1. Introduction

1.1 Motivation

The world is leading an energy transition for improving the energy production from renewable sources instead of fossil fuel to address the challenge of climate change and carbon emission. In response to the climate protection, numerous countries have proposed the goal of achieving climate neutrality or carbon neutrality, such as Germany, Denmark and China (Zhao et al. 2022). In 2021, the world has consumed 595.15 EJ primary energy in total, however, renewable energy only accounts for 6.7% (BP 2022). Figure 1.1 displays the composition of primary energy consumption worldwide in the last decade. It can be seen, in the past ten years, the global primary energy consumption has shown a slow growth trend, although due to the global COVID-19 epidemic in 2020, the consumption has decreased a little in 2020. In 2012, the renewable energy in primary energy consumption shared a proportion of 2.62%. Compared to 2012, the latest proportion of renewable energy in primary energy consumption in 2021 was 6.7%. Even though the proportion is still low, it has increased by 2.55 times compared to 2012 and this significant growth must be acknowledged. And another fact that needs to be acknowledged is that, currently, coal, oil, and natural gas remain the top three primary energy sources in the world's energy structure. To attain climate neutrality or carbon neutrality, nations with such objectives must prioritize the development and investment of renewable energy. In 2021, Germany announced its commitment to achieving climate neutrality by 2045 (Bundesregierung 2021). To this end, the country has set ambitious interim targets, including a 65% reduction in CO_2 emissions by 2030 relative to 1990 levels, followed by a further reduction of 88% by 2040. These goals reflect Germany’s determination to play a leading role in the global effort to combat climate change and transition to a more sustainable, low-carbon economy. To achieve the objective of climate neutrality, a strong emphasis must be placed on the development of renewable energy. By the end of 2022, the gross electricity consumption was met by renewable energy at a rate of 46.2%, marking a significant increase of 5 percentage points from the previous year's figure of 41.2%. While the increase in renewable energy generation to 46.2% in 2022 is commendable, it falls short of the necessary milestones towards achieving climate neutrality. To reach the goal of climate neutrality, at least of 80% electricity generation from renewable energy sources must be achieved by 2030. Therefore, there is still a long way to go for renewable energy development.

The current situation also meets to China, despite the fact that China has set a target of carbon neutrality by 2060, which is 15 years later than Germany. At the end of 2022, China is expected to have an installed capacity of renewable energy of 1.213 billion kilowatts, which accounts for 47.3% of the total installed capacity of power generation over the country. Additionally, the power generation capacity of renewable energy is projected to reach 4.4 trillion kWh, sharing a proportion of 32.8% in the electricity consumption of the whole society. While China's achievement may seem impressive, considering China just proposed the carbon neutral 2060 goal in 2020, it still falls short of the target set in its 14th Five-Year-Plan. According to the 14th Five-Year-Plan, by 2025, there are three targets related to renewable energy that needs to be achieved: (1) the annual power generation capacity of renewable energy is projected to reach approximately 3.3 trillion kWh; (2) more than 40% of the incremental electricity consumption of the entire society being contributed by the incremental power generation capacity of renewable energy; (3) renewable energy accounts for more than 50% of the increase in primary energy consumption (NDRC 2022). As a response to achieve the dual carbon goals and the objectives of the 14th Five-Year Plan, the installed capacity of solar and wind power in China now is rapidly increasing. By the end of 2023, China's wind and solar power installations have reached an incredible 440 GW and 610 GW, respectively (*Figure 1.2*). The substantial installed capacities of wind and solar power highlight the urgency of developing renewable energy for China. However, renewable energy often faces issues of volatility, randomness, and intermittency. By utilizing large-scale underground energy storage to convert electrical energy during off-peak periods into other forms of energy, namely Power-to-X, it provides the opportunity to leverage power balance and maintain grid stability. Among the energies convertible through Power-to-X, hydrogen emerges as the most promising secondary energy due to its hydrogen-electric coupling properties and diverse end-use applications.

