are commonly used for achieving thermal comfort in fabrics, buildings, and various other applications. However, it is important to note that these materials tend to have relatively low thermal conductivity and can deteriorate at higher temperatures.

Paraffin

Paraffin is composed of n-alkane aliphatic hydrocarbons that are saturated [13]. The more carbon atoms there are in the backbone chain, the higher its melting temperature. Generally, paraffins with melting temperatures of 65°C for n-triacontane (n = 30) and 10°C for n-pentadecane (n = 15) are considered for TES applications. Under normal conditions, n-alkanes usually exist as a wax like solid phase above n = 16 and as a liquid phase below n = 16. n-Octadecane is the most often used paraffin in research (n = 18). Its 280 °C melting point is the most comfortable for people. Paraffin mixes with varying quantities of carbon atoms make up technical grade paraffin waxes. They can be found in melting temperatures ranging from 5°C to 100°C. The micro encapsulation technique is aided by paraffin's ability to produce O/W emulsions with water due to its non-polarity. Paraffin's benefits include resistant to phase segregation, low super cooling, odorlessness, compatibility with metal containers, and chemical stability.

Inorganic.

The suitability of inorganic materials for a given operating temperature is ascertained by measuring the phase change temperature of the system. High temperatures, where inorganic TES materials frequently operate, would have caused organic materials to thermally decompose.

Salts.

At high temperatures, salts are effective for thermal energy storage (TES) due to their elevated melting points. The storage capacity can be significantly enhanced by selecting a salt whose melting point falls within the desired operating temperature range. For example, using lithium nitrate ($LiNO_3$), which has a melting point of 250 °C, allows for the utilization of sensible heat within the operating range of 300 °C to 500 °C. This configuration yields a volumetric storage capacity of approximately 440 MJ/m^3. In contrast, potassium nitrate ($KNO3_)$, with a melting point of 335 °C, can store both sensible and latent heat, leading to a volumetric storage capacity of around 935 MJ/m^3. It is worth noting that inorganic salts generally have low thermal conductivities, typically ranging from 0.5 to 1 W/(m·K).

Metals and alloys

The greatest heat storage capacity per unit volume and the maximum thermal conductivity are the benefits of using metals and their alloys as PCM (Phase- change material). Although metals and alloys are costly, they are the greatest option for TES when volume is the determining factor. The capacity of metals and alloys to store thermal energy is limited per unit weight. As a result, people struggle with being overweight [14]. In spite of its low melting point (<~ 97 C) and latent heat (˜113 kJ kg 1), sodium (Na) is a useful liquid metal for heat storage. Consequently, sodium (Na) is not the ideal PCM even if it is a good HTF and a sensible heat storage medium. Following repeated heat cycles, metals and alloys may undergo precipitation, oxidation, segregation, and other processes that change their microstructure. Consequently, their properties, including latent heat and phase change temperatures, may shift.

Latent Heat Storage Benefits and Drawbacks

Latent heat is 50–100 times larger than sensible heat. Consequently, in the vicinity of the phase transition temperature, the energy storage density of latent heat storage materials is relatively high. PCM is used to create compact TES systems. In latent heat storage (LHS) TES systems, the output temperature of the HTF stays constant throughout discharge. However, the main drawback of latent heat storage materials is their limited thermal conductivity. In general, salt PCMs have a thermal conductivity of 0.5 to 1 W m^{1}. K $^{1.}$ Organic PCMs range in thermal conductivity from 0.1 to 0.3 W.m^{1}. K^{1}. Nearly all PCMs don't cause harm. Organic PCM is flammable, though. Long-chain fatty acids, paraffin, and esters are examples of organic PCM that cannot be stored or transported in plastic containers due to the lipophilia of plastics [15]. Metal vessels are also corroded by inorganic PCM.

Storage of Mechanical Energy

Mechanical energy storage systems (MESSs) are generally more affordable, sustainable, and environmentally friendly compared to standard energy storage systems (ESSs) [16]. The main categories of MESSs include compressed air energy storage (CAES) and pumped hydro energy storage (PHES), among others. Additional types of MESSs can include gravity, mechanical, and liquid-piston springs.

