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Integrated subsurface gas storage of CO_2 and CH_4 offers capacity and state-of-the-art technology for energy storage in China

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Abstract

Integration and development of the energy supply in China and worldwide is a challenge for the years to come. The innovative idea presented here is based on an extension of the "power-to-gas-to-power" technology by establishing a closed carbon cycle. It is an implementation of a low-carbon energy system based on carbon dioxide capture and storage (CCS) to store and reuse wind and solar energy. The Chenjiacun storage project in China compares well with the German case study for the towns Potsdam and Brandenburg/Havel in the Federal State of Brandenburg based on the Ketzin pilot site for CCS.

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Keywords: gas storage; carbon dioxide; methane; hydrogen; renewable energy; carbon cycle

1. Introduction

The energy concepts of governments' worldwide aim at a reduction of greenhouse gas emissions in the near future [1]. Within that context available renewable energy plays a far greater role in satisfying energy requirements than before [2]. Nevertheless, integration and further development of the energy supply system is and will remain a major challenge for the years to come. An energy system which is based on renewable energy sources needs to

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account for short-term as well as long-term shortages of electricity. Due to the volatile nature of wind- and solar-based electricity, large fluctuations in the supply of power can occur. Therefore, the system needs to be stabilised by a quickly responding reserve in order to maintain the supply during the day. On the time frame of weeks, little wind and sunlight can occur especially during autumn and winter. Here, storage and generation capacity must be available as well to bridge potential electricity gaps. For the latter, we suggest an integrated system of subsurface storage of carbon dioxide (CO_2) and methane (CH_4) to buffer renewable energy in chemical form between its generation and final consumption. The innovative idea presented here is based on the extension of the "power-to-gas-to-power" technology by establishing a closed carbon cycle [3]. Hydrogen generated by electrolysis from excess renewable energy is transformed into methane for combustion. Carbon dioxide produced as well as methane are temporarily stored in subsurface reservoirs [4]. Consequently, renewable energy generation units can be operated even if energy demand is below consumption, while stored energy can be fed into the electricity grid as energy demand exceeds production [5]. Any kind of carbon Capture, Utilization and Storage (CCUS) technology is needed to reduce emissions from the whole lifecycle of especially energy-intensive industries [6].

Within the study presented here, the concept of the extended "power-to-gas-to-power" technology is first outlined. Second, we recapitulate the German show case for renewable energy storage with integrated subsurface gas storage; and third, give a comparison to the situation of the Chenjiacun site in the Ordos Basin of China.

2. Concept of the extended "power-to-gas-to-gas-to-power" technology

The idea behind integrated subsurface gas storage works as follows [3-5]. When the current electricity demand is lower than the production level from renewable sources like wind and solar, the surplus is used to produce hydrogen (H_2) by means of electrolysis of water. The hydrogen is then used as a reactant for methanation of CO_2 originating from one of two subsurface storage reservoirs installed for that purpose. The generated methane, is put into the second reservoir ready for extraction and conversion back to electricity when required. To close the carbon cycle and keep CO_2 available, a power plant has to be located in close proximity to both geological storage sites to enable the produced CO_2 to be directly separated and fed back into the CO_2 reservoir again with negligible transport costs (Fig. 1).

Energy storage on the basis of methane offers four major advantages: i) it represents the current state-of-the-art and can be applied in the short term; ii) retransformation of methane into electricity can fall back on established power plant technology; iii) methane can be easily fed into the existing gas network, and iv) decades of experience exist with subsurface storage of natural gas [3-5].

3. German case study for the storage of excess renewable energy

The show case outlines advantages and disadvantages of the extended "power-to-gas-to-power" technology concept on the basis of a practical example for the cities of Potsdam and Brandenburg/Havel [3] in the Federal State of Brandenburg (Germany). This includes estimates of the process efficiency and costs of electricity [4]. Brandenburg was selected as a study area, because it is a net exporter of electricity and covers an essential proportion of approximately 15% of its energy requirements from renewable sources. Further, an essential factor is a CO_2 storage reservoir on the order of magnitude as needed for the introduced technology of approximately 100,000 t CO_2. The Ketzin pilot site was not only successful from the scientific and engineering point of view but also with regard to the public perception gained [7,8].