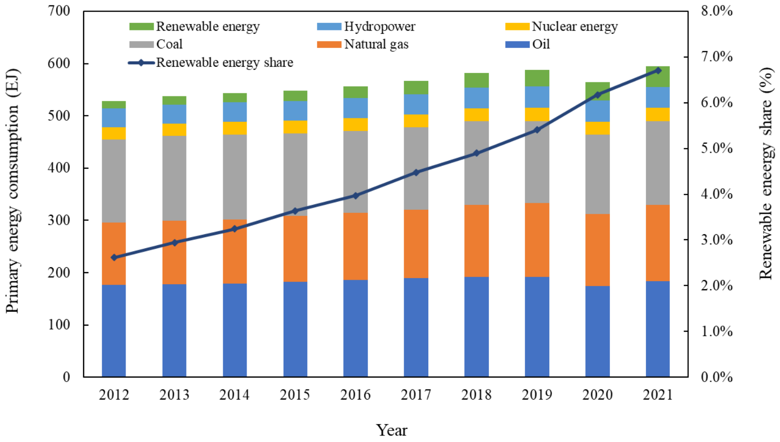

Figure 1.1 The Primary energy consumption and renewable energy share of China

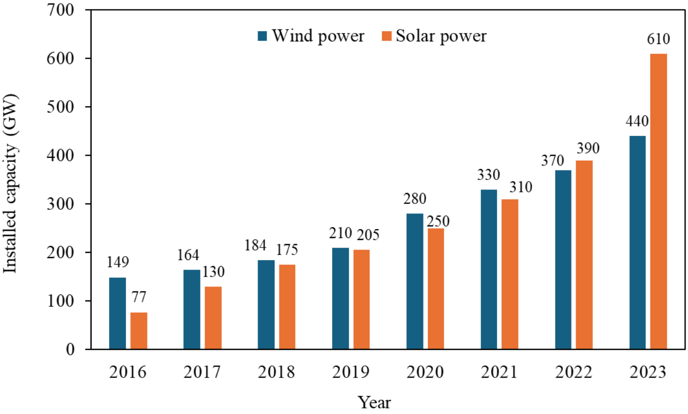

Figure 1.2 Installed capacity of wind power and solar power in China

Underground storage technology in geological reservoirs provides the feasibility for large-scale storage of green hydrogen, especially in salt cavern. Due to its extremely low permeability, damage healing ability, good creep behavior and inertia with respect to storage medium, rock salt has been recognized as an ideal medium for underground energy storage and nuclear waste disposal (Hunsche and Hampel 1999; Hou and Lux 2004; Xing et al. 2013). The corresponding technology of cavern energy storage in rock salt is widely implemented overworld for stability and security of energy supply (e.g., natural gas, crude oil, compressed air, and hydrogen) (Xie et al. 2023b). As of 2023, there are 678 underground gas storage (UGS) facilities, with a working capacity of 429 billion m^3. While countries like the Unites States (US), Germany, and Canada hold most global share, China has significantly increased both scale and number of its UGS facilities in recent years. Even though salt cavern gas storage represents only 8% share, it plays a crucial role in capacity, constituting 26% of the global withdraw rate. Currently, China has five operational salt cavern UGS facilities, with Hanjiang salt cavern being the planned largest UGS facility in Asia (Table 1.1). Although China already has operational natural gas storage facilities and compressed air energy storage facilities, there are no hydrogen storage facilities currently under construction. However, UHS in salt cavern is not a new concept for large-scale hydrogen storage. There are four existing UHS facilities as salt cavern for pure hydrogen in operation, one in UK and other three in USA (Crotogino et al. 2010; Tarkowski 2019). Considering that hydrogen energy development in China is still in its early stages, utilizing a small salt cavern for hydrogen storage as a pilot project would be a preferred choice.