Energy storage by pumping hydro (PHES)

The pumped hydro storage system relies on two man-made or natural bodies of water to store energy at different elevation levels. Water is transported through pipes to a hydroelectric generator, where it is stored in the lower water reservoir during peak energy demand hours. To pump the water back into the higher reservoir during off-peak hours, additional electricity is required. Electricity is then generated again by the generators. According to Mohd *et al*. (2008) and Mears and EPRI-Doe (2003), [17]. When it is less popular, water is pushed back into the higher body of water. Pumped Hydro Energy Storage (PHES) primarily consists of two large water reservoirs, a motor-generator, and a reversible pump-turbine.

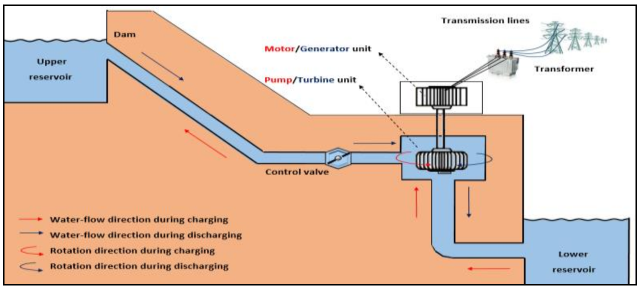

Fig 4: Diagrammatic representation of a pumped hydro storage facility.

The system can be assembled and maintained in just a few minutes, depending on the amount of water stored in the upper reservoir. The dependence of this process on the climate and environment of the plant region is one of its disadvantages. According to EPRI-DOE (2003), [18] conversion efficiency ranges from 65% to 80%, depending on the climate and the equipment used. While the energy storage capacity of a waterfall is influenced by its height and water volume, it typically takes 4 kWh of energy to produce 3 kWh. Comprehensive tests indicate that a mass of one ton of water falling from a height of 100 meters can generate approximately 0.272 kWh. This energy can be stored for extended periods. Additionally, the energy storage from the Pumped Hydro Energy Storage (PHES) system can serve as a "black start" source in the event of a power outage.

Energy Storage in Compressed Air (CAES)

In the Compressed Air Energy Storage (CAES) system, power is utilized during off-peak hours to pressurize air and store it in an underground reservoir. During peak hours, the turbine/generator unit generates electricity by releasing the compressed air. Apart from pumped hydro storage, CAES is the only financially viable technology that can be implemented in large-scale energy storage systems, with single unit capacities of 100 MW or more, for consumer use (Ibrahim *et al*., 2008b) [19]. About 12 kWh/m^3 is the energy density for CAES (Multon *et al*., 2003), and Robyns (2005) [20]. The technology is estimated to have an efficiency of 70%. During off-peak hours, it requires 0.7 to 0.8 kWh of electricity to compress air, while in peak hours; it returns 1 kWh back to the grid. Many businesses in Europe are adopting this technology to store electricity in the grid system. This process involves both exothermic and endothermic reactions as air is compressed, expanded, and heat is exchanged. According to Cheng and Choobineh (2017) [21] there are three different designs of CAES systems: isothermal, adiabatic, and diabatic. Isothermal and adiabatic storage systems are appropriate for lesser power requirements, however adiabatic storage systems are more suited for commercial CAES systems due to their higher density and flexibility of regeneration and storage. For energy storage, a high-pressure dual chamber and a liquid-compressed air storage tank are both used.

