Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 76 (2015) 59 – 66

Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Geological underground will contribute significantly to the implementation of the energy policy towards renewables in Germany

Sonja Martens* and Michael Kühn

GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Abstract

The demands to utilize the geological underground are increasing. In addition to traditional production of raw materials or groundwater extraction for drinking water supply the subsurface will most likely also be used to implement the policy objectives in the context of the energy transition to renewables. These include e.g. the use of geothermal energy, storage of energy from renewable sources, and possibly long-term storage of CO_2 to reduce the release of greenhouse gases into the atmosphere. This paper addresses the question which contribution can be expected from the geological underground for the transition to the new energy era in Germany.

Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: energy era; renewable energy resources; Groß Schönebeck; geothermal energy; Ketzin pilot site; carbon dioxed (CO_2) storage

1. Introduction

The energy supply in Germany is subject to a profound change. The objectives for the transition to a new energy era (referred to as "Energiewende" in German) are very ambitious as the German Federal Government decided to

* Corresponding author. Tel.: +49 (0)331-288-1965; fax: +49 (0)331-288-1529.
E-mail address: martens@gfz-potsdam.de

Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.846

step back from nuclear power and to expand renewable energy resources to become the central pillar of the future energy mix.

The energy concept which was introduced in 2010 and amended after Fukushima in 2011 sets out Germany's energy policy for an environmentally sound, reliable and affordable energy supply and is about designing and implementing an overall strategy up to 2050 [1]. According to the energy concept greenhouse gas (GHG) emissions in Germany are to be cut by 40 % by 2020, 55 % by 2030, 70 % by 2040 and 80 to 95 % by 2050 compared to the emissions of 1990 (~1,250 million tons CO_2 equivalents). When the 95 % reduction would be met, the present annual level of GHG emissions per head would be reduced from approximately 11 tons to 1 ton. Germany also seeks to make renewable energies to account for the following proportion of gross final energy consumption: 18 % by 2020, 30 % by 2030, 45 % by 2040 and 60 % by 2050. In 2013, there was a GHG reduction reached of about 24 % compared to the 1990 level and a share of about 12 % of renewables in primary consumption in Germany [2-3].

The present paper addresses the question which contribution can be expected from the geological underground to the implementation of Germany's new energy policy. Hereby we focus on resources and potentials of geothermal energy und underground storage reservoirs in Germany and provide a comprehensive overview on corresponding research activities of the GFZ German Research Centre for Geosciences.

2. Scenarios of a future greenhouse gas-neutral Germany

The world energy demand is currently met in large part by the use of fossil energy (about 90 %) [4]. The reason is that for all fossil fuels considered together, there is a comfortable supply situation, based on the available resources and reserves and compared to the total amount of energy currently being produced. Today, Germany accounts for approximately 3 % of global energy consumption [4]. For coal, the largest reserves and resources are recognized globally as compared to other fossil fuels. Natural gas is available from a geological point of view to meet the demand for decades even when the demand increases as predicted. Oil is the only resource which cannot meet a growing demand in the upcoming decades. This means that further use of fossil energy could fulfil two of the three premises of Germany's new energy policy: an affordable and secure supply. However, the environmental aspect would not be met. Therefore, it is interesting to take a look into different scenarios of a future greenhouse gas-neutral Germany.

According to the study "Germany in 2050 - a greenhouse gas-neutral country" of the Federal Environment Agency [5] it is technically feasible to achieve greenhouse gas neutrality in Germany with an annual per capita emissions of one ton of CO_2 equivalents in 2050, and hence a 95 % reduction in emissions compared to 1990 levels. The analysis is based on the scenario of switching the entire energy supply to renewables and extensive exploitation of the potential for efficiencies. The key component of the analysis is the conversion of electricity generated using renewables into hydrogen (H_2), methane (CH_4) and long-chain hydrocarbons (power-to-gas and power-to-liquid technology) assuming that some of the electricity required in Germany will be generated abroad. The use of nuclear energy is not seen as an option. The authors also exclude for sustainability reasons the cultivation of biomass crops solely to generate energy from their scenario and do not consider carbon capture and storage (CCS) as one option to reduce greenhouse gas emissions into the atmosphere.