Unlike the massive salt domes found in Western countries, China's salt formations are mainly bedded with interlayers, which brings challenges for UHS, especially considering that interlayers may provide the leakage pathway for hydrogen. To address the research gap of UHS in bedded rock salt, this paper establishes preliminary site selection criteria for UHS in bedded rock salt based on massive simulations. Furthermore, to promote the UHS pilot development, Anning salt mine is targeted and the feasibility of short-term and long-term UHS in Anning salt mine is validated based on convincing simulations.

Table 1.1 Status of salt cavern UGS facilities in China

Facility Location	Status	Operator	Storage medium	Designed total gas volume (10^8 m^3)	Working gas volume (10^8 m^3)
Jintan	Commission, 2007	PipeChina	Natural gas	26.39	17.2 (current 4.1)
Jintan	Commission, 2016	SINOPEC	Natural gas	11.79 (current 6.62)	7.23 (current 3.3)
Jintan	Commission, 2022	China Huaneng	Compressed air	1000 MW (current 300 MW)	-
Jintan	Commission, 2018	Towngas Smart Energy Company Limited	Town gas	10 (current 4.6)	6 (current 2.6)
Jianghan	Commission, 2022	SINOPEC	Natural gas	48.09 (current 2.37)	28.04 (current 1.4)

1.2 Hydrogen development and application

Since natural gas storage is critical for winter energy supply, it typically follows a seasonal (long-term) storage mode. For any energy storage facility, clearly defining its role and storage mode is essential before conducting a feasibility study, as the storage model is always associated with the as application. Therefore, this chapter investigates the development and application of hydrogen in China to elucidate why hydrogen is promising and explores potential storage modes for UHS.

Given China's commitment to the goals of carbon peak emissions and carbon neutrality, energy transition has become an inevitable necessity. As hydrogen is an abundant, clean and highly efficient secondary energy in widespread applications, developing hydrogen is gradually emerging as one of the important pathways for energy transition (Parra et al. 2019; Kovač et al. 2021; Capurso et al. 2022). In the global context of carbon neutrality, as early as 2020, a total of 11 countries or regions, including the European Union, Germany, Spain, and Canada, have successively released hydrogen development strategies. Especially, in these published hydrogen strategies, it is explicitly stated that green hydrogen is the direction for future development. Although China has not yet released a national hydrogen energy strategy, in March 2022, the "Mid- to Long-Term Development Plan for the Hydrogen Energy Industry" was issued, which has already established the strategic importance of hydrogen energy in facilitating China's energy transition. Hydrogen gas, as a clean energy storage medium, can be produced through electrolysis of water. When hydrogen gas is produced through the electrolysis of water using renewable energy sources, it is referred to as green hydrogen (Velazquez Abad and Dodds 2020).

Green hydrogen exhibits a diversified potential for end-use applications and can be fully utilized for deep decarbonization in various sectors such as industry, transportation, power generation, and construction (Rasul et al. 2022; Hou et al. 2023) (Figure 1.3).

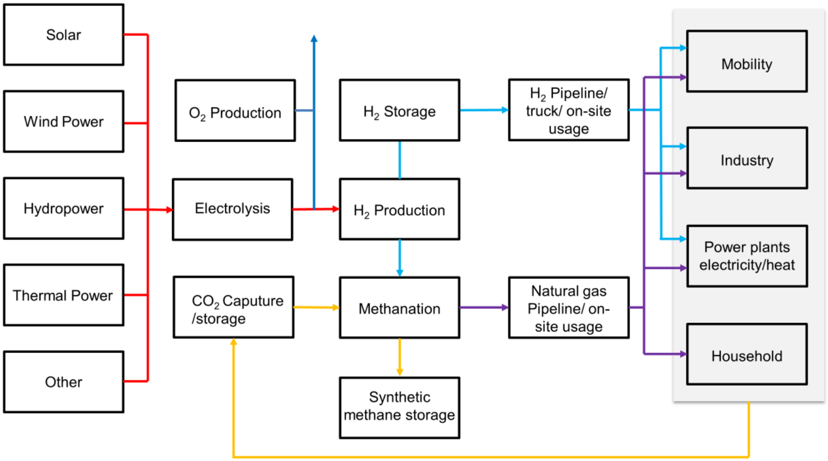

Figure 1.3 The concept of coupled deep decarbonization and hydrogen utilization in different fields (from (Hou et al. 2023)).