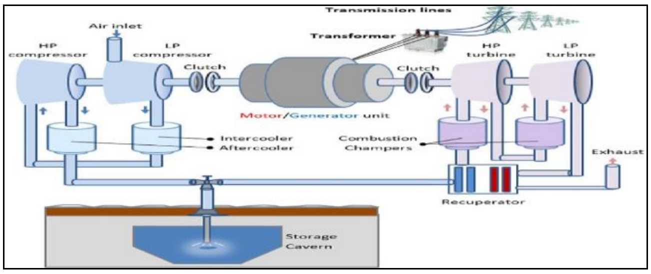

Fig 5: An illustration of the source of a compressed air storage plant

Hydrogen and Fuel cells

Hydrogen is an ideal, clean, sustainable, renewable, and highly efficient energy carrier produced through the electrolysis of water and thermo chemical splitting of water. The energy yield of hydrogen is 2.75 times greater than that of hydrocarbon fuels, at 122 kJ/g. However, hydrogen is a hazardous energy source due to its high diffusion coefficient, wider ignition limits, and elevated flame temperature and explosive potential. A device known as a fuel cell continuously converts the chemical energy in fuel into electrical energy as long as there is fuel and an oxidant available.

Fuel cell vehicle

In many nations, FCV is crucial for reducing environmental stress and fossil fuel consumption (Tanç *et al*., 2019) [22]. Fuel cells convert the chemical energy of hydrogen directly into electrical power, with the only byproduct being water. Two common types of fuel cells are solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC), which are used for grid support, backup power, and transportation purposes. Vehicles that use a fuel cell as part of their power system are known as fuel cell vehicles (FCVs). There are two types of FCVs: fuel cell hybrid electric vehicles (PFCVs) and pure fuel cell vehicles. To maximize the efficiency of hydrogen in practical applications, several measures are necessary: a reliable energy management system is needed to monitor performance in real time, a network of hydrogen stations should be established to make hydrogen as accessible as gasoline, and fuel cells must be designed for longevity (Sulaiman *et al*., 2015) [23].

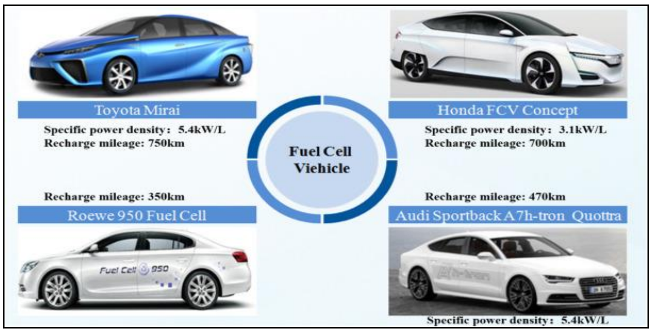

Fig 6: Recent advancements in the technologies of hydrogen and oxygen fuel cells

Fortunately, a lot of national governments are interested in the FCV, and a lot of money has been invested in this area. The current research direction is toward effective controller design for the system and efficient power conversion.

Hydrogen generation

The production of hydrogen is fundamental to its widespread commercialization. One of the most promising and environmentally friendly methods for producing hydrogen is through water electrolysis. To address the issue of silane production during the hydrolysis of magnesium sulfide (Mg_2S), Tan *et al*. (2019) [24] studied the kinetics and processes of magnesium silicide (Mg_2Si) hydrolysis using solutions of NH_4Cl and NH_4F. Their results showed that although the rate of hydrolysis and hydrogen production can be enhanced by ball milling and increasing the temperature, NH_4F can almost completely convert silanes into hydrogen. The energy stored in hydrogen (H_2) can be utilized by fuel cells to generate electricity, despite some systems converting other forms of energy into hydrogen before supplying the fuel cell with the necessary reaction gas. A hybrid system combining photo thermal hydrogen production with photovoltaic's has been developed, utilizing Au-TiO_2 as a spectrum selector. This system effectively captures ultraviolet, visible, and infrared energy from full-spectrum sunlight, leading to rapid production of photothermal hydrogen. In 2020, Tang and colleagues introduced an Au-TiO_2 mixed methanol/water reaction solution that acts as an absorbent selector to enhance hydrogen synthesis. This solution transmits the visible to near-infrared (Vis-NIR) spectrum to power the integrated photovoltaic (PV) cell while absorbing the ultraviolet, visible, and infrared bands, thereby enabling more efficient use of energy.

