# 1 Introduction

## 1.1 Background and motivation

Reducing dependence on fossil fuels and achieving net-zero carbon emissions have become central objectives of global sustainable development. In pursuit of carbon neutrality, numerous countries are accelerating their energy transitions by increasing the penetration of renewable energy into the power system (Chen et al., 2022; De La Peña et al., 2022; Zhang and Chen, 2022; Igeland et al., 2024; Hou et al. 2025). According to the International Renewable Energy Agency (IRENA), the total installed generation capacity of renewables amounted to 3 865 GW in 2023, accounting for 43.0% of the global installed capacity. Furthermore, renewable energy sources contributed to approximately 8 440 TWh of electricity in 2022, representing 29.1% of global electricity generation (IRENA, 2024a, 2024b). As illustrated in Figure 1-1, both installed capacity and electricity generation from renewables have increased steadily over the past decade, reflecting the accelerating global transition towards clean energy.

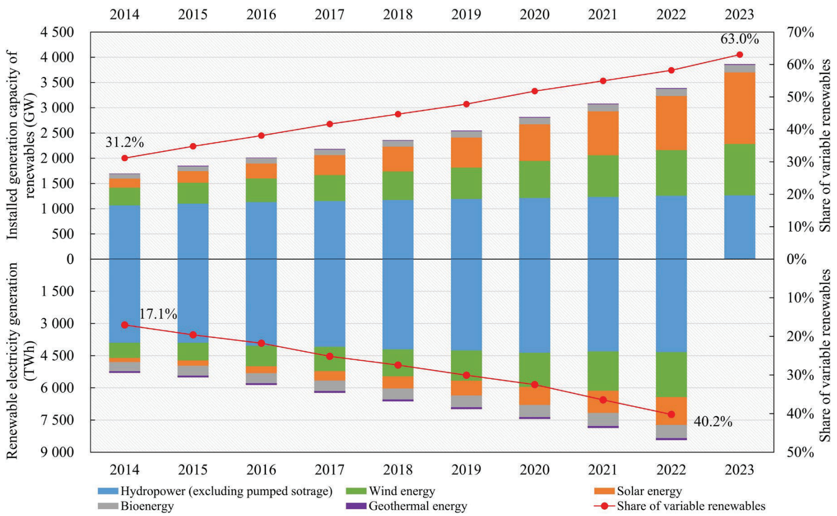


***Figure 1-1*** *Global electricity generation and installed capacity from renewables (Data source: IRENA).*

Among renewable energy sources, wind and solar power, commonly classified as variable renewables, have been the principal drivers of global renewable electricity growth. Wind power generated 2 098 TWh of electricity in 2022, representing a 14.0% increase compared with 2021. Meanwhile, solar energy, the fastest-growing renewable source in recent years, produced 1 294 TWh, marking a year-on-year increase of 25.6%. In 2023, solar power became the largest contributor to global renewable installed capacity, accounting for 36.7% (1 418 GW), while wind power comprised 26.3% (1 017 GW). During the last decade, variable renewables have steadily expanded their shares of both installed capacity and electricity generation among all renewable sources, rising from 31.2% and 17.1% to 63.0% and 40.2%, respectively. These trends indicate that future renewable energy systems will increasingly depend on variable and intermittent energy sources.

However, the intermittent and fluctuating nature of variable renewables presents a significant challenge in balancing energy supply and demand across spatial and temporal dimensions. Solar generation is generally dependent on sunlight intensity, while wind generation relies on wind availability. Meanwhile, electricity demand varies continuously, as consumption patterns fluctuate throughout the day and across seasons. To address this mismatch, various energy storage technologies have emerged as indispensable components of modern energy systems and have attracted widespread research interest (Ang et al., 2022; Wang et al., 2022; Beck et al. 2025). Energy storage systems, particularly at the grid-scale, are vital for mitigating fluctuations in renewable power output, compensating for hourly and seasonal variability, and maintaining overall grid stability and reliability. A range of technologies have been developed and deployed for large-scale energy storage, including pumped hydro storage, compressed air energy storage, thermal energy storage, and underground gas storage (Budt et al., 2016; Gur, 2018; Koohi-Fayegh and Rosen, 2020; Zivar et al., 2021; Huang et al., 2024b; Taabodi et al., 2025; Wu et al. 2025).

