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CO_2 geological storage and utilization for a carbon neutral "power-to-gas-to-power" cycle to even out fluctuations of renewable energy provision

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Abstract

Underground methane (CH_4) gas storage offers capacity and state of the art technology to temporarily store and reuse wind and solar energy. Carbon dioxide (CO_2) for methanation can be readily provided in the same way and used in a closed cycle with CO_2 separation at the power plant. With enhanced gas recovery employed, CH_4 and CO_2 could be placed in the same reservoir to be mutually working and cushion gas for each other. Selected gas storage sites of Germany show that they already have the potential to take up 20-60 % of the 90-270 TWh excess energy estimated for 2050.

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Keywords: renewable energy; power-to-gas-to-power; underground gas storage; methane; carbon dioxide; enhanced gas recovery; EGR

1. Introduction

The integration and further development of the energy supply system in Europe is a major challenge for the years to come. The European Strategic Energy Technology Plan (SET Plan) sets the agenda on the implementation of a low carbon energy system based on carbon dioxide capture and storage (CCS), an improved electricity grid, a solar and a wind initiative. Across European countries these innovative technologies have so far been implemented only up to very different levels. One reason is that the massive roll-out of renewable energy production units (wind

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turbines and solar panels) leads to date to excess energy which cannot be consumed or stored at the time of production. In Germany for example, excess energy amounted to 421 GWh in the year 2011 and is predicted to be between 90 TWh and 270 TWh in 2050 [1]. Excess energy will always be produced in significant amounts within countries planning to rely on renewable energy as primary energy source.

In previous publications we have outlined an innovative idea to extend the "power-to-gas-to-power" (PGP) technology by establishing a closed carbon dioxide (CO_2) cycle [2,3]. Thereto, hydrogen (H_2) generated from renewable energy by electrolysis is transformed into methane (CH_4) for combustion in a combined cycle gas turbine power plant (CCGT). To comply with the fluctuating energy demand, CO_2 produced during CH_4 combustion and required for the methanation processes as well as excess CH_4 are temporarily stored in two underground reservoirs located close to each other. Consequently, renewable energy generation units can be operated even if energy demand is below consumption, while stored energy can be converted and fed into the electricity grid as energy demand exceeds production. Based on a case study for the cities of Potsdam and Brandenburg/Havel in the State of Brandenburg in Germany, and supported by numerical computer simulations, we determined an overall energy efficiency of the entire process chain from renewable power via stored gas and back to power of about 28 % [2]. This then served as input for calculating the costs of electricity (COE) to 20 euro-cents/kWh [3] using an integrated techno-economic modelling approach [4,5]. Conclusion was that although the level of efficiency is lower than for pump and compressed air storage, the resulting costs are similar in magnitude, and thus competitive on the energy storage market. Advantages of the described concept are the possibility of immediate deployment, because it is complementary to available infrastructure, its support of base load energy supply and decrease of countries dependence on energy imports.

Next and further step we investigate here is the question if one underground storage formation for both gases, CH_4 and CO_2, at the same time in combination with the so called enhanced gas recovery (EGR) operation is an option and of benefit for the outlined concept (Fig. 1).