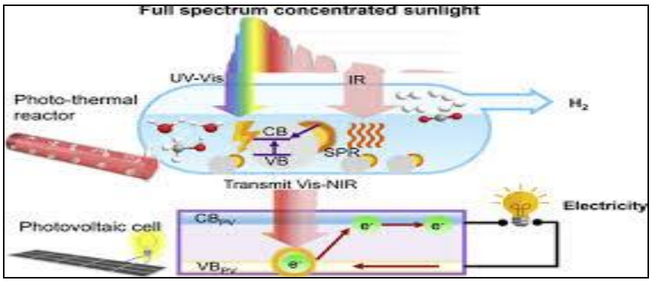

Fig 7: Synergizing Concentrated Photo-Thermal Hydrogen and Photovoltaic's

A crucial tool for converting methanol, CH_4, bio-oil, or even NH_3 into hydrogen is the reformer. The remaining hydrogen is produced through water electrolysis, which is powered by the combustion of fossil fuels. Currently, methane reforming accounts for about 95% of large-scale hydrogen production. Hydrogen can be generated through various methods, and there is a growing emphasis on innovations that utilize renewable energy sources.

Energy Storage Systems' Impact on the Environment and Health

The production, use, storage, handling, disposal, and recycling of batteries can significantly impact the environment. Batteries are manufactured in large quantities around the world in various sizes and types due to their diverse applications, leading to numerous environmental and public health concerns. The following subsections discuss the harmful effects and risks associated with batteries.

Sources of raw materials

Batteries require a variety of metals and non-metals in significant quantities. The elements involved include lead (Pb), lithium (Li), nickel (Ni), cobalt (Co), zinc (Zn), manganese (Mn), magnesium (Mg), mercury (Hg), lanthanum (La), and cerium (Ce) [25]. Non-metals such as fluorine (F), germanium (Ge), sulfur (S), bromine (Br), carbon or graphite (C), fluorine (F), and chloride vanadium (Cl) are used [26]. Increased battery production affects both the availability and the economics of natural resources. This is because metal supplies are spread out across different geographic locations, often in unstable or limited economies, and the most accessible sources are usually depleted first. Currently, batteries utilize only 3 percent of the nickel produced worldwide. [27]. Batteries use around 5% of the world's mercury consumption [28], although due to toxicity concerns and technological advancements, this percentage is declining [29]. Recent spikes in raw mineral costs have increased battery recycling and metal recovery (e.g, copper, nickel, cobalt, and lead).

Negative impacts and contamination of the environment brought on by battery use

Certain metals and non-metals used in battery production can be hazardous to human health if ingested, injected, inhaled, or if they come into contact with the skin or eyes. Lead (Pb), in particular, is typically absorbed by humans through consumption, inhalation, and skin contact. [30], cadmium (Cd) through ingestion and inhalation [31], and mercury (Hg) through skin contact, inhalation, and ingestion. A variety of factors influence metal toxicity, including the chemical species, dose absorbed, duration and frequency of exposure, as well as the individual's age, gender, genetics, and nutritional status. [32]. Metals and metal compounds can enter surface waterways, groundwater, and soil through mining and industrial operations, coupled with environmental factors and the anticipated growth in battery production.

Table 1: Environmental impacts of different types of batteries

Type of battery	Effects on the environment
Ni–MH (established)	Nickel is poisonous and not environmentally friendly because it is difficult to obtain and not sustainable. Not uncommon, but difficult to locate recyclable
Pb-A (established)	Limited capacity to cycle at high temperatures Even though 95% of lead may be recycled, it is still toxic. Cobalt is a depletable element in most applications; iron and manganese are sustainable and abundant alternatives.
Li–ion (established	Although lithium is abundant, its chemistry has to be improved.
Al–CFx (future)	Despite being "green," the industries of fluorine and aluminum cannot be recycled.

