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Completion of five years of safe CO_2 injection and transition to the post-closure phase at the Ketzin pilot site

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Abstract

The Ketzin pilot site for geological storage of CO_2 in the German Federal State of Brandenburg about 25 km west of Berlin was the first European pilot site for onshore storage of CO_2 in saline aquifers. A total amount of 67 kt of CO_2 was injected without any safety issues between June 2008 and August 2013 when injection ceased and the site entered the post-closure phase. Research and activities on site will continue in order to address and finally close the entire life cycle of the storage site. Within the post-closure phase the multidisciplinary monitoring program will further be applied and a stepwise abandonment of the five wells is foreseen which has already started with the partial plugging of one observation well in fall 2013.

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Keywords: carbon dioxide storage; Ketzin pilot site; saline aquifer; CO_2 injection; operation; monitoring; post-closure; well abandonment

1. Introduction

In the context of climate policy, capture of carbon dioxide (CO_2) for geological storage is a potential measure to reduce anthropogenic greenhouse gas emissions. This conclusion has been strengthened in the recent IPCC report which assigns CO_2 storage an important role in limiting the global temperature increase by 2 degrees after 2100 [1]. One of the most promising storage options to be utilized in Carbon Capture and Storage (CCS) projects are saline aquifers [2]. The Ketzin pilot site in Germany is an example of this storage type. It is located about 25 km west of

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Berlin in the Federal State of Brandenburg (Fig. 1a). The Ketzin project was initiated by the GFZ German Research Centre for Geosciences in 2004 as the first onshore project in Europe that is dedicated to research and development (R&D) for a better understanding of geological CO_2 storage [3-6].

Injection of CO_2 began in June 2008 and ceased in August 2013 after injecting a total amount of 67 kt of CO_2. Thus the Ketzin project represents 62 months of valuable experience in operating a CO_2 storage site [7] and has achieved an enviable record of monitoring data from different disciplines. In this paper, we give a comprehensive overview on the injection operation, the monitoring concept and outline future activities within the post-closure phase. For additional information and further reading on accompanying laboratory and modelling studies for the Ketzin project the reader is kindly referred to e.g. Fischer et al. 2013 [8] and Kempka et al. 2013 [9].

2. The Ketzin pilot site

2.1. Life cycle phases

Fig. 2 shows the life cycle for the Ketzin pilot site separated into the six fundamental phases according to the European Directive on the Geological Storage of Carbon Dioxide [10]. It has to be noted that the Ketzin site was permitted under the German Mining Law, thus transfer of liability will finally follow the regulations set by the German Mining Law. However, R&D activities on CO_2 storage will continue in order to address and close the entire life cycle of the storage site according to the EU Directive.

The figure also depicts major milestones that have already been achieved in the project. These include the start of the first research project CO_2SINK in 2004 which was funded by the European commission and industry until 2010. Up to now, the research activities at the pilot site Ketzin have received funding from a total of 18 German and European projects. Milestones also include the permits of the main and several special operation plans by the Brandenburg State Mining Authority which allowed e.g. for the necessary drilling work and injection. Phase 5 has started after cease of the CO_2 injection in August 2013. Well abandonment, post-injection monitoring and transfer of liability are the major objectives of the current life cycle phase.