As illustrated in Figure 1-2, pumped hydro storage typically provides power capacities on the order of 100 MW or higher, with storage duration extending from several hours to multiple weeks, making it highly suitable for grid-scale energy management. Moreover, given its widely recognised reliability, efficiency, and technological maturity, pumped hydro storage is extensively deployed, with a global installed capacity approaching 160 GW, accounting for over 90% of global energy storage capacity (Ghorbani et al., 2019; Javed et al., 2020; Mahmoud et al., 2020; Hoffstaedt et al., 2022; Zhang et al., 2025). Nevertheless, the deployment of pumped hydro storage power plants (PSPs) is often constrained by topographical conditions, environmental considerations, and other siting limitations.

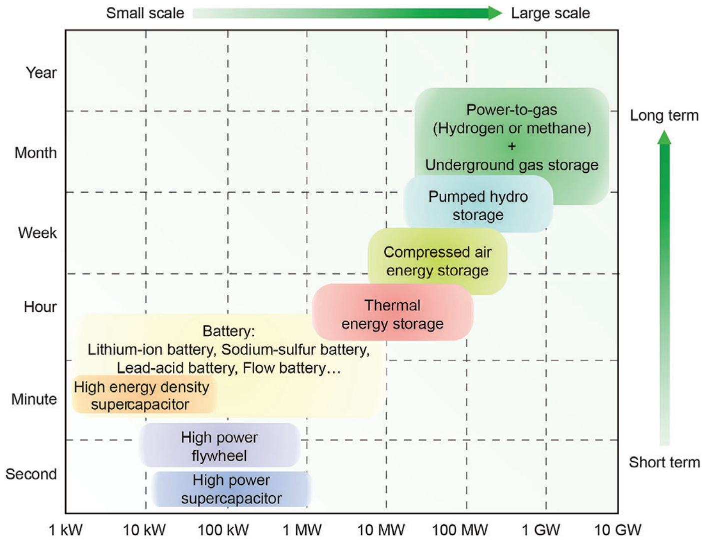


***Figure 1-2*** *Comparison of regulation capacity and energy storage scale of typical energy storage technologies (Wu et al., 2024).*

Meanwhile, the global number of closed and abandoned mines is enormous, making their management and resource utilisation an increasingly pressing issue. Following prolonged intensive mining activities, extensive mine closures have occurred worldwide because of mineral resource depletion, complex deep-mining conditions, declining economic returns, and policy-driven capacity reductions. The total number of closed and abandoned mines globally is estimated to exceed one million (Castorino et al., 2025; Chu et al., 2025). Germany, the United Kingdom, Canada, and the United States all contain substantial numbers of abandoned coal, metal, and non-metal mines (Mayes et al., 2009; Hou et al., 2010; Madlener and Specht, 2020; Ermakova et al., 2022; Bao et al., 2023). China also faces a large-scale mine-closure challenge. According to data from the China Geological Survey, approximately 100 000 closed or abandoned mines exist nationwide, including energy-related mines, metal mines, and non-metal mines (Xi et al., 2020; Lin et al., 2025). With the continued adjustment of industrial and energy structures, the number of abandoned mines is expected to increase further (Yuan et al., 2018; Lyu et al., 2022a; Chu et al., 2025).

