The Impact of Compressed Air Storage Technology on the Environment During a Lifecycle

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Abstract: Compressed Air Energy Storage (CAES) technology offers an effective method for energy storage during periods of low demand by utilizing underground mines to store compressed air, which is then released when energy is needed. As new energy technologies rapidly advance and the integration of renewable energy sources such as wind and solar power into the power grid increases, the adoption of CAES has become more widespread. This technology stands out due to its minimal physical space requirements, extensive load capacity range, cost-effectiveness, and low operational and maintenance costs. However, for strategic planning, it is critical to perform a comprehensive lifetime evaluation of environmental contaminants associated with CAES. But the construction and maintenance activities of CAES systems can lead to significant environmental degradation, including solid waste, exhaust gas, wastewater pollution, and land destruction. Furthermore, the process of demolishing structures generates waste and pollutants, with dust and noise pollution present in multiple phases. These environmental impacts present substantial challenges to the sustainable deployment of CAES technology. This paper explores the dual nature of CAES, highlighting both its advantages and its environmental concerns. We conduct a thorough analysis of the lifecycle environmental impacts of CAES systems, focusing on pollution and resource depletion during construction, operation, maintenance, and demolition. Moreover, we propose some potential solutions to mitigate these environmental impacts, emphasizing the need for sustainable construction practices, advanced pollution control technologies, and efficient resource management. By addressing these issues, CAES can be optimized to support the growing demand for renewable energy storage while minimizing its ecological footprint.

1 INTRODUCTION

CAES is a promising technology for large-scale energy storage. It has the potential to advance the development of renewable energy and enhance system flexibility. Renewable energy is anticipated to have a significant impact on energy transformation in the future. However, during its implementation, it is critical to consider and address the potential environmental consequences. Appropriate measures for environmental protection should be implemented. The current research on the environmental effects of CAES systems is insufficient and requires more extensive investigation. This text presents a concise overview of the environmental impact of compressed air energy storage over its entire life cycle. It also offers recommendations for appropriate ways to address these impacts.

2 POLLUTION DURING CONSTRUCTION

During the preliminary phase of the CAES system, a significant amount of infrastructure must be prepared as shown in the table 1.

Table 1 The CAES system largely consists of the following components

Components	Raw materials
Compressor	Stainless alloy
Gas storage tank	Carbon steel or alloy steel
Pipes and fittings	Stainless steel or composite materials
Heat exchanger	Stainless alloy
Sealing element	Rubber
Control components	Plastic Ceramic

Based on the information provided, creating a compressed air energy storage system requires a

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substantial number of raw materials, with various alloys being the most important. Alloys commonly use components such as carbon, manganese, silicon, nickel, and others to enhance their hardness, corrosion resistance, and other properties. The following contaminants may be present during the alloy formation.

2.1 Solid Waste

2.1.1 Smelting Slag

The smelting of alloys produces a significant quantity of smelting slag, primarily made up of oxides and sulfides. Some smelting slag may include large quantities of heavy metals and radioactive elements. For starters, the disposal and storage of a large amount of slag not only occupy a lot of lands but also cause serious environmental problems (Kong et al, 2023). Furthermore, waste residue contributes to soil erosion, which leads to disasters like mudslides. Furthermore, when acidic rainwater meets acidic wastewater containing a range of heavy metal components found in smelting slag, it can contaminate surrounding water bodies, causing environmental deterioration. Ultimately, failure to efficiently recover smelting slag may result in the waste of important resources.

2.1.2 Coatings

Alloy goods sometimes require surface plating or coating treatment, which can eventually delaminate with use. Electroplating sludge refers to the solid waste produced during the treatment of electroplating wastewater. This waste contains heavy metal components that exhibit properties such as high resistance to heat, a strong capacity to move, and resistance to biodegradation. Hence, the potential for heavy metals to leach from electroplating sludge is considerable, leading to rapid accumulation within the food chain and presenting a significant environmental hazard (Shi & Li, 2024).

2.2 Waste Gas

Exhaust gas emissions during smelting and casting processes Only a few enterprises have extensive waste gas collection and treatment systems in place for alloy metal smelting and casting. Most enterprises use induced draft fans or directly discharge gases, which frequently contain high levels of metal dust, nitrogen oxides, and sulfur oxides, posing a considerable risk to the local air environment (Zhou, 2005).