An essential factor of the energy storage concept is a combined cycle gas turbine (CCGT) power plant in the immediate vicinity of the storage location. The smallest economically viable power plant is 120 MW_{el}. However, this exceeds the demand of the city of Potsdam, but was found to be suitable for additionally supplying the city of Brandenburg/Havel. The two cities represent a non-industrial supply area with a total population of about 227,000 and a total electricity demand of 900 GWh per year of which 30% are supposed to be provided from renewable sources. Our calculations are based on the assumption that the power plant contributes 2,800 full-load hours to supply the area under investigation and that it is able to support covering the increased daytime demand of both cities [9].

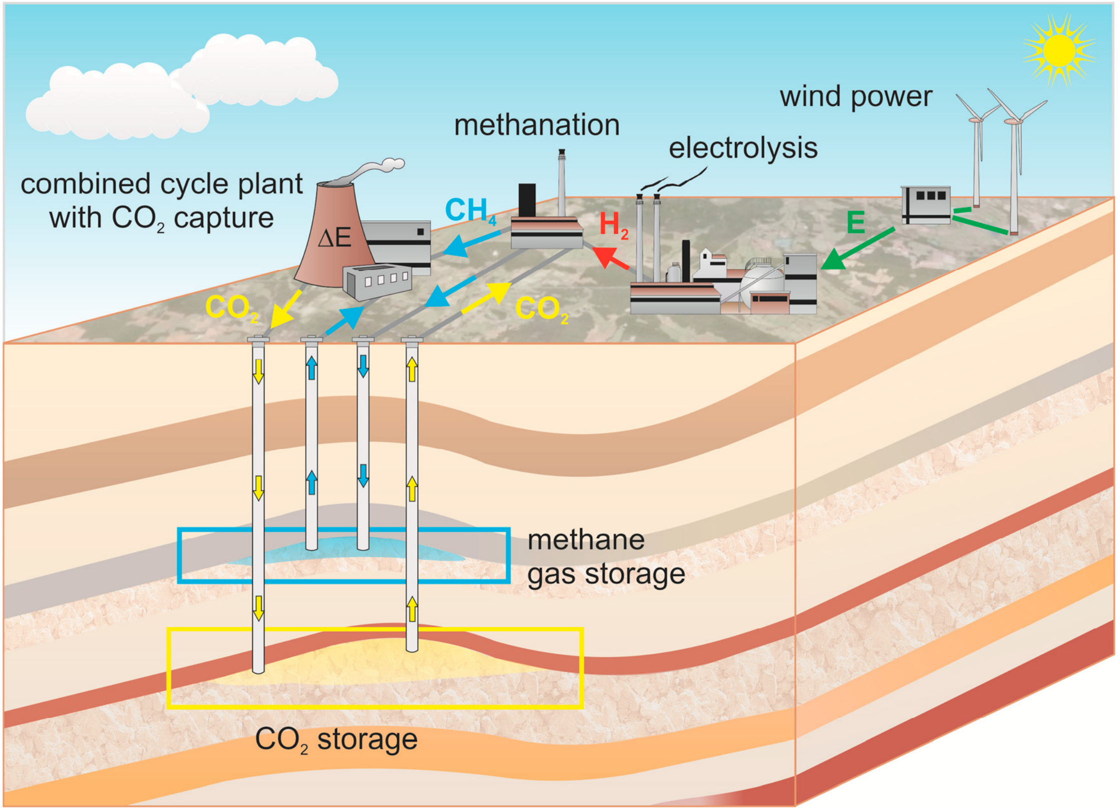

Fig. 1. Schematic of integrated subsurface gas storage of carbon dioxide and methane within the “power-to-gas-to-gas-to-power” technology system. The concept is based on a closed carbon cycle. Hydrogen is generated from renewable energy by electrolysis and transformed into methane with carbon dioxide taken from a subsurface geological reservoir. Methane produced is stored in a second reservoir and combusted in a combined cycle power plant on demand. Carbon dioxide is separated during energy production and re-injected into the storage reservoir.

The show case is based on numerical simulations of two separate gas storage reservoirs, both at a depth of 1,000 m. For CO_2 the injection rate varied over one year between 0.1 kg/s and 2.7 kg/s with a pressure increase of 20% above hydrostatic and a total volume of 2.5 million metric tonnes. For CH_4 the injection rate varied between 0.3 kg/s to 1.6 kg/s with a pressure increase of 60% and a total volume of 31,500 metric tonnes of CH_4.

