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The Role of Civil Engineering in Renewable Energy Storage: Contributions and Challenges

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Abstract. Renewable energy generation is characterized by intermittency; consequently, energy storage is a prerequisite for its large-scale utilization. Existing research primarily focuses on power systems and electrochemical materials, often overlooking the civil engineering aspects of energy storage projects. This paper employs a literature review approach to examine the engineering characteristics of four mainstream technologies, namely pumped hydro storage, compressed air energy storage, battery energy storage stations, and hydrogen energy storage, and summarizes the roles of civil engineering and the typical issues involved. The study reveals that civil engineering encompasses the entire lifecycle of energy storage projects from site selection and design to construction, and that the extent of civil engineering involvement directly impacts project feasibility and long-term operational safety. Specific challenges include lining cracking and hydraulic fracturing risks in pumped hydro storage; surrounding rock degradation and sealing performance in lined-cavern compressed air energy storage; caprock integrity and fault avoidance in salt-cavern hydrogen storage; pollution containment following thermal runaway in battery storage; and the prevention of hydrogen embrittlement in pipelines for hydrogen transport. This study demonstrates that the engineering constraints associated with energy storage technologies are fundamentally civil and geotechnical issues, which should be systematically considered during the evaluation of energy storage solutions.

Keywords: Energy Storage, Renewable Energy, Civil Engineering, Geotechnical Engineering, Underground Energy Storage

1. Introduction

Nowadays, people's basic daily operations heavily rely on coal, oil and gas. These energy sources are the important support for economic development, but they are not efficient, and their emissions keep polluting the environment. Burning fossil fuel produces significant emissions of greenhouse gases. According to statistics from the full-scope greenhouse gas accounting framework, carbon dioxide (CO_2) produced by global fossil fuel combustion and industrial activities currently accounts for two-thirds of total greenhouse gas emissions, making it the main driver pushing up global total emissions [1]. The warming effect of methane, nitrogen oxides, and fluorinated gases are much stronger than that of carbon dioxide. Their combined emissions make up around a quarter of total global emissions, and the emission volume of these non-CO_2 greenhouse gases is still on the rise [2].

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Many countries aim to cut emissions of CO_2 and other greenhouse gases that accelerate global warming, in order to protect the planet. To achieve this goal, they have put forward "Dual Carbon" targets such as "Net Zero" or "Carbon Neutrality," along with corresponding action plans [3]. Countries engaged in the above carbon governance initiatives are also promoting the development of renewable energy, so as to reduce greenhouse gas output. However, most renewable energy generation is intermittent, particularly wind and solar power, making energy storage a critical prerequisite for the large-scale utilization of renewable energy [4]. Existing research on energy storage primarily follows three main lines of inquiry: power system operation and optimization, electrochemical materials and battery performance, and the comparison of storage technology pathways alongside policy assessments [5]. While these studies address "why energy storage matters" and "which technical metrics are superior," they generally treat energy storage as an issue internal to electrical engineering or materials science, rarely examining it systematically from a civil engineering perspective. Specifically, the feasibility of energy storage projects relies heavily on site geological conditions; for instance, pumped storage hydropower depends on natural elevation differences and sufficient overburden. Consequently, many issues that are fundamentally civil and geotechnical in nature lack a systematic analysis from the standpoint of engineering construction. This gap gives rise to the core questions addressed in this paper: What role does civil engineering play across various energy storage technologies? How does it influence project feasibility and long-term operational safety? What engineering challenges currently exist?

To address these questions, this paper selects four mainstream technologies, namely pumped storage hydropower, compressed air energy storage, battery energy storage stations, and hydrogen energy storage, and analyzes them according to a logical framework comprising technical principles, civil engineering involvement, critical engineering issues, and major challenges. The paper's contribution lies in adopting civil engineering as an analytical lens for understanding the feasibility and safety of energy storage projects, rather than treating it merely as an adjunct to electrical or materials research. It outlines the principles of the four technologies, summarizes the specific stages of civil engineering involvement and typical engineering issues associated with each, and attempts to discuss geological conditions, structural requirements, and long-term operational safety within a unified framework, thereby providing a reference for future research on design standards and assessment systems for energy storage applications.