2.2.1 Exhaust Gas Emissions During Surface Treatment

Surface treatment of alloy products involves various processes such as anodizing, spray painting, and electroplating. These processes produce acid mist and exhaust gas, both of which contain heavy metal-containing contaminants. Failure to efficiently collect and handle these exhaust gases can have a negative impact on operators' health and cause environmental hazards such as acid rain and photochemical smoke (Zhang, 2019).

2.2.2 Emissions Produced During the Welding and Cutting Processes

The laser cutting process generates a substantial amount of exhaust gas, mainly consisting of nitrogen oxides, volatile organic compounds, and particle debris. Nitrogen oxides, specifically nitrogen dioxide and nitric oxide, are the main gaseous pollutants produced during laser cutting. These pollutants have the potential to significantly pollute the atmosphere. Not effective in improving air quality.

2.3 Wastewater

2.3.1 Acidic Wastewater Generated During the Smelting and Refining of Raw Materials

Waste acid and workpiece-washing water combine to form acidic wastewater. It contains a substantial amount of free acid, metal ions, and extremely acidic compounds like sulfuric acid and hydrochloric acid. Unaddressed direct discharge can disrupt the pH balance of water bodies, causing acidification and hurting aquatic biodiversity. Furthermore, acidic wastewater is highly corrosive and can deteriorate discharge pipelines, potentially leading to soil infiltration and subsequent soil acidification. The accidental introduction of acidic wastewater into drinking water sources can pose a serious risk to human health (Zheng & Zhang, 2019).

2.3.2 Heavy Metal-Containing Wastewater Generated During Aluminum Alloy Production

Aluminum alloy pre-treatment involves a variety of techniques, such as oil removal, coloring, neutralization, and sealing. These processes use corrosive liquids as raw materials, including sulfuric acid, nitric acid, and sodium hydroxide. Typically, when the anodizing treatment is completed, more chemicals enter the tank of the machinery used to wash the overflow water (Zhang, 2019).

When heavy metals, such as lead, cadmium, and mercury, enter water bodies, they can contribute to ecological issues such as eutrophication and water pollution, endangering aquatic creatures. Simultaneously, large levels of heavy metal contamination can have a negative impact on businesses such as agriculture and fishing, putting a considerable strain on both social and economic advancement.

2.3.3 Oil-Containing Wastewater Generated During Equipment Cooling and Cleaning Procedures

The process of cooling equipment will generate a substantial amount of effluent. The equipment cleaning process generates a significant amount of oily effluent. When released into the water, it forms a film of oil on the surface, obstructing the exchange of oxygen and light. This will have a severe impact on aquatic plant photosynthesis while also disrupting the aquaculture industry, resulting in the death of organisms or stunted growth and development. Certain oily wastewater is flammable and can cause fires.

2.4 Terrestrial Devastation

While the CAES systems and related amenities were constructed, land development is unavoidable. Land use has a wide range of environmental effects, which are most visible in the following areas.

2.4.1 Environmental Degradation

Zones designated for economic development, such as suburban areas, often host CAES systems. Land overexploitation degrades the natural biological environment, resulting in the loss of plant and animal habitats. The size of natural landscapes, including green spaces and wetlands, is constantly shrinking. Furthermore, certain innovations have ravaged the natural settings in which rare and endangered animals live.

2.4.2 Effects on the Landscape

The installation of cable infrastructure to support the CAES system has significantly altered the land's natural form and look. Impractical building and facility designs have had a negative impact on the surrounding landscape, causing a loss of diversity, coherence, and identity. Such alterations often bring about negative consequences like habitat loss, species decline, soil erosion, and disruption of ecosystem processes (Hajibayov, 2017).

3 ISSUES ARISING AFTER COMPLETING AND IMPLEMENTING THE CAES SYSTEM

3.1 Resource Waste

In a CAES system, power transfer is achieved by first generating high-pressure air using a compressor and then storing it in a storage tank. An expander must be employed to utilize the high-pressure air in the storage tank for performing external tasks (Sun, 2015). The increase in power is derived from the utilization of compressed air. There is a risk of energy storage material leakage in CAES systems, where high-pressure air is the principal energy storage medium. Following high-pressure air leaks, a variety of dangers can arise, Leakage can result in significant energy loss, leading to resource waste and decreased application efficiency.