Abandoned mines, particularly underground mines, retain substantial exploitable legacy resources, including underground space, groundwater, geothermal energy, and cultural or tourism assets (Menéndez et al., 2019b; Du et al., 2022; Lyu et al., 2022a; Colas et al., 2023; Oppelt et al., 2025). From an engineering perspective, deep shafts, multi-level drift networks, underground chambers, and mined-out areas constitute a large stock of anthropogenic underground space. As illustrated in Figure 1-3, post-mining reutilisation pathways of such underground space can generally be categorised into three modes: (i) energy storage and regulation, (ii) material storage and sequestration, and (iii) public and civil facilities (Du et al., 2022; Bu et al., 2024; Safaei-Farouji et al., 2024). Among these, redeveloping abandoned mines for underground energy storage not only offers a second life to otherwise idle assets but also facilitates the advancement of local renewable energy systems (Morstyn et al., 2019; Q. Chen et al., 2023).

Within the energy storage mode, underground pumped hydro storage power plants (UPSPs) are especially compatible with abandoned mine environments. Mining and excavation activities have created extensive networks of drifts and chambers at distinct elevations, which can provide potential spaces for upper and lower reservoirs. Additionally, mine water or nearby surface water may serve as operational water sources or supplements. Furthermore, surface lands awaiting restoration may accommodate wind and photovoltaic installations to provide charging power, thereby forming integrated renewable-storage clusters (Fan et al., 2020). Compared with conventional surface PSPs, converting abandoned mines into UPSPs may reduce land acquisition, resettlement, reservoir construction, and excavation requirements, while improving the reuse value of existing mine infrastructure (Menéndez et al., 2019b; Wen et al., 2024; Castorino et al., 2025). Moreover, abandoned-mine UPSPs may contribute to post-mining regional transformation by supporting labour resettlement, environmental remediation, infrastructure reuse, and local renewable-energy development (Gombert et al., 2020; Xie et al., 2023; Yang et al., 2023).

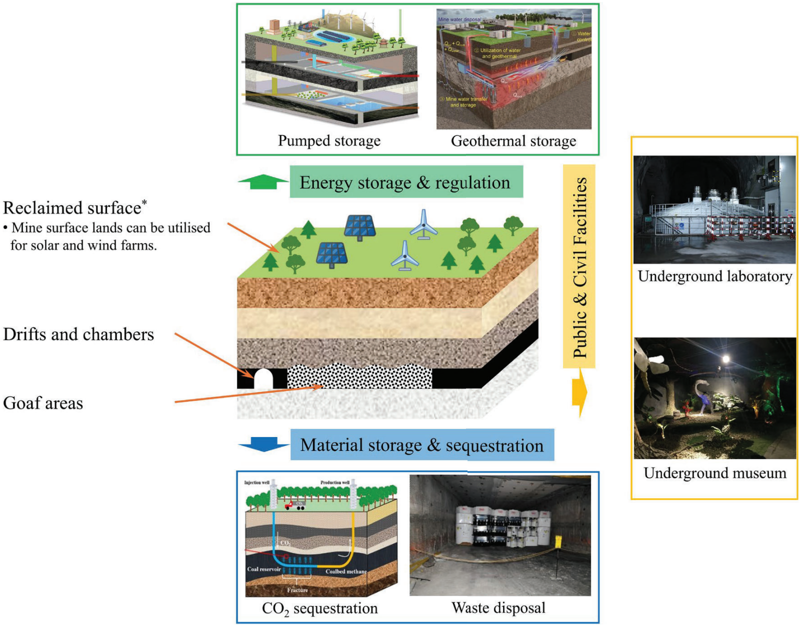


***Figure 1-3*** *Three utilisation modes of underground space resources in abandoned mines.*

Therefore, repurposing abandoned mines for UPSPs can simultaneously support renewable energy integration and sustainable post-mining redevelopment. However, such redevelopment is not a simple process of assigning underground spaces as reservoirs. It requires a systematic understanding of mine-specific geological conditions, underground space distribution, water-resource availability, existing infrastructure, engineering layout, operating strategy, and structural safety. In this context, three closely connected issues are particularly important. First, suitable candidate mines must be identified through a rational site-selection framework that can handle heterogeneous and uncertain decision information. Second, after a suitable mine is selected, its existing shafts, drifts, elevation differences, surface terrain, and water resources must be transformed into a feasible engineering scheme rather than a generic storage layout. Third, the stability of key underground hydraulic structures must be verified to ensure safe construction and operation.