2. Current status of main energy storage technologies

2.1. Pumped storage

Pumped storage is a highly flexible large-scale energy storage technology. In a hybrid large power grid that incorporates intermittent energy sources such as wind power and photovoltaics, a hydropower station with a buffer reservoir can fully serve as an energy storage facility. In most countries where hydropower is the primary power source, the conventional operational logic is quite clear. Water is stored in large basin reservoirs, and is only released to drive turbines for power generation when there is an electricity supply gap. The entire process of pumping and storing water is completed by electric motors driving the pumps [6]. When the power grid has insufficient supply, the stored water in the upper reservoir is released downward, passing through Francis turbines directly connected to the generators to generate electricity. The entire unit set is rigidly coupled with the generator. The energy conversion mechanism of a pumped storage power station is clear. During periods of low electricity demand on the grid, the station consumes surplus off-peak electricity from the grid to drive the pump units. The units transport water from the lower reservoir to the higher

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upper reservoir, converting electrical energy into gravitational potential energy of the water for storage. When the grid enters periods of peak demand, the stored water in the upper reservoir is released downward through the turbines back to the lower reservoir. The gravitational potential energy of the water is then reconverted into electrical energy and sent back to the grid [6].

In pumped storage capacity expansion projects, the load on pressure tunnels and shafts is extremely high. Selecting a waterway alignment with sufficient overburden thickness is the core prerequisite to balance economy and operational safety. Raise-boring construction technology has been continuously improved. Now, a single drilling operation can complete the construction of vertical pressure shafts with a maximum depth of 800 meters [7]. With favorable rock mass cover conditions, vertical pressure shafts can support a more optimized waterway alignment design. As long as the shaft is embedded deep enough into the rock mass, the risk of hydraulic jacking can be completely eliminated. Meanwhile, the rock mass itself has very low permeability, so there is no need to lay traditional steel liners at all. It is only necessary to design a reinforced concrete lining according to the crack width control requirements, to keep the water seepage within the allowable limit. Against the current background of sharply rising steel prices, this optimization scheme can greatly reduce project cost. It makes the economic advantage of pumped storage projects extremely prominent.

In addition, the full-cycle implementation of pumped storage is highly dependent on dam construction. Water conservancy engineering practitioners need to combine the actual local geographical conditions to complete the selection and construction of dams, pumps and turbines [8]. This makes civil engineering the core sector with the deepest participation depth and the longest industrial chain coverage across the whole technical route of pumped storage.

2.2. Compressed air energy storage

The compressed air energy storage method often utilizes some surplus or fluctuating electricity from nature, such as wind and solar power, to compress the air and store it in storage devices, converting electrical energy into the internal energy of the air for storage [9]. During peak electricity consumption periods, the storage devices release high-pressure air and then drives a turbine to generate electricity.

This energy storage device is a key facility used to store high-pressure air. Its gas storage site can rely on underground salt caverns, hard rocks, or depleted oil and gas reservoirs. On the ground, compressor workshops, generator infrastructure, and heat exchange systems need to be built. For example, some regions lack favourable geological conditions such as salt rock, saline aquifers or abandoned mines yet still have construction demands. South Korea built a 100-meter-deep experimental compressed air energy storage gas-storage test facility in 2011, which is a fact that indicates that artificially-excavated hard-rock caverns have become an important option for underground air storage [10]. Before the energy storage device based on the above scheme is set up, a comprehensive geological survey is required to conduct an in-depth study of the most basic facilities and geological conditions involved in the natural gas storage device. Therefore, geotechnical engineering plays a vital role in this energy storage technology.