3.2 Concerns Regarding Energy Usage and Emissions from CAES

Even though fossil fuel power generation is the primary source of electricity in the grid, the CAES system emits indirect carbon emissions during charging. The emissions during the whole lifecycle are mostly influenced by the operational phase, particularly during the initiation of energy storage systems and the continued need for alternative power sources during system operation. Given the variability in operational efficiency of CAES systems, it is necessary to conduct assessments of carbon consumption (Geng et al, 2022). In energy consumption assessments, the CAES technique necessitates the inclusion of compression equipment, electronic control systems, and other power-consuming devices.

4 POLLUTION PRODUCED DURING CAES SYSTEM MAINTENANCE AND UPKEEP

4.1 Resource Allocation

The expected operational lifespan of CAES systems varies from 20 to 40 years, contingent upon subsequent maintenance and management. Throughout the subsequent management procedure, the following pollutants may be present, as shown in table 2.

Table 2 Vulnerable parts required for CAES equipment operation

Compressor unit	Compressor impeller seals and bearings
Bearings heat exchange equipment	Heat exchanger tube bundle, sealing ring and valve
Electrical control system	Control board, sensors and relays.

Producing new components releases pollutants, while disposing of items can contribute to the environmental burden. Inadequate management can lead to the release of pollutants and the excessive use of resources.

4.2 Contamination Caused by Chemicals

The expected operational lifespan of CAES systems varies from 20 to 40 years, contingent upon subsequent maintenance and management. Throughout the subsequent management procedure, the following pollutants may be present.

4.2.1 Oil Pollution

CAES systems commonly utilize synthetic base oil or mineral oil as its lubricant. Mineral oil can get contaminated with a range of hazardous substances, such as heavy metals, molecules from the benzene family, and polycyclic aromatic hydrocarbons. These substances require expert gathering and processing, and any leakage can increase ecological susceptibility. When repairing electrical equipment in the CAES system, several harmful compounds, such as insulating oil, are used. Additionally, there is the concern of combustibility.

4.2.2 Pollution Caused by Toxic Substances

Regular maintenance of heat exchange equipment involves the use of chemical cleaning agents that often contain acidic and alkaline substances, such as hydrochloric acid and sodium hydroxide. Furthermore, it is possible that the gas storage tank is deteriorating and necessitates anti-corrosion treatment. The anti-corrosion coating is composed of a substantial amount of heavy metals and organic solvents, which pose environmental risks.

5 POLLUTION FROM THE DISMANTLING OF THE CAES SYSTEM

At present, the implementation of the CAES system is not widespread, and there are no instances of disassembly that adhere to the CAES lifecycle. During the time of the CAES system, the following environmental deterioration may occur. The dismantling of industrial facilities will produce a substantial quantity of construction debris. This comprises scrap steel and concrete, metal elements, and spent lubricating oil and coolant. Inadequate management not only damages the local scenery, but it also fosters the growth of bacteria and viruses, affecting the cleanliness of the surrounding environment.

6 POLLUTION IS PREVALENT AT SEVERAL STAGES

Apart from the ambient contamination, there are specific pollutants that are widespread during certain stages of the CAES lifecycle.

6.1 The Presence of Dust Particles

Blasting is employed in the construction process to extract raw materials, while the crushing, screening, and grinding of ores are significant contributors to dust pollution. During land development, the CAES system necessitates the use of specialized containers to hold compressed air at high pressures. This process may involve construction activities in mines or salt caverns, leading to the generation of a significant amount of non-dispersible dust (Liang, 2024). Dust is generated because of several activities, such as the functioning of the air filtering device, wear in the lubrication system, deposition in storage tanks, equipment maintenance, pipeline cleaning, material replacement, and dismantling processes. Furthermore, the presence of dust is inevitable during the loading and transportation. Dust pollution can lead to the following problems

6.1.1 Declining Air Quality

An escalation in dust emissions leads to a corresponding rise in the concentration of suspended particulate matter in the atmosphere. Elevated concentrations of particulate matter can hinder visibility, obstruct sunlight, and disturb individuals' daily activities and professional endeavors. Dust originating from different sources comprises a wide range of chemical constituents, which have the potential to influence the composition of pollutants present in the atmosphere. Certain toxic heavy metals or organic compounds can adhere to dust particles and disperse throughout the atmosphere. Dust particles can disperse and take in light, which can impact the optical properties of the atmosphere. This will affect the intensity of sunlight, visibility, and meteorological conditions, resulting in decreased visibility and less intense sunlight.

6.1.2 Ecological System Destruction Leading to Climate Change

Dust deposition can modify the growth of flora, disturb animal habitats, and lead to an imbalance in the ecosystem, resulting in a decrease in biodiversity. Certain anthropogenic emissions of fine particulate matter can potentially affect the production of cloud condensation nuclei, hence impacting local climate. Certain noxious heavy metals can increase in concentration and build up within the environment by means of the food chain.