All batteries pose a danger to the environment and human health if not disposed of properly. Some types of batteries are more hazardous than others because they contain toxic metals. In China, most used batteries (except for lead-acid batteries) are discarded with household waste and end up in landfills or incinerators [33]; the majority of alkaline batteries are disposed of in landfills in the United States [34]. The Environmental Protection Act of 1995 designated batteries as universal and hazardous wastes, requiring regulations for their storage, recycling, treatment, and disposal. Alkaline and zinc-cadmium batteries are often burned or land filled in large quantities instead of being recycled.

Climate change

The electricity generated by each technology affects its contribution to climate change. The infrastructure impacts are significantly higher than Belgium's threshold of 183 g of CO_2 equivalent per kWh [35]. Lead-acid and lithium-ion batteries are recognized as the primary contributors to environmental impact during the manufacturing phase. Lithium-ion batteries are affected by the mining of copper and lithium, as well as the energy required for their production. In contrast, lead-acid batteries are primarily impacted by the disposal processes associated with lead smelting.

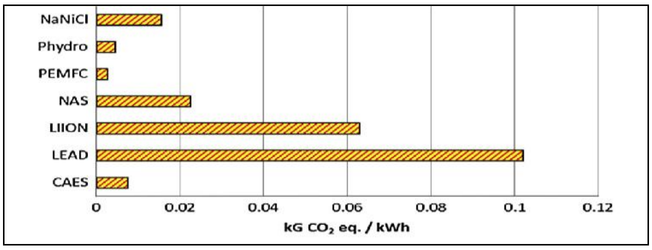

Fig 8: The role of infrastructure in climate change

The renewable electricity sources, such as wind and solar, generally perform better than the average kilowatt-hour (KWh) from the Belgian energy mix. Additionally, the lower total life cycle energy of lead-acid systems negatively impacts their environmental performance, as they do not dilute overall damages as effectively as other systems with greater capacity.

Hazardousness to people

The average energy production cost for 1 kWh using the 2011 power mix in Belgium is challenging to surpass, according to human toxicity assessments. The infrastructure ratings for technologies such as Compressed Air Energy Storage (CAES), Sodium Sulfur (NAS), Proton Exchange Fuel Cells (PEMFC), and Pumped Hydro (PHydro) are below the human toxicity requirements for the average kilowatt-hour (kWh) in Belgium [36]. The efficiency of technology significantly impacts the use phase in relation to climate change. For instance, photovoltaic power systems cannot operate effectively below the threshold level set by major energy providers, such as Compressed Air Energy Storage (CAES) and pumped hydroelectric storage (PHydro). The extraction of raw materials for solar panels through mining is a major source of environmental stress. Most industrial facilities for manufacturing these panels are located in China, where the production process consumes a significant amount of energy. Additionally, lithium-ion, lead-acid, and sodium nickel chloride (NaNiCl) batteries have lower performance compared to 1 kWh sourced from the Belgian power mix, making them potentially less environmentally friendly options for energy storage [37]. CAES and PHydro have less of an impact due to the reservoir's architecture and the amount of cement and steel needed to hold the air and water, respectively, during the lifetime of the energy delivered.

Social index

The social impact of the energy transition has been assessed using a new social index, which also offers tools for identifying energy infrastructure that takes social impact into account [38]. Assuming that installing the plant in a specific area could lead to new investments, job opportunities, and increased local taxes, the goal is to identify the best location for maximizing social impact. This section has outlined each item related to the social index, and additional details can be found in the Supporting Information.

$$\text{Social Score}=10\ (\text{Value} - \text{Value}_{\text{Min}} / \text{Value}_{\text{Max}} - \text{Value}_{\text{Min}})$$

Region-specific installed capacity loss relative to overall capacity loss

As part of the energy transition, some infrastructure—primarily nuclear and coal-fired power stations—will be decommissioned. This decommissioning leads to a loss of economic activity, local taxes, and job opportunities, which is most keenly felt in the communities surrounding these facilities. Consequently, areas with a higher rate of decommissioning will experience more significant negative impacts on their social and economic well-being [39]. A factor equal to the inverse of the number of usable life years is multiplied by the total capacity to determine the lost installed capacity.

