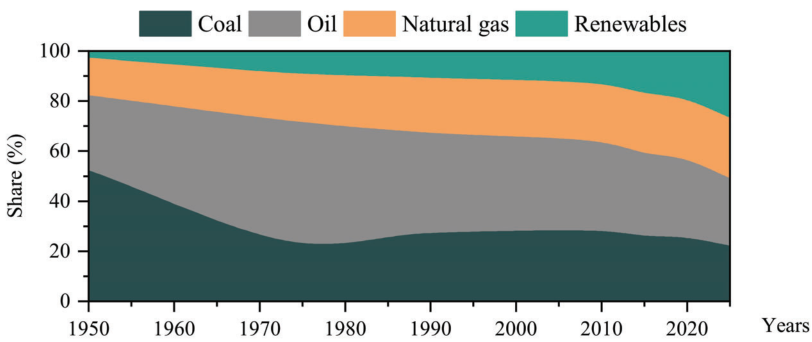
1 Introduction

1.1 Motivations and Objectives

In response to global climate change and the carbon neutrality target, the large-scale integration of renewable energy sources, especially wind and solar power, has become a major trend in the transition of the energy system (Hou et al., 2023, Wang et al., 2021). Over the long term, the global primary energy mix has become increasingly diversified, while the share of renewables has risen markedly in recent decades (**Figure 1.1**). However, the inherent intermittency and variability of renewable energy create major challenges for real-time power system balancing. This has led to an urgent need for large-capacity and long-duration energy storage technologies to improve system flexibility and resilience (Xie et al., 2023, Adeyinka et al., 2024).



(Data sources: BP Statistical Review of World Energy, IEA World Energy Outlook)

Figure 1.1 Global primary energy consumption share by source.

According to the storage medium and deployment space, energy storage technologies can be broadly classified into surface energy storage and underground energy storage (**Figure 1.2**). Among them, large-scale underground energy storage is widely regarded as a key option for peak shaving and load balancing in future power systems because of its large storage capacity, long service life, high safety, and relatively low unit cost (Huang et al., 2024, Chen et al., 2023b).

Salt caverns are particularly suitable for use in both compressed air energy storage (CAES) systems and underground hydrogen storage (UHS) systems. Owing to their excellent sealing capacity, structural stability, and relatively low construction cost, salt caverns have already been successfully applied in projects such as Huntorf in Germany, McIntosh in the United States, and Jintan and Feicheng in China (Wan et al., 2023, Matos et al., 2022).

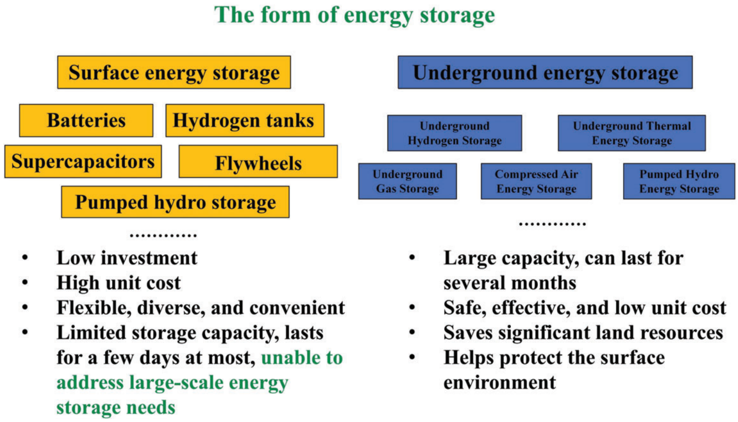


Figure 1.2 Comparison of surface and underground energy storage.

Despite their strong potential for large-scale and long-duration storage, underground salt cavern energy storage technologies still face several critical challenges in both research and engineering practice. First, existing evaluation frameworks often focus on a single thermodynamic or efficiency indicator, while the coupled effects of site resource endowment, economic cost, environmental impact, and technology maturity remain insufficiently addressed. Recent studies have introduced integrated energy, exergy, exergoeconomic, and exergoenvironmental (4E) analyses, showing that single-dimensional assessment cannot fully capture the overall merits and limitations of a system (Esmaeilion et al., 2024, Bayat et al., 2025). Although conventional CAES has reached commercial deployment and exhibits relatively high technology maturity, its dependence on natural gas combustion during discharge often results in weaker environmental performance than low-carbon alternatives involving hydrogen or fuel-free thermal compensation (Ma et al., 2024, Jankowski et al., 2024).