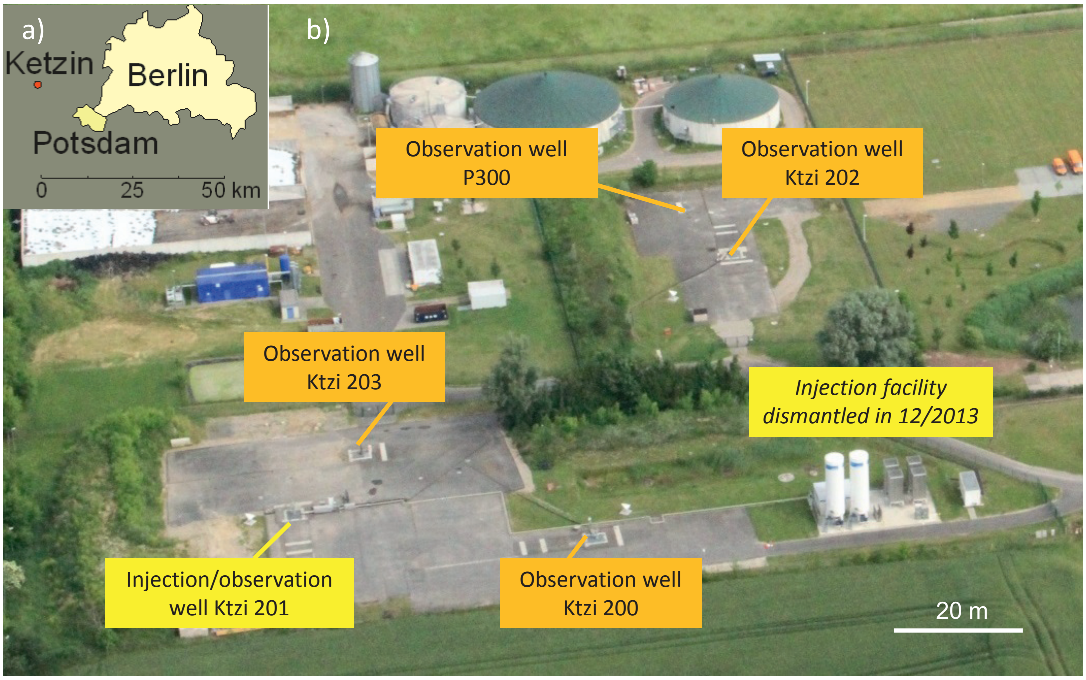

Fig. 1. Ketzin pilot site (a) location; (b) aerial view with scientific infrastructure in June 2013, looking northwest

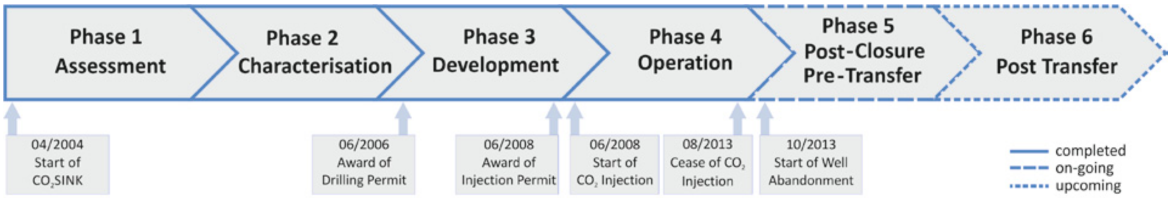

Fig. 2. Summary of life cycle phases of the Ketzin pilot site and major milestones

2.2. Research infrastructure

To meet the operational and scientific needs of the Ketzin project a total of five wells (Fig. 1b) were drilled in three campaigns between 2007 and 2012 and an injection facility was built in 2008. Prior to the start of injection the boreholes Ktzi 200, Ktzi 201 Ktzi 202 were drilled to a depth of about 750 m to 800m [11]. The well Ktzi 201 was used as a combined injection and observation well while the other two serve as pure observations wells. In summer 2011, the shallow observation well P300 was drilled for above-zone monitoring within the indicator horizon [6]. This 446 m deep borehole reaches into the lowermost aquifer above the cap rock. In summer 2012, the infrastructure was completed by the 701 m deep observation well Ktzi 203 which was drilled close to the injection point to gain rock cores from the cap rock and reservoir which have been in contact with the injected CO_2 for more than four years and is also used for monitoring.

All four deep wells are completed with a smart casing concept [11] which include permanently installed cables for distributed temperature sensing (DTS) and heating experiments, 45 electrodes (Vertical Electrical Resistivity Array VERA; apart from well Ktzi 203), pressure and temperature (p-T) gauges. The shallow well P300 is equipped with two pressure sensors and a U-tube fluid sampling system for pressure and fluid monitoring of the indicator horizon [6].

2.3. Injection history

CO_2 injection at Ketzin began on June 30, 2008 and ended on August 29, 2013. During this period of over five years, a total amount of 67 kt of CO_2 was injected without any health, safety or environmental issues into a saline aquifer (Upper Triassic sandstone layers) of the Northeast German Basin at a depth of 630-650 m. The CO_2 used was mainly of food grade quality (purity > 99.9%). In addition, 1.5 kt of captured CO_2 from the Vattenfall oxyfuel pilot plant Schwarze Pumpe (power plant CO_2 with purity > 99.7%) was used from May to June 2011. In July and August 2013, a co-injection experiment with CO_2 and N_2 was performed to test and demonstrate the technical feasibility of a continuous impure CO_2 injection scenario. A total of 613 tons CO_2 and 32 tons N_2 were continuously mixed on site and injected resulting in an average CO_2 to N_2 mass ratio of approximately 95 to 5.