2.3. Battery energy storage station

Lithium-ion batteries show noteworthy energy density and efficiency characteristics, making them the preferred technology for large-scale stationary energy storage applications. Battery energy storage station is characterized by thermal runaway, gas generation, overpressure. A large amount of

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data shows that when the battery components undergo exothermic decomposition reactions within the battery, the temperature will rise exponentially at a rate exceeding the heat dissipation capacity, resulting in the release and accumulation of toxic or explosive gases, which can cause fires [11]. Therefore, the concept of sustainable and fire-resilient (SAFR) buildings has been introduced to achieve the sustainable goals (including reducing energy consumption, decreasing material usage, increasing the utilization of renewable energy sources, and improving indoor environmental quality), while also meeting the resilience targets for fire incidents. In this way, it can achieve explosion-proof pressure relief walls, fire separation distances, large-tonnage battery rack foundations, and anti-leakage floors for corrosive electrolytes. The SAFR can also optimize the building layout and improve factors such as personnel occupancy and evacuation conditions, thereby reducing the occurrence of fires [12]. Hence, its implementation is of vital importance for battery energy storage.

Beyond fire resilience, the implementation of battery energy storage stations relies on a series of civil engineering measures covering site layout, structural design, and construction. Regarding site layout, battery enclosures should be centrally located outdoors, isolated from other functional areas, and positioned upwind relative to the direction of the least frequent wind; fire separation distances must comply with standards. Specifically, a minimum of 20 m from production buildings, 25 m from oil-immersed main transformers, and 5 m from emergency oil pits [13]. Additionally, the site must be divided into fire zones, with each zone typically having a rated energy capacity not exceeding 50 megawatt-hours and a minimum separation of 10 m between adjacent zones. In terms of structural design, heavy battery racks and prefabricated enclosures exert concentrated loads on the foundations; since uneven foundation settlement can cause rack deformation, crush battery casings, and trigger internal short circuits, foundation design must address both load-bearing capacity and differential settlement. In seismic zones, seismic verification is required for battery racks, enclosures, and busbar connections, alongside adequate anchoring measures to resist overturning and sliding, thereby preventing equipment collapse and electrolyte leakage during an earthquake. For enclosed battery rooms, pressure relief panels and explosion vents must be installed in accordance with National Fire Protection Association 68 principles to ensure that deflagration pressure resulting from thermal runaway is released in a controlled direction, away from personnel areas and adjacent equipment [14]. Regarding site grading and drainage, rainwater and firefighting water must be diverted away from battery areas; a peripheral fire access road with a minimum width of 4 m is required, complemented by emergency drainage facilities and oil pits to collect contaminated firefighting wastewater and transformer oil, preventing soil and surface water pollution.

2.4. Hydrogen storage

At the gigawatt-hour to terawatt-hour scale, large-scale hydrogen storage is currently regarded as an important component of the cost-optimal solution for building a 100% variable renewable energy system [15]. Leong et al. introduced a hydrogen storage method called lined engineered tunnels with the construction methods typically employed in conventional tunnels, such as those used in subways and underground highways [16]. The research has shown that among various engineered cavity configurations for lining, the engineered vertical shaft in soft rock strata demonstrates outstanding application prospects. It has lower drilling costs and simpler excavation procedures, and can further enhance safety and economy compared to other schemes. For medium-hard rock strata, the lined rock caverns are more suitable solutions.

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Salt cavern is another method of hydrogen storage, which includes its rapid injection and extraction capabilities, as well as its greater cost-effectiveness compared to other hydrogen storage methods (such as hydrogen storage in depleted oil and gas reservoirs, aquifers, and above-ground storage tanks), and its minimal environmental impact. But, when constructing underground salt cavern hydrogen storage systems, special attention should be paid to the hydrogen embrittlement risk and the issues arising from the interaction between hydrogen flow and infrastructure [17].

3. Contributions of civil engineering and the challenges

Pumped storage facilities are equipped with two reservoirs for matched use. One is the upper reservoir, and the other is the lower one. Both reservoirs are impounded by dams, and the two reservoirs are connected by long water conveyance tunnels and shafts. These underground structures are directly excavated in rock or soil mass. This combination of "dual reservoirs + underground water conveyance structures" is the standard engineering layout for current pumped storage projects. The Panlong pumped-storage power station is a typical domestic implemented engineering case located in Chongqing, China, and this project is fully equipped with the upper reservoir, the lower reservoir, water conveyance systems, power generation systems and other auxiliary facilities [18].