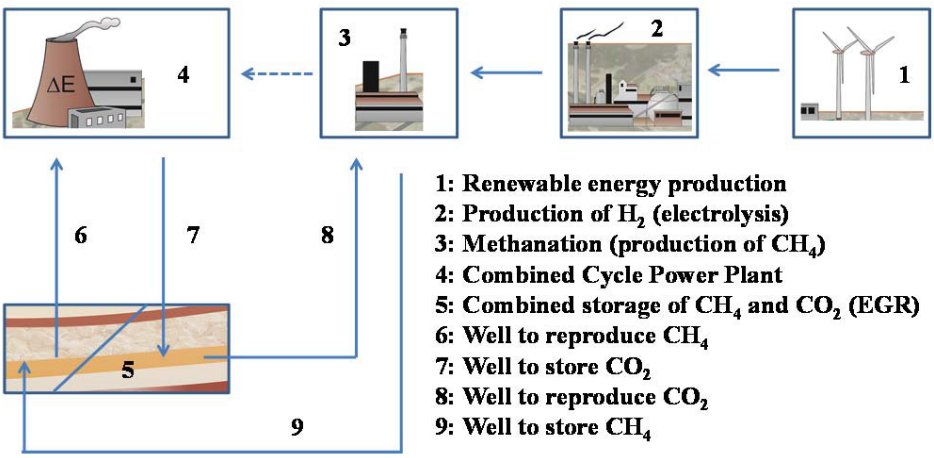

Fig. 1. "Power-to-gas-to-power" concept with closed carbon cycle using one underground storage formation for CH_4 and CO_2 at the same time and location supported by enhanced gas recovery in a way that both gases are mutually working and cushion gas for each other.

2. Enhanced gas recovery and carbon dioxide storage

In most cases enhanced gas recovery (EGR) has been mentioned and studied in the context of CO_2 storage as mitigation method to reduce human greenhouse gas emissions. In that sense, various options including EGR are extensively discussed by the Intergovernmental Panel on Climate Change [6]. Basics with regard to relevant processes, storage feasibility and potential storage capacities are outlined by van der Meer [7].

2.1. Experiences from pilot sites for enhanced gas recovery

Two pilot sites for EGR were developed and tested during the last decade. On the one hand this was field K12-B, a depleted natural gas reservoir in the Dutch sector of the North Sea [8]. Based on the monitoring results it was concluded that CO_2 injection into the formation did not bring any unforeseeable problems. On the contrary an EGR effect could be shown due to pressure support. On the other hand there is the Otway site in Victoria, Australia, which is as well a depleted gas field [9]. In this case the success of CO_2 storage is demonstrated based on geochemical assurance monitoring and reservoir surveillance which will continue post injection. In the future, further analysis and additional investigations will serve to reduce uncertainty in forecasting long term fate of injected CO_2 in such reservoirs and in the context of EGR. Results gained in Otway emphasize that safe storage and effective monitoring of CO_2 in depleted gas fields is feasible [10].

In Germany an EGR pilot test with 100.000 t of CO_2 to be injected in deep seated Rotliegend sandstones of a depleted gas field in the Altmark in the State of Saxony-Anhalt was prepared from the year 2009 on [11] and deemed ready to start a few years later [12]. However, due to significant political influence on the permitting procedure the mining authority in charge did not issue a permit for CO_2 injection [13]. Although this was a setback for the technology in Germany, the results of the project led to a comprehensive evaluation of the EGR potential of the Altmark field based on digital databases and modelling assessments with regard to consequences and risks. Technologies and methods were developed for CO_2 based EGR and the work deepened the understanding on the behaviour of CO_2 injected into a depleted gas field [14].

In the context of the presented extended PGP concept in application with one storage formation for CH_4 and CO_2 and based on EGR fundamentals (Fig. 1), two remaining questions are of major importance: (i) Does CH_4 and CO_2 stay largely unmixed to avoid asset reduction and (ii) is the process chain economical?

2.2. Mixing of methane and carbon dioxide in the reservoir and their displacement efficiency

It is assumed that EGR helps to maintain and manage the reservoir pressure, increase the sweep efficiency and accelerate production rates of CH_4 [6,7]. Important for the concept presented here is the fact that EGR should work in both directions. On the one hand CO_2 injection needs to enhance CH_4 recovery, and on the other hand CH_4 injection should displace CO_2 towards its production well in an equally efficient way. Major limitation is therefore the potential mixing of CH_4 and CO_2 which are miscible in all proportions at reservoir conditions, because separation of CO_2 and CH_4 mixtures would increase the overall costs. Hence, the amount of mixing that occurs between both gases in the reservoir is important in determining whether EGR is technically and economically feasible.