Second, CAES and UHS involve different forms of energy conversion, namely mechanical energy and chemical energy. Analysis based only on energy conservation cannot adequately reflect differences in energy quality among systems. Exergy analysis is therefore required to identify irreversibility and exergy destruction, and to provide a more general basis for cross-technology comparison (Safaei and Aziz, 2017, Cao et al., 2023).

Third, the engineering feasibility of underground energy storage is highly dependent on site-specific conditions. For salt cavern UHS and CAES, geological sealing capacity, burial depth, formation thickness, salt quality, and related engineering conditions directly affect storage pressure, equipment configuration, cavern construction cost, and operational safety. As a result, performance evaluation without site-specific constraints is often of limited value for practical engineering design and technology selection (Taiwo et al., 2024, Wu et al., 2024).

To address these issues, this study develops an integrated Site-Performance-Technology Maturity (S-4E-T) evaluation framework for large-scale underground energy storage systems, thereby enabling a unified analysis of site constraints, theoretical performance, and practical deployability. Specifically, the study first establishes a site evaluation system for salt cavern underground energy storage and defines the transformation of site conditions into boundary inputs for subsequent performance analysis. It then performs a comparative 4E evaluation of five representative underground energy storage and power generation pathways, namely conventional compressed air energy storage (C-CAES), adiabatic compressed air energy storage (A-CAES), hydrogen-heated compressed air energy storage (HH-CAES), hydrogen energy storage coupled with gas turbine power generation (HES-GT), and hydrogen energy storage coupled with fuel cell power generation (HES-FC), under unified site constraints and system boundaries. Furthermore, a quantitative technology maturity assessment method is developed based on bibliometric and patentometric data to identify the maturity levels and stage characteristics of different pathways. On this basis, a technology-maturity-based realism correction is introduced and combined with the Analytic Hierarchy Process–Technique for Order Preference by Similarity to Ideal Solution (AHP–TOPSIS) method for comprehensive decision analysis, in order to support technology selection, staged deployment, and engineering implementation for salt cavern underground energy storage projects.

1.2 State of the Art and Scientific Challenges

1.2.1 Development and Evolution of CAES and Hydrogen Storage Power Generation

C-CAES systems (**Figure 1.3**) store excess electricity by using it to power compressors that compress air, which is then stored in underground salt caverns, abandoned mines, or specially designed storage reservoirs during periods of low electricity demand, such as at night or when there is an excess of renewable energy (Li et al., 2024, Bazdar et al., 2022). When electricity demand peaks, the compressed air is released and heated with natural gas, driving a gas turbine to generate electricity. However, C-CAES systems face significant efficiency challenges due to substantial heat losses and the need for additional thermal input (Yu et al., 2024, Zhang and Zhao, 2025). For example, the Huntorf CAES Plant in Germany achieves a cycle efficiency of 42% by using natural gas to heat the air before it drives the turbine. In contrast, the McIntosh CAES Plant in the United States improves its cycle efficiency to 54% by implementing waste heat recovery systems to reclaim heat from exhaust gases (Budt et al., 2016).

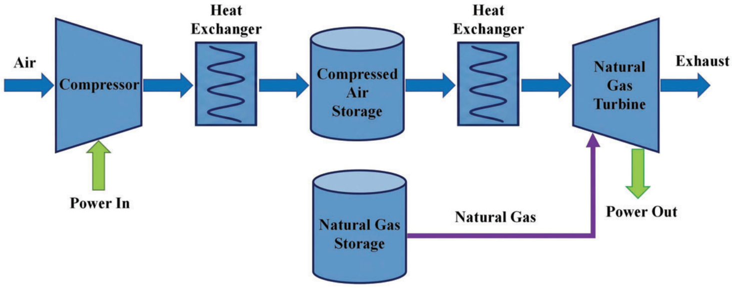


Figure 1.3 Schematic diagram of C-CAES system.

A-CAES represents an advancement over traditional CAES technology by mitigating heat loss during the energy storage process (Chen et al., 2026). In A-CAES systems (**Figure 1.4**), the heat generated during air compression is captured and stored, and is subsequently reused to heat the compressed air during discharge, thereby avoiding the need for external fuel input (Zuo et al., 2025, Tola et al., 2022). In 1976, the Pacific Northwest Laboratory in the USA conducted the first analysis of the technical and economic feasibility of fuel-free compressed air energy storage (Kreid, 1976). However, due to immature technology and high costs, the A-CAES concept was not initially implemented in CAES power plant projects (Zhou et al., 2019). Since the early 21st century, growing concern over climate change and continued advances in renewable energy systems have renewed interest in A-CAES and promoted the development of more advanced thermal management and heat storage configurations (Bullough et al., 2004, Pickard et al., 2009). Among these, advanced adiabatic compressed air energy storage (AA-CAES) can be regarded as an enhanced form of A-CAES, featuring more efficient heat recovery and thermal storage arrangements, and in some cases multi-stage energy conversion, which may further improve overall system efficiency (Zhang et al., 2014). Thermodynamic and dynamic simulations have suggested that such advanced adiabatic systems could achieve overall efficiencies above 70% (Mozayeni et al., 2017, Mei et al., 2015). Nevertheless, despite considerable theoretical and experimental progress, fully commercial operation of such systems remains limited (Xu et al., 2025). In this study, these advanced adiabatic configurations are discussed within the broader category of A-CAES.