Accordingly, this thesis focuses on the site selection and integrated scheme development of UPSPs in abandoned mines. A two-step site-selection framework is developed to support candidate-mine screening and ranking under uncertain decision information. The framework is then applied to underground mines in Yunnan Province, China, to identify a suitable site for UPSP redevelopment. Based on the selected Dahongshan Iron Mine, an integrated hydropower–UPSP scheme is proposed by combining rainy season diversion hydropower generation with dry season underground pumped-storage operation. Finally, the stability of the proposed penstock shaft, as a key hydraulic structure in the redevelopment scheme, is evaluated through three-dimensional numerical modelling.

## 1.2 UPSPs in abandoned mines: concepts, development status, and redevelopment pathways

### 1.2.1 Types and working principle of UPSPs

PSPs typically comprise an upper reservoir, a lower reservoir, a powerhouse, and a water conveyance system. For conventional surface PSPs, both reservoirs are usually constructed above ground and are strongly dependent on favourable terrain conditions. By contrast, UPSPs make use of existing underground spaces in abandoned mines, such as drifts, shafts, chambers, and goaf areas, to provide potential reservoir spaces and water conveyance routes. This configuration expands the range of possible sites and reduces dependence on large surface reservoirs.

Based on reservoir configuration, UPSPs in abandoned mines can be further classified into two subtypes, referred to here as semi-underground PSPs and all-underground PSPs. Semi-underground PSPs employ one surface reservoir, often utilising open pits, subsidence basins, or natural lakes, while converting underground mine spaces into the other reservoir. All-underground PSPs, on the other hand, use underground spaces at different mining levels to form potential upper and lower reservoirs, as illustrated in Figure 1-4. During retrofitting, existing shafts or inclines can be repurposed as water conveyance routes, while other openings may continue to serve auxiliary functions, such as ventilation, access, drainage, or maintenance, thereby realising the functional reuse of the mine's original infrastructure.

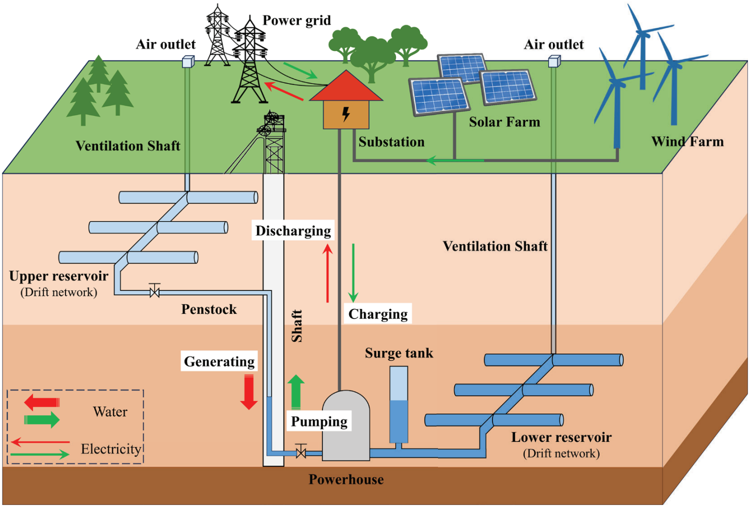


***Figure 1-4*** *Schematic layout of an all-underground PSP in an abandoned mine.*

The basic operating principle of UPSPs is the same as that of conventional PSPs. Both technologies store energy by converting electrical energy into the gravitational potential energy of water and generate electricity by reversing this conversion through pump–turbine units. As shown in Figure 1-5, UPSPs mainly operate in two modes. In pumping mode, surplus electricity or low-cost off-peak power is used to pump water from the lower reservoir to the upper reservoir. In generating mode, water is released from the upper reservoir to the lower reservoir under gravity, driving the turbine to generate electricity and supply power to the grid.