The CO_2 was delivered in liquid state by road tankers to the Ketzin pilot site and stored in two intermediate storage tanks (Fig. 3a) at about -18°C and 18 bars on site. Prior to injection, the CO_2 was preconditioned: Plunger pumps raised the pressure to the necessary injection pressure and CO_2 was pre-heated to 45°C by ambient air heaters and an electrical heater in order to avoid liquid-vapour phase transition of the injected CO_2 and associated pressure build-up within the reservoir. The CO_2 was transported via a pipeline to the well Ktzi 201. Typical injection rates ranged between 1,400 and 3,250 kg CO_2/h with a maximum monthly injection rate of 2,300 tons.

Within a so called “cold-injection” experiment between March and July 2013, the injection temperature was stepwise reduced from 45°C down to 10°C to study the thermodynamics in the wellbore for an injection at ambient temperatures and its impact on the reservoir. A total amount of 3 kt of CO_2 was injected throughout this experiment where monitoring included injection wellhead and downhole pressure, temperature point information and profiles. Down to an injection temperature of 25°C the entire injection process continued to occur single-phase with gaseous CO_2. At an injection temperature of 20°C, the CO_2 started to condense liquid CO_2 droplets and the injection process occurred under two-phase conditions in the surface installations and the upper parts of the injection well Ktzi 201.

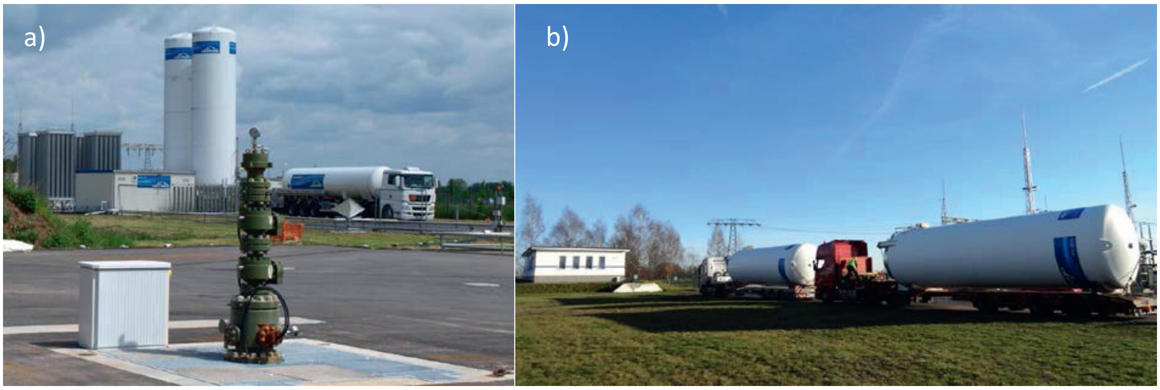

Fig. 3. (a) View of the Ketzin pilot site in May 2013, looking southeast to the observation well Ktzi 203 (foreground) and the injection facility (background) with ambient air heaters (left), two intermediate storage tanks (middle), CO_2 delivery by road tanker and pipeline (right); (b) Dismantling of the tanks in December 2013.

Due to increasing temperature with increasing depth, these liquid CO_2 droplets re-evaporated in the injection well and the lower part of the well was again single-phase. Decreasing the injection temperature to 15°C and finally 10°C resulted in two-phase conditions throughout the entire injection process and pressure fluctuations within the wellbore Ktzi 201 (Fig. 4). Corresponding pressure fluctuations at the nearby well Ktzi 200 located 50m away from the injection point could not be observed. The injection facility was finally dismantled in December 2013 (Fig. 3b).

3. Monitoring and well abandonment

3.1. Multidisciplinary monitoring

The integrated monitoring concept at Ketzin includes a wide range of techniques from different disciplines as listed in Table 1 in order to study the well and reservoir behavior and to monitor the CO_2 migration in the underground on different spatial and temporal scales.

The operational monitoring during CO_2 injection was mainly based on pressure and temperature data which was continuously acquired on site. This program included e.g. measurements of fill levels in the two intermediate storage tanks, outlet temperature of the injection facility, injection rate, wellhead pressures, annular pressures for all wells, bottom hole pressure and distributed temperature sensing (DTS) along the injection tubing for the injection well Ktzi 201 [7]. This pressure-temperature monitoring successfully ensured and proved a safe and reliable injection over the 62 months of operation [7].