Employment loss in the energy transition sector relative to regional employment overall

The region will experience a loss of both direct and indirect jobs due to the decommissioning of old power facilities. This job loss is especially significant in areas where the overall population of active residents is declining. As a result, the impact of the energy transition will be more pronounced in regions where the proportion of job losses relative to the total active population is high [40]. The region will experience a loss of both direct and indirect jobs due to the decommissioning of old power facilities. This job loss is especially significant in areas where the overall population of active residents is declining. As a result, the impact of the energy transition will be more pronounced in regions where the proportion of job losses relative to the total active population is high.

Installation capacity loss as a percentage of the region's overall GDP

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Comparing the region's GDP to the nation's overall GDP

This component reflects the first aspect of the area's general social environment. The introduction of new facilities, such as the one proposed in this paper, tends to have a more significant social impact in areas that contribute less to the nation's overall GDP.

Unemployment rate

Power generation and storage facilities can be an effective way to help reduce the rising unemployment rates that are especially high in certain areas [42, 43]. As a result, there is a need for increased social initiatives and improved social index scores to address these growing unemployment challenges.

Decrease in population throughout the past 20 years

Due to migration from small and medium-sized villages to towns, the population of some rural areas has dropped as a percentage of the total population to dangerously low levels [44]. In order to address the population and combat this demographic issue, the facilities examined in this paper could be introduced. Therefore, areas where a sharp population drop has occurred are likely to see a greater societal impact.

Conclusion

TES is a solution to reducing our reliance on burning fossil fuels. Fossil fuels are typically burned because thermal energy dissipates into the environment if not properly stored. Future research should focus on the advantages of developing new materials for super capacitors, considering their characteristics, power density, and cycle life compared to batteries with increased energy storage. An interesting aspect of this field is the variety of strategies available, such as enhancing the power density of batteries or increasing the energy storage density of supercapacitors. The integration of Thermo-Mechanical Energy Storage Systems (TMES) with external heat sources and sinks, including waste-heat sources, provides enhanced functionality, flexibility, and the capacity to manage multiple energy vectors beyond electricity, such as heat or cold. Energy improvement and technological advancement face three main challenges: material, structural design, and system integration. Fuel cell structures need to be optimized for greater efficiency, while hydrogen generation and storage technologies should focus on material improvements to enhance stability and safety in use. Today’s batteries boast extremely large capacities, capable of powering electricity grids and large vehicles. However, the costs related to capital, operation, maintenance, labor, and eventual replacement of energy storage devices vary significantly. The methods and equipment used for energy storage can have both positive and negative environmental impacts. The benefits may include reduced reliance on fossil fuels and a diminished effect on global warming. Addressing the environmental and social factors is crucial to minimizing the adverse social consequences of the energy transition and the socioeconomic disparities in society. Planning a new energy system at a national or continental level through this lens is a significant challenge for the future of this field. This work aims to provide an environmental and social assessment for various locations to effectively implement these new technological requirements. Empowering individuals with the tools necessary to make informed decisions is paramount in creating a more equitable and sustainable society. The energy source highlights the importance of correctly sizing storage systems, where capacity must match application requirements for efficient use and, consequently, positive environmental outcomes. A well-functioning recycling network is essential, as consumers need the resources and knowledge necessary for battery recycling. Energy storage systems generally have minimal negative environmental effects during usage, with the most significant impacts occurring during construction and decommissioning. As we move forward, energy storage will become increasingly necessary, and technologies and materials will evolve to utilize more environmentally friendly resources.