Owing to the rapid response capability of pump–turbine units, pumped hydro storage systems can provide peak shaving, valley filling, frequency regulation, emergency backup, and black-start support. For abandoned-mine UPSPs, these grid-regulation functions are achieved through the reuse or reconstruction of underground mine spaces and hydraulic connections. Therefore, the technical feasibility of a UPSP depends not only on the hydraulic head and reservoir capacity, but also on the geometric layout, connectivity, stability, and reconstruct-ability of the existing mine infrastructure.

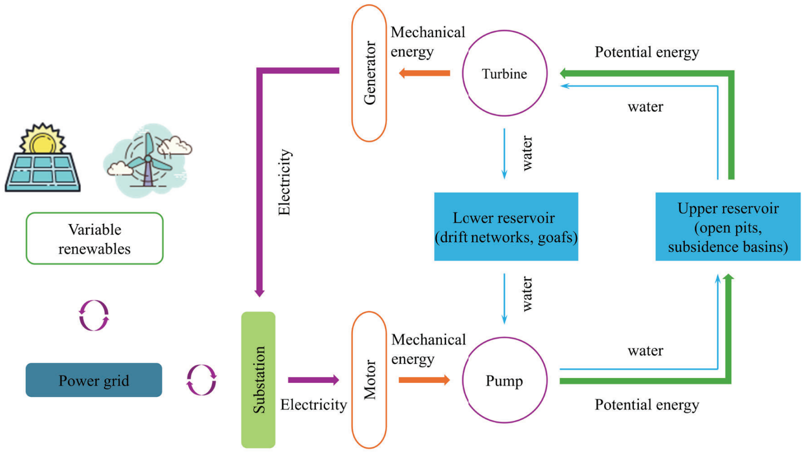


***Figure 1-5*** *Schematic diagram illustrating the working principle of pumped hydro storage using abandoned mines.*

## 1.2.2 Feasibility studies and pilot projects

The conceptual foundation for utilising underground spaces for energy storage dates back to the early twentieth century, when Fessenden (1917) proposed storing intermittent natural energy sources such as solar and wind power. The specific idea of repurposing underground or open-pit mines as lower reservoirs for PSPs was later suggested by Harza (1960). In 1968, several Swedish engineers proposed developing underground cavern-based lower reservoirs to complement surface reservoirs for pumped hydro storage (Isaaksson et al., 1968). Tam et al. (1979) explored the market potential, site-selection criteria, lower reservoir construction, and geological considerations for UPSPs. These early studies established the conceptual basis for developing UPSPs using abandoned mine spaces.

In recent years, the increasing demand for low-carbon energy storage has renewed interest in the “abandoned mines + pumped hydro storage” model. Existing studies have mainly focused on technical feasibility, economic viability, environmental impacts, and operational performance. From a technical perspective, numerical modelling, computational fluid dynamics, and hydraulic analyses have been used to evaluate the feasibility of using underground drifts, caverns, and goaf areas as potential reservoir spaces, with particular attention to air-pressure fluctuation, ventilation conditions, surrounding-rock stability, and hydraulic performance (Winde et al., 2017; Menéndez et al., 2019a, 2019c; Fan et al., 2020; Jiang et al., 2021). From an economic perspective, deterministic and stochastic models have been applied to assess investment feasibility, revenue uncertainty, power capacity, reservoir volume, capital expenditure, and electricity-price sensitivity (Madlener and Specht, 2020; Menéndez et al., 2020; Wessel et al., 2020; Gao et al., 2022). Environmental studies have further examined the potential effects of UPSP operation on groundwater flow, piezometric-head oscillation, water quality, sulphide oxidation, and carbon-emission reduction (Pujades et al., 2016, 2017; Bodeux et al., 2017; Ge et al., 2020). Overall, these studies indicate that abandoned-mine UPSPs can be technically and economically feasible under favourable site conditions, but their performance is strongly controlled by mine geometry, hydraulic head, storage capacity, hydrogeological conditions, and rock-mass stability (Xi et al., 2022; Yang et al., 2023).