6.2 Environmental Noise Contamination

At each of the above steps, noise is consistently produced, and the construction of mechanical equipment in each phase generates extra noise. For the impact of animals, including damage to wildlife physical wellbeing, vital survival mechanisms, social and reproductive processes, and habitat continuity (Teff-Seker et al, 2022). Under extreme conditions, it might lead to a decrease in the population of animals. Moreover, plant growth can be adversely affected by high-intensity noise, leading to decreased photosynthetic efficiency and disruption of normal plant development. In general, environmental contamination exhibits complex interdependencies, with various forms of pollution in the environment being interconnected. Environmental pollution often worsens the severity of major environmental problems.

7 SUGGESTION

To address the aforementioned concerns, the following section will provide a concise summary and solutions.

7.1 Streamlining Industrial Equipment Connections to Improve Performance

The emphasis should be on using auxiliary goods that are nontoxic, benign, or have little toxicity or damage. Utilizing cutting-edge industrial technologies and equipment to improve resource efficiency and reduce polluting emissions. Install treatment facilities for wastewater, exhaust gas, solid waste, and chemical pollutants that meet discharge standards. Consistently maintain and improve governance equipment to ensure that processing efficiency meets the required criteria.

7.2 Maximizing Land Utilization

The CAES system can use defunct subsurface mines or salt caverns to store energy, allowing for the recycling of existing resources while reducing the requirement for further land use. Additional research can be conducted on the development and application of subsurface energy storage regions in CAES to increase energy storage capacity per unit area while decreasing land use intensity.

7.3 Regulation of Carbon Emissions

The CAES system does not directly release fossil fuels; rather, the quantity of carbon emissions it creates is ultimately determined by the source of the electricity used. CAES can be combined with renewable energy sources such as wind and solar to achieve carbon-free operation. Carbon capture and storage technology can be used in governance to address a small portion of the inevitable carbon emissions. The CAES system effectively reduces carbon emissions through processes such as absorption, separation, compression, and underground storage, resulting in near-zero emissions.

7.4 Measures to Reduce Noise Pollution

Initially, a well-planned site location for the CAES system, located away from areas sensitive to noise, such as residential areas, can considerably reduce the negative effects on the surrounding environment. To control the noise level of equipment, select appropriate equipment and prioritize utilizing equipment that generates less noise. Measures such as placing sound insulation covers and silencers on the equipment casing and base can also help to lessen the noise impact.

7.5 Measures to Reduce Dust Pollution

During the land development and demolition phases, materials with low dust emissions, such as rock salt, are used to reduce dust creation. To prevent dust particles from dispersing, apply water at regular intervals. During the operational phase, precise control techniques are used to effectively encapsulate dust-producing machinery such as compressors and turbines, preventing dust from escaping. Perform frequent inspections and maintenance to ensure that all enclosed systems remain airtight. Implement extremely effective dust collection systems at dust-producing places, such as bag filters, scraper dust collectors, and other appropriate equipment. To reduce dust dispersion, trees and plants should be planted around the factory and on either side of the road.

7.6 Waste Management

To reduce waste production, implement a CAES equipment recycling system, as well as disassemble and recycle used equipment. Implement a consistent strategy for solid waste and chemical management throughout the CAES system's development and operation, ensuring proper disposal of all waste categories.

8 CONCLUSION

More specifically, CAES emits zero direct greenhouse gas emissions when in operation, with only a tiny amount of indirect emissions from the power grid. Nonetheless, the extraction and processing of materials such as aluminum alloys would cause significant pollution during the stages of extracting raw materials and producing equipment. Furthermore, the development and maintenance of CAES systems will necessitate a certain number of resources and electricity. In order to lessen the ecological imprint of CAES, future research should focus on the following aspects. The primary objective is to develope novel lightweight materials for gas storage tanks to reduce resource utilization in equipment construction. The second objective involves improving the energy conversion efficiency of the CAES system by optimizing its design and operation mode and closely integrate the CAES system with renewable energy sources to reduce grid emissions. The final objective is to investigate the feasibility of using waste heat in CAES systems to improve overall energy efficiency, and improve the environmental impact evaluation and monitoring of the CAES system during its whole lifecycle. Implementing the procedures will increase the environmental sustainability of CAES technology, contributing significantly to sustainable development.

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