1.2.1 Industry

In the industrial sector, green hydrogen can be used as a substitute for coke as a reducing agent in the steel and iron production processes (Devlin et al. 2023). Currently, the applications of hydrogen in the steel industry can be broadly divided into two aspects: (1) as a reducing agent to reduce iron oxide, which is mainly involved in the blast furnace (BF) production process and the gas-based direct reduction iron (DRI) process; (2) as fuel for heating, including in the assistant sintering production, pelletizing process, heating ladle furnace, and other processes (Liu et al. 2021). In these two aspects, H2-DRI combined with the electric arc furnace (EAF) (termed H_2-DRI-EAF) has widely been regarded as a leading deep decarbonization option despite a range of issues to be addressed (Kim and Sohn 2022). The hydrogen metallurgy technology of DRI, which employs 100% renewable energy to perform water electrolysis for hydrogen production, is currently in the prototype development stage (Technology Readiness Level, or TRL, 6). Some demonstration research projects based on H_2-DRI have been carried out, such as the HYBRIT project in Sweden and the SALCOS project in Germany (HYBRIT 2024; SALCOS 2024). According to the research results from the HYBRIT demonstrative phase, utilizing a high-purity green hydrogen direct reduction process can reduce the CO_2 emissions in steel production to as low as 25 kg per ton of steel. The first commercial-scale HYBRIT plant would be operated by 2036. Additionally, both the partial use of a hydrogen and coal coke oven gas mixture in the BF production process, and the utilization of a natural gas-hydrogen mixture in the DRI process are currently in the quasi-commercial demonstration stage (TRL 7). Besides being used as a reducing agent, hydrogen or hydrogen-rich gas also shows great potential as fuels in the steel manufacturing process. The potential applications of hydrogen or hydrogen-rich gas as fuels mainly involve in pellet production, sinter production, and heating ladle and reheating furnaces. Recently, domestic iron and steel companies such as China Baowu Steel, and Hebei Steel have signed framework agreements to implement hydrogen metallurgy demonstration projects. Besides being used as a reducing agent, hydrogen or hydrogen-rich gas also shows great potential as fuels in the steel manufacturing process.

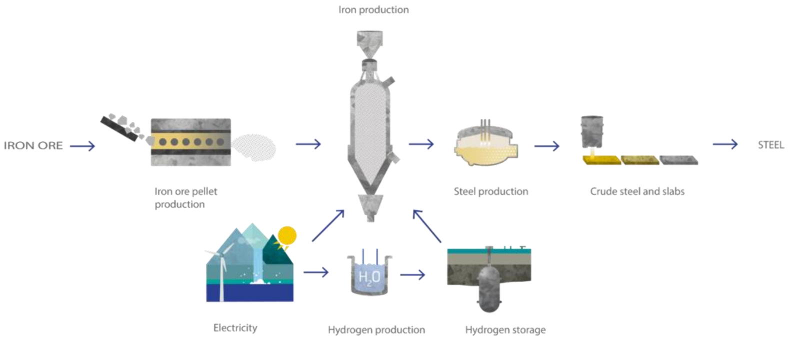

Figure 1.4 HYBRIT demonstration project process diagram (from (HYBRIT 2024))