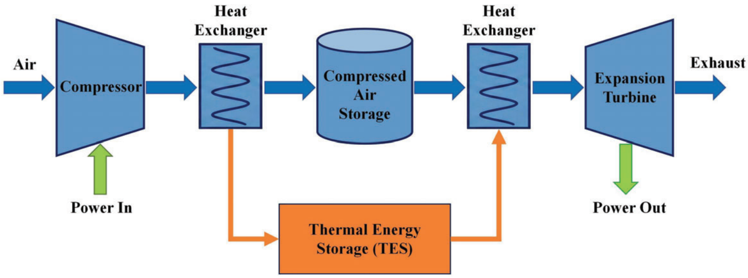


Figure 1.4 Schematic diagram of A-CAES system.

To reduce greenhouse gas emissions associated with the operation of CAES technology, an effective strategy involves integrating the system with hydrogen storage. Ma et al. (2024) analyzed the impact of using natural gas-hydrogen mixtures as fuel for CAES systems. They found that increasing the hydrogen proportion in the mixture significantly enhances the overall performance of the CAES system and reduces exergy destruction in the combustor. Utilizing green hydrogen as an energy source instead of natural gas, the HH-CAES system (**Figure 1.5**) can meet thermal energy demands while substantially decreasing carbon dioxide and other pollutant emissions (Khaitan and Raju, 2012, Alirahmi et al., 2021).

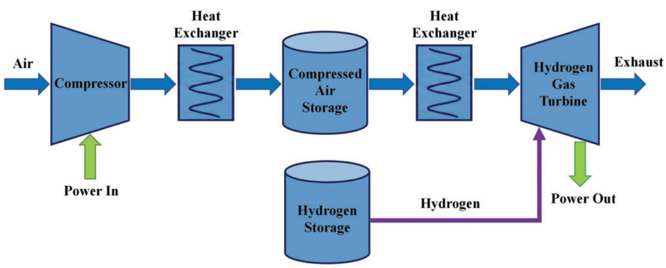


Figure 1.5 Schematic diagram of HH-CAES system.

With the compressed air subsystem removed, HH-CAES can be reconfigured as a dedicated hydrogen energy storage and power generation system (HES-GT, **Figure 1.6**). In this setup, electrical energy is first converted into chemical energy and stored as hydrogen. When electricity is needed, the stored hydrogen is supplied to either a hydrogen gas turbine or a fuel cell, facilitating efficient conversion back to electrical energy.

In a hydrogen gas turbine power plant, pure hydrogen is combusted to produce high-temperature, high-pressure gases. These gases drive the turbine blades, which, in turn, rotate the connected generator, converting mechanical energy to electrical power (Nemitallah et al., 2025, Alnaeli et al., 2023). The primary combustion product is water and no direct CO_2 is generated; however, high-temperature hydrogen combustion can still lead to NOx formation. (Nazari et al., 2022). Additionally, the high temperatures from hydrogen combustion elevate water vapor content, potentially affecting the heat transfer efficiency and material stability within the gas turbine (Zhou et al., 2024). These issues impose higher performance demands on turbine components and stricter operational and environmental conditions.

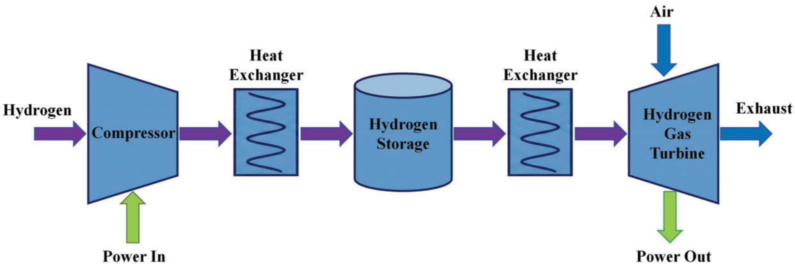


Figure 1.6 Schematic diagram of HES-GT system.