Reference

1. Kullmann S. A case study of the barriers preventing solar photovoltaic expansion and the most viable locations for solar in Athens-Clarke County, Georgia [master’s thesis]. Athens (GA): University of Georgia, 2022.
2. Newell RG, Raimi D. Global energy outlook comparison methods, 2020 update. Resources for the Future, 2020.
3. Capasso C, Veneri O. Experimental analysis on the performance of lithium-based batteries for [authors from Yang *et al*., 2011].
4. Yang Z, Zhang J, Kintner-Meyer MC, Lu X, Choi D, Lemmon JP, *et al*. Electrochemical energy storage for *green grid*. *Chem Rev*,2011:111(5):3577-3613.

5. Rychcik M, Skyllas-Kazacos M. Characteristics of a new all-vanadium redox flow battery. J Power Sources,1988:22(1):59-67.
6. Shaqsi AZA, Sopian K, Al-Hinai A. Energy Reports, 2020.
7. Xu K. No aqueous liquid electrolytes for lithium-based rechargeable batteries. *Chem Rev*,2004:104(10):4303-4418.
8. Utomo NW, Hong S, Sinha R, Kim KI, Deng Y, Coahoma P, *et al*. Solid-state polymer-particle hybrid electrolytes: Structure and electrochemical properties. *Sci Adv*,2024:10(27):eado4719.
9. Gil A, Medrano M, Martorell I, Lázaro A, Dolado P, Zalba B, *et al*. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization. Renew Sustain Energy Rev,2010:14(1):31-55.
10. González-Roubaud E, Pérez-Osorio D, Prieto C. Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. Renew Sustain Energy Rev,2017:80:133-148.
11. Monteagudo SM, Moragues A, Gálvez JC, Casati MJ, Reyes E. The degree of hydration assessment of blended cement pastes by differential thermal and thermo gravimetric analysis. Morphological evolution of the solid phases. Thermochim Acta,2014:592:37-51.
12. Cárdenas B, León N. High temperature latent heat thermal energy storage: Phase change materials, design considerations and performance enhancement techniques. Renew Sustain Energy Rev,2013:27:724-737.
13. Stamatiou A, Obermeyer M, Fischer LJ, Schuetz P, Worlitschek J. Investigation of unbranched, saturated, carboxylic esters as phase change materials. *Renew Energy*,2017:108:401-409.
14. Fernández Renna AI, Barreneche Güerisoli C, Belusko M, Segarra Rubí M, Bruno F, Cabeza LF. Considerations for the use of metal alloys as phase change materials for high temperature applications.
15. Ghedamsi K, Aouzellag D, Berkouk EM. Control of wind generator associated to a flywheel energy storage system. *Renew Energy*,2008:33(9):2145-2156.
16. Suvire GO, Mercado PE. DSTATCOM with flywheel energy storage system for wind energy applications: control design and simulation. *Electr Power Syst Res*,2010:80(3):345-353.
17. Merlet C, Rotenberg B, Madden PA, Taberna PL, Simon P, Gogotsi Y, *et al*. On the molecular origin of supercapacitance in nanoporous carbon electrodes. *Nat Mater*,2012:11(4):306-310.
18. Mohd A, Ortjohann E, Schmelter A, Hamsic N, Morton D. Challenges in integrating distributed energy storage systems into future smart grid. In, 2008 IEEE International Symposium on Industrial Electronics, 2008 June. p,1627-1632.
19. Ibrahim H, Ilinca A, Perron J. Energy storage systems—Characteristics and comparisons. *Renew Sustain Energy Rev*,2008:12(5):1221-1250.
20. Molina MG. Energy storage and power electronics technologies: A strong combination to empower the transformation to the smart grid. *Proc IEEE*,2017:105(11):2191-2219.
21. Cheng J, Choobineh FF. A comparative study of the storage assisted wind power conversion systems. In, 2017 6th International Conference on Clean Electrical Power (ICCEP), 2017 June. p. 608-613.