With regard to the geological underground and national storage capacities, Purr et al. (2014) [5] assume that the existing natural gas infrastructure with its underground reservoirs can be used to store the renewably sourced H_2 and CH_4 and still has expansion potential. With respect to the contribution of deep geothermal energy to a sustainable supply, Paschen et al. (2010) [6] calculate the potential for geothermal power in Germany to 2050 considering ecological, regional planning and technical restrictions. According to their forecasts, Germany would be able to realize an installed net geothermal capacity of 6.4 GW by 2050 which could generate around 50 TWh p.a. of baseload electricity.

A study of Henning and Palzer (2014) [7] models the energy balance of the electricity and heat sectors, which correspond to about 62 % of Germany's current energy demand, including all renewable energy converters, storage components and loads for a future energy system. They show that supply of the electricity and heat sectors with 100 % renewables is technically possible and economically feasible in Germany by 2050. The mobility sector and the industry are not covered by the study. In the quantitative models only technologies which are already available today are taken into account within their respective potential limits. According to the forecast, following the conversion of the energy system, the total annual cost (119-126 billion EUR) will not be higher than the annual cost of today's energy supply (electricity and heat ~120 billion EUR). A full coverage of electricity and heat with renewable energy requires under these constraints, however, that the heating demand for buildings through energy efficiency measures is reduced to approximately 50 % of the value of 2010. Due to the discontinuous energy production from solar and wind power storage is needed. In this study, these are pumped-storage power plants, batteries, heat and CH_4 storage (for CH_4 there is a capacity of 86 TWh needed). Shallow geothermal energy (required are 140 GW) is integrated over electric heat pumps into the system. Deep geothermal energy has not been considered in the models because it still does not have a large-scale market today.

Based on [7] and [8], our estimates underline that already in 2015 more than 100% of the required CH_4 storage capacities therein are available and more than 100 % of the heat pump demands might be covered by shallow and deep geothermal energy production in the future, respectively. In addition, we show that a newly developed energy storage system [9, 10] could be applied to store 20-60 % of the surplus energy from renewables expected for 2050 with integrated gas storage of CH_4 and CO_2 (cf. chapter 5.)

3. Resources and potential of geothermal energy and underground gas storage in Germany

The demands to utilize the geological underground are increasing. In addition to traditional production of raw materials or groundwater extraction for drinking water supply the underground will most likely also be used to implement the objectives of Germany's new energy policy. As the new energy system is facing enormous challenges in the years to come, the concept of geoenergy including the utilization of subsurface reservoirs as potential energy sources and storage sites for matter and energy obtains a new relevance [11].

3.1. Geothermal energy

Geothermal energy uses the existing heat in the accessible part of the earth's crust and is continuously available. As there is a mean heat flow of 0.065 W/m^2 in Germany, the temperature of the ground increases with depth by about 3 K per 100 m. For comparison, the heat flux from the sun is with 125 W/m^2 about 2,000 times higher. Classifying geothermal systems with regard to the depth of heat exploitation makes a distinction between shallow and deep geothermal energy. For shallow geothermal energy, heat is extracted from depth down to about 100 meters using ground source heat pumps and used for direct heating or cooling and to store excess heat in the summer and use it in winter. In the case of deep geothermal energy, heat is extracted from depths of about 1,500 meters and deeper and e.g. used for district heating systems.

The theoretical geothermal potential for Germany is calculated from the amount of heat that is stored in the top 10,000 m of the earth's crust beneath ground surface. The value of 1,500,000 PJ/year is about three times the current global and 115 times the German consumption (Table 1). However, the theoretical potential is technically not extractable due to a number of restrictions. For example, areas which are far away from potential consumers are not suitable for shallow or deep geothermal energy due to losses in energy transport. The technical potential demand (economic potential) results from further constraints. Geothermal energy would be sustainable for Germany, if only the permanent natural heat flow near surface (0.12 W/m^2), which is driven by the heat flow from the sun and the earth's interior would be used. This performance can be increased if, in addition to heat use in winter, the excess of heat by building cooling in summer is stored in the underground.