In contrast, a hydrogen fuel cell power plant generates electricity using hydrogen fuel cell technology (HES-FC, **Figure 1.7**), characterized by its cleanliness, quiet operation, and efficiency of over 60%, regardless of weather conditions, with minimal emissions (Fan et al., 2021, Edwards et al., 2008). The core components of a hydrogen fuel cell include the anode (negative electrode), cathode (positive electrode), and electrolyte. At the anode, hydrogen molecules are split into protons (H^+) and electrons (e^-) by a catalyst. Electrons flow through an external circuit to the cathode, generating an electric current, while protons pass through the electrolyte to the cathode. At the cathode, oxygen (O_2) combines with protons and electrons to form water (H_2O), producing a continuous electric current that can power various electrical devices or be fed back into the grid (Fan et al., 2021, Singla et al., 2021).

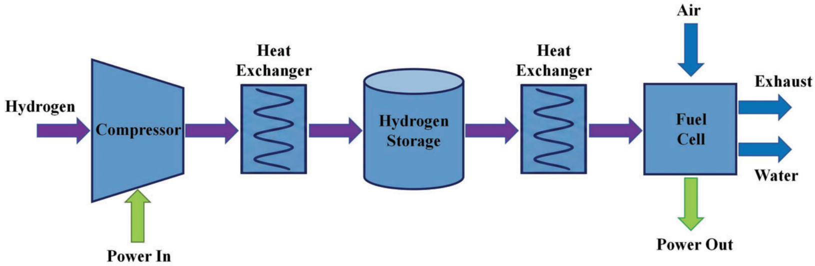


Figure 1.7 Schematic diagram of HES-FC system.

In summary, drawing on previous research (Huang et al., 2025, Beck et al., 2024, Klaas, 2023), **Table 1.1** outlines the five CAES and hydrogen storage power generation systems analyzed in this study. Salt caverns are considered ideal storage sites for compressed air or hydrogen due to their excellent sealing properties, structural stability, and relatively low cost. In fact, notable CAES facilities, such as the Huntorf CAES Plant in Germany, the McIntosh CAES Plant in the United States, and those in Feicheng, Jintan, and Yingcheng in China, utilize salt caverns for compressed air storage. Accordingly, this study also selects salt caverns as the primary storage medium for the examined compressed air and hydrogen storage projects. Given the complexities of hydrogen production, this research focuses solely on the storage and power generation stages.

Table 1.1 Overview of five CAES and hydrogen-based power generation systems.

Abbreviation	Description	Storage Medium	Power Generation Method
C-CAES	Conventional compressed air energy storage	Compressed air	Natural gas turbine
A-CAES	Adiabatic compressed air energy storage	Compressed air and heat	Expansion turbine
HH-CAES	Hydrogen-Heated compressed air energy storage	Compressed air and hydrogen	Hydrogen gas turbine
HES-GT	Hydrogen energy storage coupled with gas turbine power generation	Hydrogen	Hydrogen gas turbine
HES-FC	Hydrogen energy storage coupled with fuel cell power generation	Hydrogen	Fuel cell

1.2.2 Methodological Development of 4E Evaluation and Multi-Objective Optimization

The methodology for energy system evaluation has evolved continuously from single-efficiency indicators to multidimensional integrated assessment. Early studies were mainly based on the first law of thermodynamics and employed energy analysis, which focuses on energy conservation and system energy utilization efficiency. Its main advantages lie in its intuitive physical meaning and relatively simple calculation, making it a useful basis for system design and operational performance evaluation (Blok and Nieuwlaar, 2016, Müller, 2007). However, energy analysis essentially emphasizes the quantitative balance of energy and is therefore unable to capture differences in energy quality among different forms of energy or to reveal the sources of irreversible losses during energy conversion processes (Park et al., 2014). As a result, energy analysis alone is often insufficient for in-depth optimization and cross-technology comparison of complex energy systems.

With the broader application of the second law of thermodynamics in system engineering, exergy analysis has gradually become an important tool for identifying system performance bottlenecks (Sieniutycz and Shiner, 1994). Compared with energy analysis, exergy analysis quantifies the loss of useful work potential during energy conversion from the perspective of energy quality, namely irreversibility or exergy destruction, and thus helps identify the actual weak points in overall system efficiency and key components (Kazem et al., 2025, Tsatsaronis, 1999). More importantly, exergy analysis can indicate not only where losses occur, but also why they occur, thereby providing a more rigorous basis for system optimization than energy analysis alone (Shamoushaki et al., 2021).