The water conveyance tunnels of pumped storage are exposed to fluctuating high internal water pressure for a long time, and are the parts with the highest failure risk in the whole project. A clear failure evolution rule has been summarized in relevant fields. If the hoop tensile stress on the inner lining surface exceeds the tensile strength of concrete, longitudinal cracks will appear in the concrete lining. These open cracks will make the internal water pressure spread directly to the outer surface of the lining, and this will further cause obvious local water leakage problems. If these defects are not repaired in time, the leaked water will continuously erode the filler materials inside the structural joints, and finally, the risk of hydraulic jacking failure in the surrounding rock will rise sharply [19].

Pumped storage is currently the most technically mature and largest-scale mechanical long-duration energy storage route, but its implementation is highly dependent on natural elevation difference and sufficient surface water resources, with extremely strict site selection constraints. As another core mechanical long-duration energy storage technology, compressed air energy storage does not need to adapt to large elevation difference terrain and large-scale surface water bodies. It can complete energy storage relying on underground closed caverns, and its core engineering constraints have shifted from traditional hydraulic structures to the stability and tightness control of underground geotechnical storage caverns. In the lined rock cavern developed for compressed air energy storage, the surrounding rock mass is subject to sustained high internal pressure loads for a long time. Under long-term cyclic loading and unloading brought by repeated air charge-discharge cycles, the inherent mechanical performance of the rock mass will gradually degrade, which will pose a direct threat to the long-term operational stability of the cavern. The pre-existing discontinuities inside the rock matrix will propagate continuously, and new secondary cracks will also form at the same time, which will eventually lead to varying degrees of damage across the whole rock mass domain [10]. The damage risk caused by rock mass degradation is not completely uncontrollable, and mature corresponding controllable engineering logic has been formed in practical operations. The lining structure may crack under long-term cyclic internal pressure, and the resulting leakage can be effectively captured via pre-installed monitoring units. The synthetic sealing layer can only reduce the tensile stress on the lining, and cannot completely cancel the load-bearing effect of the surrounding rock. Potential leakage anomalies of the storage cavern can also be identified in time through pressure monitoring outside the lining [20].

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The long-term operation safety of all underground gas storage caverns is fundamentally determined by the caprock sealing performance and fault development conditions. Therefore, the caprock integrity evaluation and fault avoidance for salt cavern hydrogen storage and compressed air energy storage caverns are the core control links in the design phase of underground geotechnical engineering. For salt dome-type caverns with complex vertical tectonic evolution, special mechanical stability verification of the caprock is required based on detailed engineering geological survey data. For bedded salt rock areas, mature in-situ stress simulation methods for underground caverns can be adopted to complete the quantitative evaluation. Civil engineering site selection specifications mandate complete avoidance of fault zones, to prevent pre-existing fractures from expanding into gas leakage channels under cyclic charge-discharge loads [17].

The leakage risk of battery energy storage systems follows a clear causal transmission chain: internal faults such as battery degradation and thermal runaway first trigger cell seal failure, then toxic leaked media spread outward, and finally cause water and soil pollution as well as secondary safety accidents. Targeting this transmission path, source prevention is the top-priority measure. Abuse tests are conducted to select cells and pack schemes adapted to operating conditions. Designs with low gas emission and no cell-to-cell thermal runaway propagation under extreme conditions are prioritized for scenarios with limited ventilation and installation space. A supporting thermal management system keeps battery temperature within a reasonable range, greatly reducing the probability of cell faults and fundamentally cutting off the trigger condition for leakage. When leakage does occur unavoidably, terminal disposal focuses on blocking the pollution diffusion path. All contaminated fire-fighting water is fully collected, and the accident impact is strictly confined within the energy storage protection zone. This prevents corrosive leaked fluid from infiltrating soil and mobilizing heavy metals to cause long-term environmental hazards, and stops risks from spreading to surrounding infrastructures, finally realizing full-process closed-loop management of leakage risks. The following Figure 1 illustrates the pollution and risks associated with lithium-ion battery incidents [21].