Table 1. Geothermal potential of Germany [8]. For comparison: Primary energy production in Germany in 2014 was 13,077 PJ [12].

Kind of geothermal potential	[PJ/year]	[GW]
Theoretical potential	1,500,000	47,550
Technical potential	7,400	235
Economical potential[#]	5,800	184
Ecological potential	1,510	48

[#]calculated for a period of use of 1,000 years

The study by Paschen et al. (2003) [6] shows that deep geothermal energy has a considerable potential in Germany. In regions with favorable conditions, such as the North German Basin, the South German Molasse Basin and along the Upper Rhine Graben, many geothermal installations are already in operation. According to Weber et al. (2015) [13], a total of 180 geothermal installations for direct use of geothermal energy are operating in Germany with an installed capacity of about 260 MWt (geothermal) and 650 MWt (total, including peak load capacity etc.). Furthermore, there are numerous decentralized geothermal heat pump units with an installed capacity of about 2,600 MWt (geothermal) and 3,500 MWt (total, including electrical energy consumed). By the end of 2013, direct thermal use of geothermal energy in Germany amounted to a total installed thermal capacity of about 2,860 MWt (geothermal) and 4,150 MWt (total).

Whereas we consider heat supply by shallow and deep geothermal energy as state of the art in Germany, large-scale production of electricity from geothermal energy is not yet possible. This is demonstrated by the current contribution of geothermal energy to the total energy supply in Germany. In 2013, about 7 % of the total heat and only about 0.1 % of the total electricity demand was provided by geothermal energy according to the data from the Working Group on Renewable Energy Statistics [12].

3.2. Underground gas storage

Subsurface storage of gas is a widespread and well-developed technology. Since more than 50 years, there is underground storage for CH_4 (mainly corresponds to natural gas) performed in Germany as geological conditions are favorable. In 2013, 51 gas storage facilities were operated which cover a total capacity of about 23.8 billion Nm^3 (norm cubic meter for constant pressure and temperature) to balance the seasonal demand and supply [14]. Germany has the largest natural gas storage capacity in the EU and the fourth largest in the world. About 45 % of the gas storage facilities can be found in porous rock formations, mostly sandstones, of depleted oil and gas reservoirs or saline aquifers in the North German Basin, the Upper Rhine Graben area and in Bavaria. The other 55 % of the storage sites are installed in caverns leached into subsurface salt structures which are mainly located in the northwestern part of the country.

The existing natural gas infrastructure including its underground reservoirs can be used to store renewably sourced H_2 and CH_4 and has a certain expansion potential [4]. According to the forecast in [14] the installed storage capacity can increase in the medium term to about 30.6 billion Nm^3 if all on-going plans are realized in Germany. Potential for new storage facilities is assumed to include 400 salt caverns with a maximum usable working volume of 21.6 billion Nm^3 [5]. Hence, the long-term total working gas volume could amount with the existing and planned natural gas storage facilities to a maximum of about 52 billion Nm^3 (~80 % in caverns, ~20 % in pore storage facilities). With regard to the different storage types, there are no restrictions seen for CH_4 whereas those for H_2 are more stringent. Salt caverns are seen as the most suitable storage solution for H_2 [5].

4. Research on geothermal resources and CO_2 storage at the GFZ

A detailed knowledge about the geological underground is a prerequisite for characterizing potential locations which might be utilized as energy sources or storage sites. The GFZ German Research Centre for Geosciences established the research platform Groß Schönebeck and the Ketzin pilot site, both located in the German Federal State of Brandenburg close to Berlin (Fig. 1), in order to conduct research on deep geothermal resources and CO_2 storage, respectively. Both projects address the entire chain from reservoir exploration to utilization, e.g. exploitation to energy conversion or CO_2 storage. Another key task of both projects is a comprehensive monitoring of all development and operating stages using multidisciplinary tools and technologies. At the Ketzin pilot site, the post-operational and abandonment phase is also already addressed.