However, pursuing thermodynamic optimality alone often leads to increased system complexity, more demanding equipment configurations, and higher initial investment, resulting in a clear conflict between efficiency improvement and economic feasibility (Chu et al., 2020, Boldyryev et al., 2025). To address this issue, exergoeconomic analysis, also referred to as thermoeconomics, was developed on the basis of exergy analysis (Tsatsaronis and Winhold, 1985). By establishing correspondences between exergy flows and cost flows, this method allocates capital, operation and maintenance, and fuel costs to individual exergy streams, thereby enabling the calculation of unit exergy cost and product cost, as well as the identification of thermodynamic inefficiencies responsible for cost increases (Sciubba, 2001, Sciubba, 2024). In this way, exergoeconomic analysis provides a unified framework for linking thermodynamic performance with economic input and supports the transition from high-efficiency design to cost-effective design in energy systems (Wang, 2025).

Since the beginning of the 21st century, global climate change and low-carbon transition goals have significantly increased the importance of the environmental dimension in energy system evaluation (Blanco et al., 2020). Traditional thermodynamic and economic assessments cannot adequately reflect the full life-cycle ecological burden of a system. Under this context, exergoenvironmental analysis, which incorporates the concept of life cycle assessment (LCA), has gradually emerged and developed. This method maps environmental burdens, such as greenhouse gas emissions, resource depletion, and toxicity potential, onto system exergy streams and component levels, thereby enabling the decomposition, attribution, and tracing of environmental impacts throughout the process. It further helps identify the main contributors to environmental burden and their coupling with thermodynamic irreversibility (Jalili et al., 2022, Nourpour et al., 2023).

On this basis, the evaluation paradigm for energy systems has further expanded from local thermodynamic assessment dominated by energy or exergy analysis to a more integrated framework combining energy, exergy, economic, and environmental dimensions. In the literature, this framework is commonly referred to as 4E evaluation (Qi et al., 2024, Zhang et al., 2025c, Zhang et al., 2025b). Within this framework, energy analysis is used to describe the overall level of energy utilization and the matching relationship between inputs and outputs; exergy analysis reveals losses in energy quality and the sources of irreversibility; exergoeconomic analysis characterizes the coupling between efficiency improvement and cost penalty; and exergoenvironmental analysis traces environmental impacts to specific components and processes (Ahmadi et al., 2025, Wang et al., 2019). These four dimensions are complementary and together form a core methodological basis for the comprehensive evaluation of complex energy systems.

With the continuous growth of computational capability, improvements in system modeling accuracy, and the rapid development of intelligent optimization algorithms, 4E evaluation has become increasingly integrated with multi-objective optimization, promoting a methodological shift from performance diagnosis to integrated design and decision support (Kayes et al., 2024, Prajapati et al., 2024). This shift has been enabled in part by the maturity of optimization algorithms such as NSGA-II, MOPSO, and ABC (Mei et al., 2024, Shamoushaki et al., 2021). In such studies, system efficiency or exergy efficiency, unit cost, environmental indicators, and other operational constraints are often incorporated simultaneously as objective functions or constraints. By searching for Pareto fronts in a multidimensional objective space, these methods reveal conflicts and trade-offs among evaluation targets and provide candidate solutions under different decision preferences (Chen et al., 2022, Su, 2022).

In recent years, the application of 4E evaluation and multi-objective optimization has continued to expand across various integrated energy systems. Existing studies have shown that this framework can not only identify critical loss sources and optimization priorities from thermodynamic, economic, and environmental perspectives, but also reveal differences in overall system performance under different operating conditions and external constraints, thereby supporting integrated design and engineering decision-making for complex energy systems (Nourpour et al., 2023, Assareh et al., 2023).

Overall, the methodology of energy system analysis has evolved along a clear path, from energy-based description to exergy-based mechanism analysis, then to economic and environmental coupling, and finally to intelligent multi-objective optimization. The combination of 4E evaluation and multi-objective optimization allows researchers to coordinate conflicts among efficiency, cost, and environmental impact within a unified framework, thereby promoting the transition from component-level improvement to system-level collaborative optimization. To illustrate this methodological evolution and its internal logic more clearly, **Figure 1.8** presents a schematic of the development of 4E evaluation in energy systems, from single thermodynamic analysis to multidimensional integrated assessment combined with multi-objective optimization. This research paradigm combines physical interpretability with engineering decision support and has become an important direction in the analysis, evaluation, and optimization of complex energy systems. It also provides the methodological foundation for the S-4E-T integrated evaluation framework developed in this study.