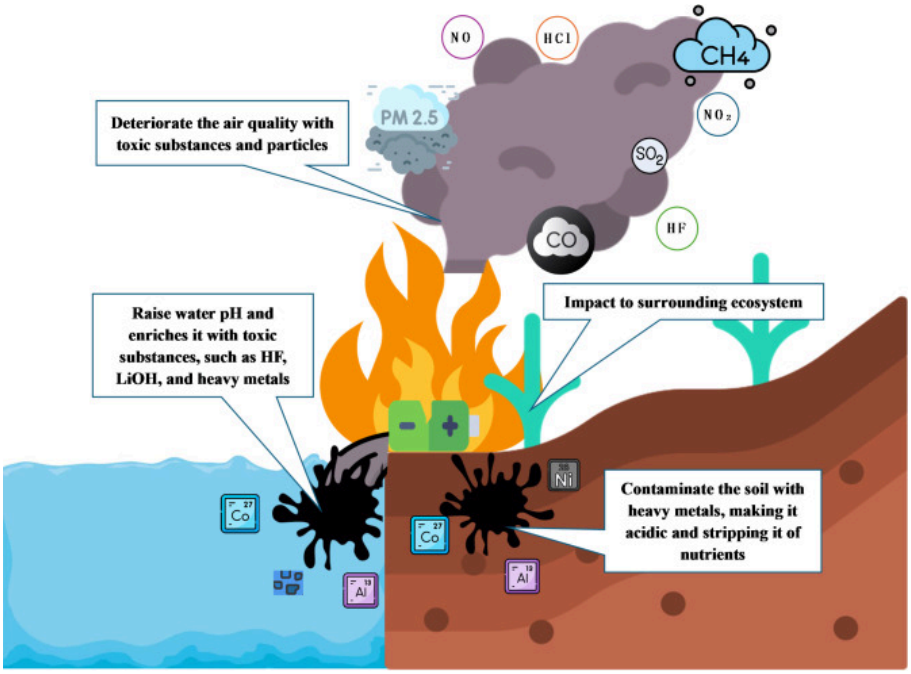

Figure 1. Environmental impacts of lithium-ion battery fires and electrolyte leakage [adapted from ref [21] with permission from Springer Nature]

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Leakage prevention and control of electrochemical energy storage have formed a complete closed-loop system covering risk identification, source blocking and terminal management. In the large-scale underground hydrogen storage scenario, seal failure caused by pipeline hydrogen embrittlement is a core safety risk at the same severity level as battery thermal runaway. In response to the practical application requirements of salt cavern hydrogen storage engineering, China has completed a series of key technological breakthroughs at the material and process levels: hydrogen-induced damage reduction is realized through steel heat treatment, vanadium copper alloys are adopted for material modification, and shot peening is applied to regulate and enhance surface stress. Meanwhile, novel hydrogen barrier coatings and hydrogen embrittlement-resistant aluminum alloys are developed in a coordinated manner to comprehensively improve the overall hydrogen embrittlement resistance of transmission pipelines, fundamentally cutting off the trigger condition for high-pressure hydrogen medium leakage and forming an active safety technical scheme adapted to the underground long-duration hydrogen storage scenario [22].

4. Conclusion

This paper reviews the engineering characteristics of four mainstream energy storage technologies. Civil engineering is not a supporting role in energy storage projects. It runs through the entire process of site survey and selection, structural design, material selection, and construction. It directly determines the feasibility, safety, and economic viability of energy storage projects. All energy storage routes rely on precise geological surveys, durable structural materials, and qualified construction quality to turn blueprints into reliable physical facilities.

It should be acknowledged that the paper primarily adopts literature review to integrate the application of civil engineering in energy storage. Some emerging energy storage technologies are still in the experimental stage. Available engineering examples and long-term operational data are limited. Future work can incorporate empirical validation based on specific pumped hydro storage and compressed air energy storage projects, promote the intersection of civil engineering, energy, and environmental disciplines, include ecological impact and social acceptance in the evaluation dimensions, and gradually form specialized design codes and multi-dimensional assessment systems tailored for energy storage scenarios.

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