The concept of constructing UPSPs in abandoned mines was proposed as early as the 1960s, with several countries developing conceptual designs. However, to date, no all-underground PSP in an abandoned mine has yet been commissioned. The Nassfeld power plant in Austria is generally regarded as the first operational semi-underground PSP of this type (Seiwald, 2007). To meet growing electricity demand, the plant required an expansion of its storage capacity in 2006. Because of technical and landscape-related constraints, expanding the lower reservoir above ground was deemed unfeasible (Madlener and Specht, 2020). Therefore, an underground cavern system was excavated, consisting of four main caverns measuring about 300 m in length and three connecting caverns, as shown in Figure 1-6. The caverns were largely unlined due to favourable rock-mass conditions. The lower reservoir is now composed of a surface reservoir and the underground cavern system, with a total volume of 230 000 $m^3$. The plant now has an installed capacity of 31.5 MW and an estimated annual power generation of 50 GWh.

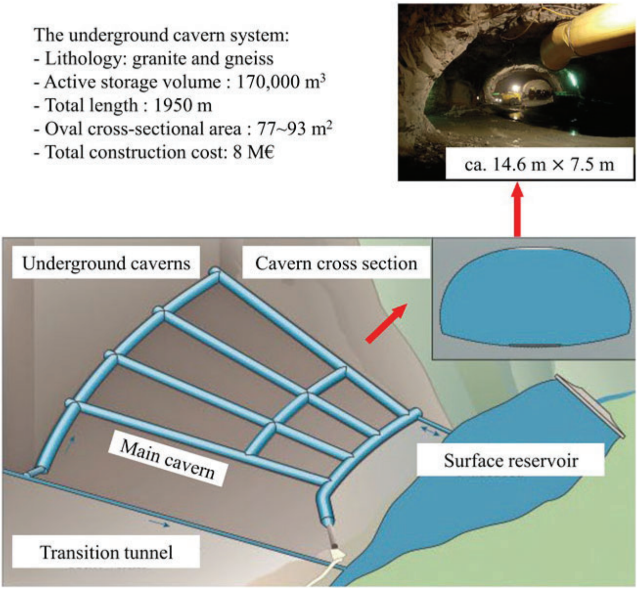


***Figure 1-6*** *The lower reservoir of the Nassfeld power plant consisting of an underground cavern system and a surface reservoir (Q. Chen et al., 2023).*

Other projects remain mainly at the planning or conceptual design stage. In the United States, the Mount Hope project in New Jersey and the Summit project in Ohio were proposed as large-scale semi-underground PSPs using abandoned iron and limestone mine spaces as lower reservoirs (Chiu et al., 1979; Uddin and Asce, 2003). In Germany, the Prosper-Haniel coal mine and the Grund gold mine were investigated as potential sites for semi-underground or all-underground PSP development, reflecting the interest in reusing deep mine infrastructure for energy storage after mine closure (Beck and Schmidt, 2011; Niemann et al., 2018). In China, research and engineering practice are still at an early stage. The distributed underground reservoir system constructed in the Daliuta Coal Mine illustrates the feasibility of large-scale water storage in underground coal mine spaces, while the proposed Shidangshan Copper Mine project in Jiangsu Province represents an important attempt to develop a semi-underground PSP using an abandoned open-pit excavation and existing underground tunnel network (Chen et al., 2016; Gao and Yuan, 2023). Representative design parameters of selected UPSP projects are summarised in Table 1-1.