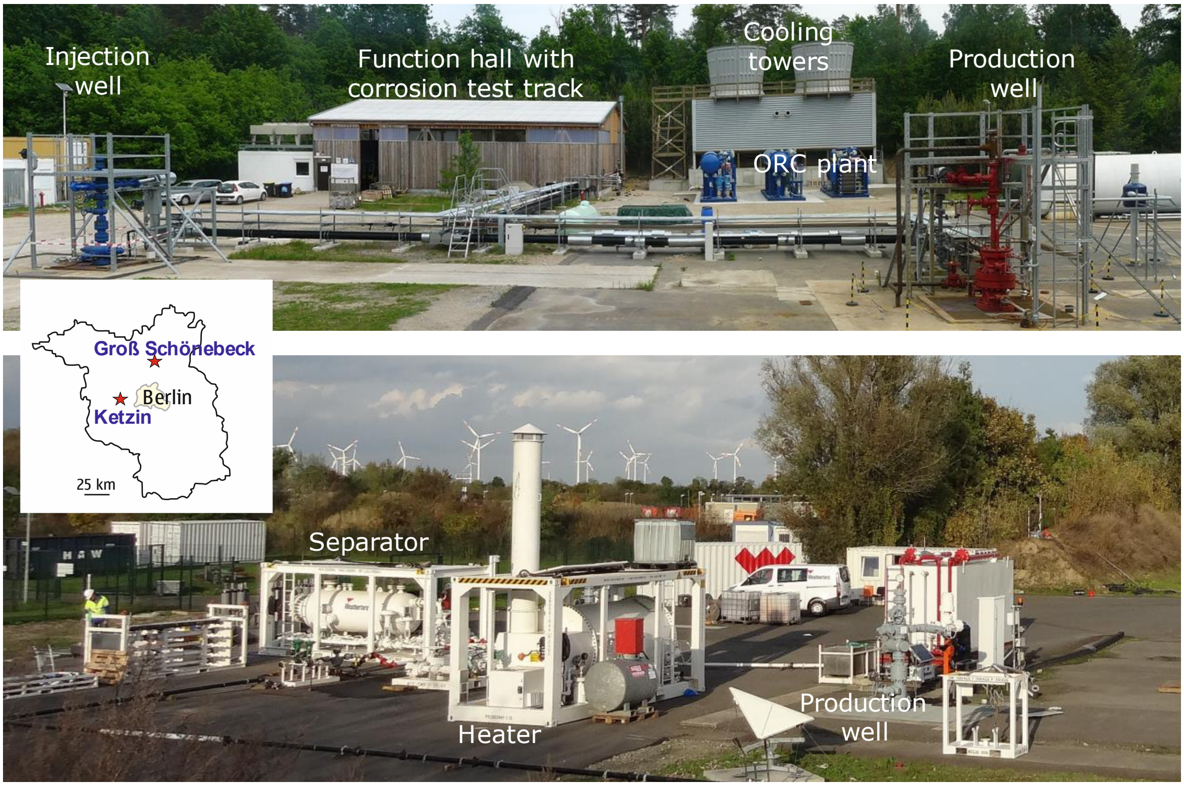

Fig. 1: Top: Infrastructure at the research platform Groß Schönebeck. Bottom: Infrastructure at the Ketzin pilot site during CO_2 back-production test (photograph by Tanja Kollersberger, GFZ).

4.1. Geothermal research platform Groß Schönebeck

The Groß Schönebeck site, located about 30 km north of the city border of Berlin (Fig. 1), was established to investigate, understand and optimize all steps related to the use of geothermal energy from a deep sedimentary basin [15]. Two wells have been completed as a geothermal doublet: the injection well, an abandoned gas well, was deepened in 2001 to 4,309 m and the production well was drilled down to 4,400 m in 2006 giving access to low porous sediments. Both wells tap water-bearing horizons of the North German basin with temperatures of ~150 °C.