For this regional showcase of both German cities, it is demonstrated how 30% of their electricity demand can be provided by using 17% of renewable electricity generated in the Federal State of Brandenburg [3]. The overall efficiency of the system is around 30% and the associated costs of electricity (COE) were calculated to 20 eurocents/kWh in 2014 [4]. The theoretical transfer and extension onto multiple gas storage sites in Germany show that the suggested concept already today has the potential to take up 20% to 60% of the 90 TWh to 270 TWh excess energy estimated for 2050 [5].

4. Chenjiacun site in Ordos Basin of China

The Shenhua Ordos CCS project is the first Chinese pilot-scale demonstration for CO_2 storage in a saline aquifer at 1,600 m depth [10]. The injection site is located in the Chenjiacun village of Wulam Len town that is about 40 km southeast of Ordos city. The project was designed to inject 300,000 t of CO_2 over 3 years. The injection operation started in 2011 and ceased in 2015. Over time the injectivity index increased. CO_2 injection at the site is interpreted to be safe, since the imposed pore pressure increase in the reservoir due to injection was 70% below the rock fracturing pressure. The project demonstrates the feasibility of large-scale commercialization of CCUS in the Ordos Basin [6].

Laboratory experiments were used for a pre-assessment of the geological structure [11]. For that purpose, hydraulic fracturing and multilayer injection procedures were suggested to improve the reservoir injectivity and reduce the risk of over-pressure. The injectivity improvement as result of the hydraulic fracturing was significant early in the operation, but decreased afterwards [10]. As a solution, an intermittent injection procedure was applied to maintain injection at the target rate [11].

Numerical simulations were applied to estimate the maximum injection rate for the Chenjiacun site [12]. Limiting the injection pressure to 1.5 times the initial hydrostatic pressure of the reservoir, an injection rate of approximately 17 kg/s was reached, leading to 536,000 t of stored CO_2. From that, the annual CO_2 storage capacity is estimated to be 0.5–0.7 Mt for a single vertical injection well. Therefore, about five injection wells may be required to handle about 3 Mt per year. These numbers outline that injectivity and storage capacity at the Chenjiacun site are not much smaller than Ketzin [7,12].

The screening and ranking framework (SRF) based on health, safety, and environmental (HSE) risk, developed by Oldenburg [13] was applied to evaluate and assess the leakage risk for the Chenjiacun pilot site in the Ordos basin [14]. However, a slightly revised methodology was used. Primary and secondary containment was taken into account. Over all, the conclusion was a low risk, beforehand, and this was as well observed in the field afterwards [10].

The current status of CCS in China is the transfer from research and development towards implementation of pilot sites [15]. From those ongoing pilot projects significant knowledge and technical expertise can be derived to move towards large-scale demonstration of integrated CCS projects. China is increasingly exploring opportunities in CO_2 utilization to drive and support deployment of CCUS [6].

5. Conclusions

The presented innovative concept extends the conventional "power-to-gas-to-power" technology with a closed carbon cycle, and in that way solves the issue of permanent carbon dioxide (CO_2) provision needed for methanation [3-5]. Excess electricity from wind and solar is transformed into hydrogen (H_2), and with CO_2 subsequently into methane (CH_4). When needed, electricity is regained in a CCGT power plant by burning the CH_4. The new idea is on the one hand to capture the CO_2 from the flue gas, and on the other hand to maintain CH_4 and CO_2 in two geological storage formations in close vicinity to the power plant (Fig. 1).

As outlined in the show case, subsurface CH_4 and CO_2 gas storage offers capacity and state-of-the-art technology to store and reuse wind and solar energy with a huge potential. Already for today, it is estimated that 20% to 60% of the 90 TWh to 270 TWh excess energy expected for 2050 can be stored in Germany [5].

The Ordos Basin is identified as one of nine inland basins in China potentially favourable for geological storage of CO_2 [15]. The Chenjiacun CCS project is China's first public demonstration [10]. Because the storage project compares well with the German show case based on the Ketzin pilot site [12], we conclude that the implementation of integrated subsurface gas storage of CO_2 and CH_4 offers significant capacity based on state-of-the-art technology for renewable energy storage in China.

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