1.2.2 Transportation

In terms of transportation applications, green hydrogen is primarily used as a feedstock for fuel cell electric vehicles (FCEVs), trains, ships and even rockets (Balat 2008; Singh et al. 2015). By the conclusion of 2022, a total of 814 hydrogen refueling stations (HRSs) had been established and operated in 37 countries. Among these, 455 were located in Asia, with Japan taking the lead at 165 stations, followed closed by South Korea with 149 stations. Additionally, approximately 138 HRSs are estimated in China. Furthermore, the construction of 315 new HRSs worldwide is already in progress planning. According to the latest report of International Energy Agency (IEA), compared to 2021, the global number of hydrogen FCEVs on the road increased by 40%, totaling over 72,000 vehicles (IEA 2022). The world's first hydrogen fuel cell train had been successfully commenced operation in Lower Saxony, Germany in 2018. The productions and sales of China's FCEVs are shown in Figure 1.5. From 2019 to 2022, the average annual sales of FCEVs in China comprised about 2192 units. Due to the pandemic, the sales of FCEVs in 2020 and 2021 dropped by more than half in comparison with 2019 year.

The entire industry is relatively fragile. By the end of 2022, it is expected that the cumulative domestic sales of FCEVs will reach 10,300, which still falls short of the target of one million vehicles set by the "14th Five-Year Plan" by 4%. According to the White Paper on Hydrogen Energy Application Development in 2022 proposed by China Hydrogen Alliance (CHA), the primary modes of application of hydrogen energy in the field of transportation in China are hydrogen-powered commercial vehicles and heavy construction machinery (CHA 2022). However, the cost of hydrogen FCEVs remains relatively high, the availability of hydrogen refueling stations is limited, and there is insufficient education regarding hydrogen energy in the market. Consequently, the adoption of hydrogen fuel cell passenger vehicles has been slow. Nonetheless, hydrogen FCEVs offer several advantages such as longer battery life, convenient charging, and superior low-temperature resistance compared to lithium battery vehicles. These attributes are more suited to the needs of commercial vehicle scenarios, where the daily operating mileage exceeds that of passenger vehicles. As a result, hydrogen fuel cell commercial vehicles have become a key driver of the development of hydrogen energy vehicles. It is projected that by 2025, the number of hydrogen energy FCEVs in China will increase to 100000, with a market size of 80 billion yuan.

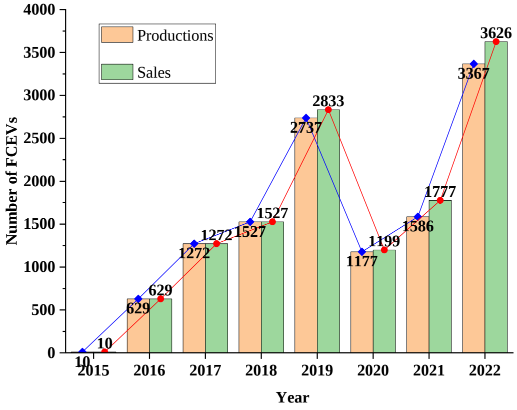

Figure 1.5 Productions and sales of China's domestic FCEVs

1.2.3 Power generation

In the field of decarbonizing electricity generation, pure hydrogen or hydrogen-blend gases (such as mixture of hydrogen and natural gas) can be used as fuel for gas turbines and combinedcycle gas turbines. On the other hand, hydrogen fuel cells can also serve as a flexible power generation technology (Oruc and Dincer 2021; Hwang et al. 2023). Most existing gas turbines can handle fuel blends with hydrogen content ranging from 3-5%. Some gas turbines are even capable of handling fuel blends with hydrogen content as high as 30% or more (Öberg et al. 2022). Siemens plans to develop a 100% hydrogen-fueled gas turbine for the Power-X-Power project in Europe by 2030 (Siemens 2023).For hydrogen-blend gas turbines, hydrogen-rich gas turbine demonstration projects have been successfully implemented in Italy, Japan, and South Korea. Hydrogen can also be mixed with nitrogen to form ammonia, which can be burned in gas or coal power plants. Another way involves utilizing fuel cells to generate flexible power through the reverse reaction of water electrolysis. Currently, most of the systems are powered by natural gas, with the largest hydrogen fuel cell power plant being the 50MW Doosan Power Plant in South Korea (IEA 2021). In China, the only operational hydrogen fuel cell power plant demonstration project is a 2MWe demonstration power plant located in Yingkou City, Liaoning Province.