For productivity enhancement, hydraulic stimulation experiments were conducted and accompanied by geophysical and geochemical monitoring methods. The reservoir stimulations led to a productivity improvement. As the geologic conditions are typical for large areas of Central Europe, the site is representative for such investigations and results obtained under these conditions open a perspective for the application of respective technologies worldwide. The infrastructure on site also includes a hall with a corrosion test track to allow for investigation of materials and an organic-rankine cycle (ORC) plant for electrical power generation.

4.2. Ketzin pilot for CO_2 storage

The Ketzin project was initiated in 2004 as the first onshore project in Europe that is dedicated to research and development for a better understanding of geological CO_2 storage [16]. The pilot site, located 25 km west of Berlin's city border (Fig. 1), was established to address and investigate all life-cycle phases of a CO_2 storage project. A total of five wells up to 800 m depth were drilled between 2007 and 2012 [17]. Between 2008 and 2013, a total of 67 kt of CO_2 were safely injected into a saline aquifer at a depth of 630-650 m [18]. Hence, the project provided valuable experience in operating a CO storage site [19] and is currently in the post-closure phase with a focus on post-injection monitoring and well abandonment. The project has achieved an enviable record of operational and scientific monitoring data and the multidisciplinary monitoring including e.g. seismic, geoelectrical methods and CO_2 flux measurements [18, 20] will be further applied.

The Ketzin project demonstrates safe CO_2 storage in a saline aquifer on a pilot scale [18]. Moreover, it was shown in a field experiment ("back-production test") in October 2014 that it is feasible to retrieve formerly injected CO_2 from the reservoir [21], where the gas might also be generally available for further utilization.

5. Newly developed energy storage concept

Due to the increasing proportion of intermittent renewable energy sources as wind and photovoltaics, energy systems need to be more flexible to assure a stable and reliable supply. Hence, energy storage systems are necessary to level the mismatch between generated renewable power and the actual consumption. For long-term periods with low renewable energy production or seasonal storage, storage of electrical power transformed into H_2 or CH_4 (power-to-gas) might be an option. When needed, electricity is regained by burning the CH_4.

Kühn et al. (2014) present an extended power-to-gas-to-power concept for flexible underground storage of renewable excess energy which is based on a closed carbon cycle [9, 10]. As shown in Figure 2, H_2 is generated from excess renewable energy by means of electrolysis and transformed subsequently into CH_4 using CO_2 extracted from an underground storage reservoir. CH_4 produced is temporarily stored in a second underground reservoir close to the first one and combusted in a combined cycle gas and steam turbine power plant when needed. CO_2 is captured from the flue gas during energy production and re-injected into the storage formation to establish a CO_2 cycle. Realizing this concept, renewable energy generation units could be operated even if the energy demand is below consumption, while stored energy could be converted and fed into the electricity grid when energy demand exceeds production.

Energy storage on methane basis offers capacities in Germany and represents state of the art technology (cf. chapter 3.2). Selected German gas storage sites already have the potential today to take up 20 % to 60 % of the 90 TWh to 270 TWh excess energy estimated for 2050 [9]. Furthermore, transformation of CH_4 into electricity can rely on an established technology and CH_4 can be fed into existing gas infrastructure. According to their study and a regional showcase of two German cities [22], the overall efficiency of this system is 28 % and the associated costs of electricity are 20 eurocents/kWh which are competitive to pump storage hydro power and compressed air storage.