22. Bullough C, Gatzen C, Jakiel C, Koller M, Nowi A, Zunft S. Advanced adiabatic compressed air energy storage for the integration of wind energy. In: Proceedings of the European Wind Energy Conference, EWEC,2004 Nov:22:25.
23. Tang S, Xing X, Yu W, Sun J, Xuan Y, Wang L, Jin H. Synergizing photo-thermal H2 and photovoltaics into a concentrated sunlight use. *iScience*,2020:23(4).
24. Sulaiman N, Hannan MA, Mohamed A, Majlan EH, Daud WW. A review on energy management system for fuel cell hybrid electric vehicle: Issues and challenges. *Renew Sustain Energy Rev*,2015:52:802-814.
25. Song Z, Hofmann H, Li J, Han X, Ouyang M. Optimization for a hybrid energy storage system in electric vehicles using dynamic programming approach. *Appl Energy*,2015:139:151-162.
26. Linden D. Linden's Handbook of *batteries*. McGraw-Hill, 2010.
27. Huisman J, Ciuta T, Mathieux F, Bobba S, Georgitzikis K, Pennington D. RMIS–Raw materials in the *battery* value chain. Publications Office of the European Union, Luxembourg, 2020.
28. Plunkert PA. *Bauxite* and *alumina*. US Geol. Survey, Minerals Commodity Summaries, 2003.
29. Maxson P. Global *mercury* supply, trade and demand. United Nations Environmental Programme. Available from: https://wedocs.unep.org/bitstream/handle/20.500, 11822, 21725, 2017.
30. Gehle K. Toxicity of polycyclic aromatic hydrocarbons (PAHs),2009.
31. Bernard A. *Cadmium* & its adverse effects on human health. Indian J Med Res,2008:128(4):557-564.
32. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. *Heavy metal* toxicity and the environment. In: Molecular, Clinical and Environmental Toxicology: Volume 3: Environmental Toxicology, 2012, 133-164.
33. Song X, Hu S, Chen D, Zhu B. Estimation of waste *battery* generation and analysis of the waste *battery* recycling system in *China*. J Ind Ecol,2017:21(1):57-69.
34. Olivetti E, Gregory J, Kirchain R. Life cycle impacts of alkaline *batteries* with a focus on end-of-life. Massachusetts Institute of Technology: Cambridge, MA, USA, 2011. p,2-5.
35. Messagie M, Boureima F, Mertens J, Sanfelix J, Macharis C, Van Mierlo J. The influence of allocation on the carbon footprint of electricity production from waste gas, a case study for *Blast Furnace gas*. Energies,2013:6(3):1217-1232.
36. Arvesen A, Hertwich EG. Assessing the life cycle environmental impacts of *wind power*: A review of present knowledge and research needs. Renew Sustain Energy Rev,2012:16(8):5994-6006.
37. Manish S, Pillai IR, Banerjee R. Sustainability analysis of *renewables* for climate change mitigation. Energy Sustain Dev,2006:10(4):25-36.
38. Davis W, Martín M. Optimal year-round operation for *methane* production from *CO2* and water using *wind* and/or *solar energy*. J Clean Prod,2014:80:252-261.

39. Schmidt O, Melchior S, Hawkes A, Staffell I. Projecting the future levelized cost of electricity storage technologies. Joule,2019:3(1):81-100.
40. Gielen D, Boshell F, Gorini R, Kiruja J, Komor P, Masuyama T, Parthan B. Renewable power generation costs in 2019 Report. International Renewable Energy Agency, 2020.
41. Gonzalez-Castellanos A, Pozo D, Bischi A. Detailed *Li-ion battery* characterization model for economic operation. Int J Electr Power Energy Syst,2020:116:105561.
42. Ali S, Stewart RA, Sahin O. Drivers and barriers to the deployment of pumped hydro *energy storage* applications: Systematic literature review. Clean Eng Technol,2021:5:100281.
43. Stančin H, Mikulčić H, Wang X, Duić N. A review on alternative fuels in future *energy system*. Renew Sustain Energy Rev,2020:128:109927.
44. De la Fuente E, Martín M. Site specific process design for Hybrid *CSP-Waste plants*. Comput Chem Eng,2020:135:106770.