1.2.4 Construction

The construction sector heavily relies on electrical energy for heating, cooling, household appliances, and lighting (Ürge-Vorsatz et al. 2015). Green hydrogen can contribute to the decarbonization of building energy consumption through four approaches: (1) Blending hydrogen into existing natural gas infrastructure and equipment; (2) Utilizing clean processes to react hydrogen with captured carbon dioxide to produce methane, which can be blended into natural gas pipelines and equipment; (3) Using 100% pure hydrogen; (4) Employing a combination of hydrogen fuel cells and combined heat and power systems to provide multi-energy services to buildings (Fang et al. 2022b). At present, hydrogen heating does not present any significant advantages over competing technologies such as natural gas heating in terms of efficiency, cost, safety, and infrastructure availability. Using pure hydrogen in buildings is a costly affair due to the requirement for new hydrogen boilers or extensive modifications to existing pipelines. Presently, the cost of hydrogen heating in Europe is more than double the cost of natural gas heating. Even by 2050, when heat pumps are expected to be the most cost-effective option, hydrogen heating is expected to be about 50% more expensive than natural gas heating (DNV 2022). Hydrogen can be delivered either in its pure form or mixed with natural gas, but utilizing pure hydrogen necessitates substantial modifications to existing pipelines or new hydrogen boilers, which results in higher costs. This method is more suitable for larger commercial buildings or district heating networks due to the high cost, while smaller residential units may not find it feasible. Thus, the early use of hydrogen in buildings will likely involve a mixed form. Hydrogen can be blended with natural gas up to 20% by volume without modifying existing equipment or piping, reducing costs and balancing seasonal energy demand. With China's fully integrated natural gas pipeline network and expected decrease in hydrogen costs, hydrogen is expected to gradually be used for heating and cooling in buildings. In the long term, with the deployment and development of the necessary hydrogen infrastructure and the increased competitiveness of hydrogen boilers (currently at TRL9), 100% combustion of hydrogen in dedicated boilers will become possible. According to the projections, it suggests that the use of pure hydrogen in buildings will exceed that of mixed hydrogen in the late 2030s. By 2050, hydrogen is anticipated to account for approximately 3-4% of the overall energy demand for heating in buildings.

1.3 Geological sites for UHS

As the demand for hydrogen energy in China and globally continues to rise, large-scale hydrogen storage has become imperative. Underground storage technology in geological reservoirs provides the feasibility for large-scale storage of green hydrogen and can be coupled with Power-to-X-to-Power technologies (Matos et al. 2019). Currently, there are four geological types of underground energy storage (UES) reservoirs in the world: depleted oil and gas reservoirs, aquifer reservoirs, salt caverns, and rock cavern reservoirs (Ozarslan 2012; Griffioen et al. 2014; Miocic et al. 2023) (Figure 1.6). Theoretically, the storage sites for hydrogen are similar to those for natural gas and can include the aforementioned four geological structures.

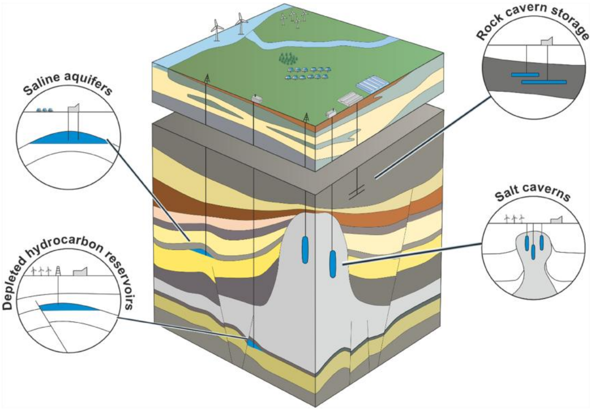

Figure 1.6 For geological structures for UES (from (Griffioen et al. 2014))