One way to assess the effectiveness of EGR are reservoir simulations, because so far only a few field tests have been conducted. These numerical simulations especially require an accurate description of the dispersive mixing of CH_4 and CO_2. To provide the respective input parameters, experiments can be applied to measure dispersion in sandstone rock cores [15]. These show that dispersion is a function of the system Péclet number (ratio between advection and diffusion) and captures variations in temperature, pressure and fluid composition. Further experiments and a compilation of data available [16] reveal that dispersivities for CO_2–CH_4 systems at reservoir conditions are less than 0.001 m, which indicates that excessive mixing will probably not occur in an EGR setting. Nevertheless, site-specific injection and production dynamics as well as pressure gradients have to be considered.

A sharp interface between two fluids, which is required for an efficient displacement, is favoured the higher the fluid density difference is. Taking into account the difference between CH_4 and CO_2 with depth, and therefore depending on temperature and pressure (Fig. 2), we define the ideal depth range for EGR between 700 m and 2,000 m, because it is characterized by highest density ratios of at least factor 5 and 10 in maximum. The densities of CH_4 and CO_2 vary with depth due to the hydraulic pressure gradient, given here with 10 bars per 100 m depth and a geothermal gradient of 3 °C per 100 m depth (Fig. 2). This favourable depth range is the basis for the example given for Germany below. It is most certain that both gases only mix to a small extent within this section and offer in that way best conditions for the PGP concept in combination with EGR. We select potential gas storage sites to estimate their potential capacity to store and reuse renewable energy.

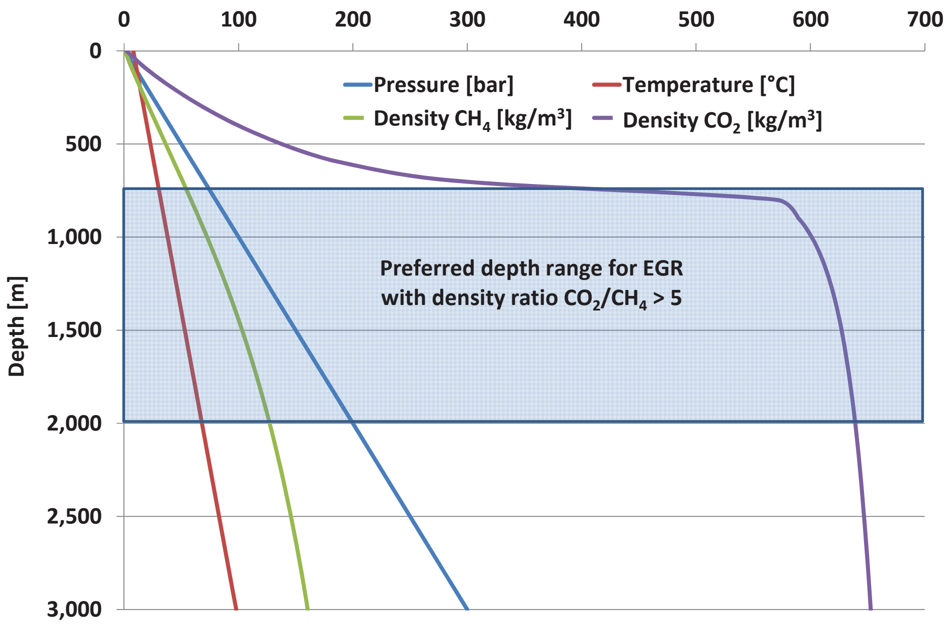

Fig. 2. Density of CH_4 and CO_2 with depth depending on pressure and temperature gradients.