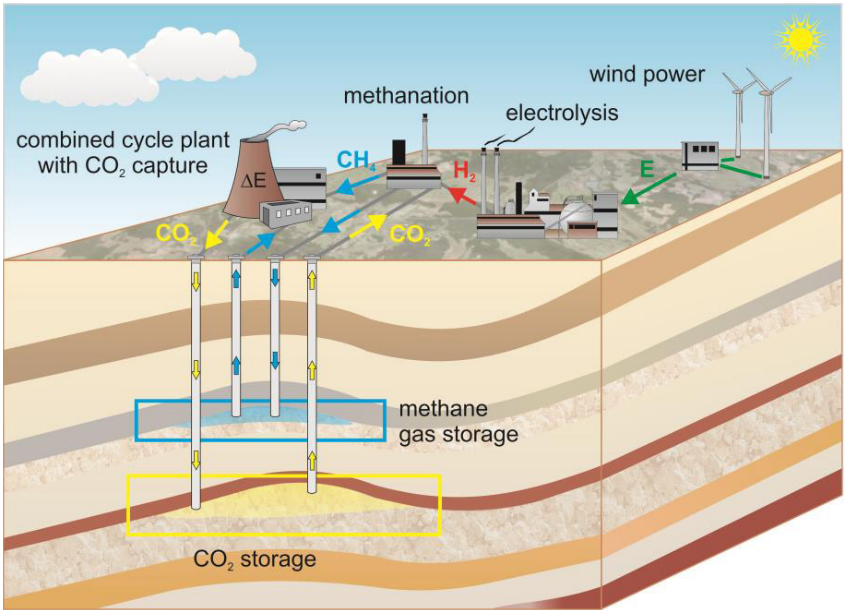

Fig. 2. Schematic of integrated underground storage of CO_2 and CH_4 to decarbonise the "power-to-gas-to-power" technology.

6. Conclusion

Ambitious climate and energy targets were set by the German government in 2011. In the course of the "Energiewende" and the country's withdrawal from nuclear energy, the Federal Government foresees renewable energy resources to become the central pillar of the future energy supply. Here, the utilization of the geological underground obtains a new relevance. It will contribute significantly to the implementation of the energy policy as both, potential energy source and storage site for matter and energy. Different studies show that a greenhouse gas-neutral Germany is technically possible and economically feasible by 2050.

Heat supply by shallow and deep geothermal energy is considered state of the art in Germany, whereas large-scale production of electricity from geothermal energy is not yet possible. For research on deep geothermal resources GFZ established the in-situ laboratory Groß Schönebeck north of Berlin.

With more than 50 years of experience, subsurface storage of CH_4 to balance seasonal demand and supply is a well-developed technology in Germany. Furthermore, research on geological CO_2 storage as one promising technique to reduce CO_2 emissions into the atmosphere is ongoing at the Ketzin project demonstrating safe CO_2 storage on a pilot scale.

Excess energy produced from renewables can be stored and reused via the power-to-gas-to-power technology. This technology might be extended by integrated underground storage of CH_4 and CO_2 to close the entire carbon cycle.

References

[1] Federal Ministry of Economics and Technology. Germany's new energy policy - Heading towards 2050 with secure, affordable and environmentally sound energy. Berlin: 2012; 55 pp.

[2] Federal Ministry for the Envirionment, Nature Conservation, Building and Nuclear Safety; http://www.bmub.bund.de/themen/klima-energie/klimaschutz/berichterstattung/artikel/daten-zu-den-treibhausgasemissionen-in-deutschland/. Accessed: 24 April 2015.

[3] Enerdata. Global Energy Statistical Yearbook 2014; https://yearbook.enerdata.net/. Accessed: 24 April 2015.

[4] Kümpel J. Situation der Energierohstoffe – Retrospektive und Ausblick. In: Kausch P, Bertau M, Gutzmer J, Matschullat J, editors. Energie und Rohstoffe – Gestaltung unserer nachhaltigen Zukunft. Spektrum Akademischer Verlag, Heidelberg; 2011, p. 27-39.

[5] Purr K, Strenge U, Werner K, Nissler D, Will M, Knoche G, Volkens A (eds.). Germany in 2050 - a greenhouse gas-neutral country. Climate Change 07/2014. Federal Environment Agency 2014; 360 pp.

[6] Paschen H, Oertel D, Grünwald R. Possibilities for geothermal electricity generation in Germany – Summary. Working report no. 84. Office of Technology Assessment at the German Bundestag 2003.

[7] Henning HM, Palzer A. A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies - Part I: Methodology. Renewable and Sustainable Energy Reviews 2014; 30: 1003-1018.

[8] Kaltschmitt M, Streicher W, Wiese A. Erneuerbare Energien - Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. Springer Vieweg, Heidelberg, 931 pp; 2013.

[9] Kühn M, Nakaten N, Streibel M, Kempka T. CO_2 geological storage and utilization for a carbon neutral "power-to-gas-to-power" cycle to even out fluctuations of renewable energy provision. Energy Procedia 2014; 63: 8044-8049. doi: 10.1016/j.egypro.2014.11.841.

[10] Kühn M, Streibel M, Nakaten N, Kempka T. Integrated underground gas storage of CO_2 and CH_4 to decarbonise the "power-to-gas-to-gas-to-power" technology. Energy Procedia 2014; 59: 9-15. doi:10.1016/j.egypro.2014.10.342.

[11] Scheck-Wenderoth M, Schmeißer D, Mutti M, Kolditz O, Huenges E, Schultz HM, Liebscher A, Bock M: Geoenergy: new concepts for utilization of geo-reservoirs as potential energy sources. Environ Earth Sci 2013; 70: 3427-3431. doi: 10.1007/s12665-013-2877-y.

[12] Working Group on Renewable Energy Statistics (AGEE-Stat). http://www.erneuerbare-energien.de/die-themen/datenservice/agee-stat/

[13] Weber J, Ganz B, Schellschmidt R, Sanner B, Schulz R. Geothermal energy use in Germany. Proceedings World Geothermal Congress 2015. Melbourne, Australia, 19-25 April 2015.

[14] LBEG. Untertage-Gasspeicherung in Deutschland (Underground gas storage in Germany). State Authority for Mining, Energy and Geology (LBEG). Erdöl Erdgas Kohle 2014; 130, 11: 402-411.

[15] Frick S, Regenspurg S, Kranz S, Milsch H, Saadat A, Francke H, Brandt W, Huenges E. Geochemical and process engineering challenges for geothermal power generation. Chemie - Ingenieur - Technik 2011; 83, 12: 2093-2104. doi:10.1002/cite.201100131.

[16] Würdemann H, Möller F, Kühn M, Heidug W, Christensen NP, Borm G et al. CO_2SINK - From site characterisation and risk assessment to monitoring and verification: One year of operational experience with the field laboratory for CO_2 storage at Ketzin, Germany. Int J Greenhouse Gas Control 2010; 4 (6): 938-951. doi:10.1016/j.ijggc.2010.08.010.

[17] Prevedel B, Wohlgemuth L, Legarth B, Henninges J, Schütt H, Schmidt-Hattenberger C et al. The CO_2SINK boreholes for geological CO_2-storage testing. Energy Procedia 2009; 1: 2087-2094. doi:10.1016/j.egypro.2009.01.272.

[18] Martens S, Möller F, Streibel M, Liebscher A, the Ketzin Group: Completion of five years of safe CO_2 injection and transition to the post-closure phase at the Ketzin pilot site. Energy Procedia 2014; 59: 190-197. doi: 10.1016/j.egypro.2014.10.366.
[19] Liebscher A, Möller F, Bannach A, Köhler S, Wiebach J, Schmidt-Hattenberger C, Weiner M, Pretschner C, Ebert K., Zemke J. Injection operation and operational pressure-temperature monitoring at the CO_2 storage pilot site Ketzin, Germany - Design, results, recommendations. Int J Greenhouse Gas Control 2013; 15: 163-173. doi:10.1016/j.ijggc.2013.02.019.
[20] Giese R, Henninges J, Lüth S, Morozova D, Schmidt-Hattenberger C, Würdemann H, Zimmer M, Cosma C, Juhlin C, CO_2SINK Group. Monitoring at the CO_2SINK Site: A Concept Integrating Geophysics, Geochemistry and Microbiology. Energy Procedia 2009; 1 (1): 2251-2259.
[21] Martens S, Kempka T, Liebscher A, Möller F, Schmidt-Hattenberger C, Streibel M, Szizybalski A, Zimmer M. Field experiment on CO_2 back-production at the Ketzin pilot site. Energy Procedia 2015; this issue.
[22] Streibel M, Nakaten, N, Kempka, T, Kühn, M. Analysis of an integrated carbon cycle for storage of renewables. Energy Procedia 2013; 40: 202-211.