2.3. Economic feasibility of enhanced gas recovery

The majority of the costs of 20 euro-cents per kWh for the presented concept originate from the underlying "power-to-gas" process and methanation at the surface. Only 0.7 euro-cents per kWh, respectively 3.5 %, are allotted to the operation of both subsurface storage reservoirs [3]. With regard to EGR, reservoir simulations and an economic sensitivity analysis provide comparable results and show that the largest expense will be for carbon dioxide capture, purification, compression and transport [17]. Advantage of the presented PGP concept is that CO_2 transport can be neglected because all units of the technology will be located close to each other. The economic feasibility of EGR is therefore most sensitive to the wellhead CH_4 price, CO_2 costs and the ratio of CO_2 injected to CH_4 produced. It is outlined in that context that EGR seems to be technically feasible, but that field pilot studies are required in that sense [17]. Additional studies further emphasize economic viability of EGR based on a case study which investigates optimized operation strategies [18].

From that point of view it can be stated that economic feasibility of EGR or PGP in combination with EGR does not depend on subsurface operations. It is the direct opposite: the main cost driver for storing renewable energy in the form of CH_4 is the methanation process at the surface. Nevertheless, it is always essential to perform site specific sensitivity and scenario analyses to determine potential costs based on extensive numerical simulations.

3. Capacity estimate for selected methane gas storage sites in Germany

In Germany to date more than 40 underground storage sites for natural gas exist [19]. They provide a total storage capacity of around 20 billion sm^3 of CH_4 working gas which represents an energy equivalent of 200 TWh. These sites are either porous formations or caverns in salt structures. Because caverns should probably be used for H_2 storage in the future, our estimate is solely based on the 22 storage locations in porous rocks. The working gas volume within these sites is around 10 billion sm^3 with an energy equivalent of 100 TWh. The total gas volume stored is around 20 billion Nm^3 which represents an average ratio of 50 % working gas to 50 % cushion gas.

However, the depths of the storage formations range from 350 m to 2,900 m. The ratio between working and cushion gas strongly depends on depth and the related pressure, and therefore spreads from a minimum of 12 % working gas to 79 % in maximum [19].

In view of the EGR process, only storage sites with a working gas ratio of 50 % or more are of interest revealing a good hydraulic performance. Furthermore, the optimal depth range for the mutual displacement of CH_4 and CO_2 is from 700 m to 2,000 m as outlined above (Fig. 2). This reduces the number of suitable storage sites to 5 of 22 with a total working gas volume of around 6 billion sm^3 representing an energy equivalent of 60 TWh. Already today, this would cover 20 % to 70 % of the excess energy estimated for 2050 in Germany. In comparison with the show case for the cities of Potsdam and Brandenburg/Havel in Germany [2,3] and based on the assumptions that the stored energy is used to provide 3,000 operation hours per year of the base load of the CCGT plants and that the plants have a thermal efficiency of 50 %, 60 TWh would require 30 to 150 block units of 80 MW_{el} to 400 MW_{el}.

4. Conclusions

Underground CH_4 gas storage offers capacity and state of the art technology to store and reuse wind and solar energy. CO_2 for methanation can be readily provided from these geological storage sites and used in a closed cycle with CO_2 separation at the power plant. We investigate here if enhanced gas recovery (EGR) could be employed and CH_4 and CO_2 placed in the same reservoir to be mutually working gas and cushion gas for each other.

Most important for the technical and economic feasibility of EGR is the amount of mixing that occurs between both gases in the reservoir. Based on results from literature we conclude that excessive mixing will probably not occur in an EGR setting taking into account the density difference between CH_4 and CO_2 with depth. Depending on temperature and pressure an ideal depth range for EGR between 700 m and 2,000 m can be defined. This zone is characterized by highest density ratios of at least factor 5 and 10 in maximum.

The majority of the costs of 20 euro-cents per kWh for the presented concept originate from the underlying "power-to-gas" process and methanation at the surface. It becomes clear that economic feasibility of EGR or PGP in combination with EGR does not depend on subsurface operations but mainly on the methanation process.

Selected gas storage sites of Germany show that they already have the potential today to take up 20 % to 60 % of the 90 TWh to 270 TWh excess energy estimated for 2050. They were picked based on a working gas ratio of 50 % or more and the optimal depth range with regard to the CO_2 and CH_4 density ratio.

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