Fig. 4 depicts the downhole pressure evolution at 550 m depth in well Ktzi 201 and the cumulative mass of injected CO_2 for the period between June 2008 and December 2013. Due to the CO_2 injection since June 2008, the pressure rose from initially 60.4bar to a maximum of 76 bar in June 2009. From late summer 2009 until spring 2010 pressure stabilized between ~74 and 76 bar. By spring 2010, the overall mean injection rate was lowered and pressure smoothly decreased and again stabilized between ~70 and 73 bar until spring 2012 reflecting a stable injection regime. A positive correlation between injection rate and reservoir pressure was also noticed on the short term during shut-in phases, e.g. mid-2012 during drilling of well Ktzi 203, which were accompanied by an almost instantaneous decrease in reservoir pressure. With the stop of the CO_2 injection in August 2013, the pressure started to continuously decrease and evolves back towards initial reservoir conditions. Operational monitoring also shows that the downhole pressure was always significantly below the maximum approved pressure of 83 bar at 550m depth as permitted by the Mining Authority.

Table 1. Summary of main monitoring techniques and tools used at the Ketzin pilot site

Monitoring approach	Frequency/date	Selected references (sorted by publication year)
Operational monitoring		
Wellhead, casing, bottom hole pressures; temperature gauges; distributed temperature sensing (DTS)	permanently	Giese et al. 2009 [12]; Henninges et al. 2011 [13]; Möller et al. 2012 [14]; Wiese et al. 2012 [15]; Liebscher et al. 2013 [7]; Wiese et al. 2013 [16]
Well logging tools	~annually	Henninges et al. 2011 [13]; Baumann 2013 [17]; Martens et al. 2013 [6]
Seismic methods		
Active seismic - surface-surface (3D/4D) - surface-surface (star survey) - surface-downhole (VSP, MSP) - crosshole	 2005, 2009, 2012 2005, 2009, 2011 2007, 2009, 2011 2008, 2009	Juhlin et al. 2007 [18]; Yang et al. 2010 [19]; Bergmann et al. 2011 [20]; Lüth et al. 2011 [21]; Ivandic et al. 2012 [22]; Ivanova et al. 2012 [23]; Xu et al. 2012 [24]; Zhang et al. 2012 [25]; Ivanova et al. 2013 [26]
Passive seismic	permanently	Arts et al. 2011, 2013 [27, 28]
Eletrical and electro-magnetic methods		
Electrical resistivity tomography (ERT) - crosshole - surface-downhole - surface-surface	 weekly 2007, '08, '09, '11, '12 2009, 2011, 2012	Kiessling et al. 2010 [29]; Schmidt-Hattenberger et al. 2011, 2012 [30, 31]; Bergmann et al. 2012 [32]; Schmidt-Hattenberger et al. 2013 [33]; Bergmann et al. 2014 [34]
Controlled-source electromagnetics (CSEM)	periodic field tests	Girard et al. 2011 [35]; Streich et al. 2011 [36]; Grayver et al. 2014 [37]
Other methods		
Surface CO_2 flux measurements	biweekly to monthly	Zimmer et al. 2011 [38]; Liebscher et al. 2012 [39]; Martens et al. 2013 [6]
Fluid sampling from wells for geochemical and microbial monitoring	monthly to annually	Giese et al. 2009 [12]; Würdemann et al. 2010 [3]; Myrtinnen et al. 2010 [40]; Scherf et al. 2011 [41]; Zimmer et al. 2011 [42]; Martens et al. 2012 [5]; Morozova et al. 2013 [43]; Nowak et al. 2013 [44]; Wiese et al. 2013 [16]
Interferometric Synthetic Aperture Radar (InSAR)	permanently	Lubitz & Motagh 2013 [45]

Periodic logging at all four deep wells includes pulsed neutron-gamma for saturation measurements, video inspections and magneto-inductive defectoscopy (MID) measurements to study and characterize the state of the wellbores, e.g. possible degradation of the steel casings. In connection with the logging campaings, fluid samples are gained from the pressurized wellbores for further geochemical and microbial analysis. The repeat saturation measurements, which have been conducted since 2009 at least annually, imaged the CO_2 accumulation within the reservoir sandstone horizons but gave no indication to any upward migration of CO_2 along the wellbores [39]. The video inspections of the wellbores provided also no hints to any pitting corrosion of the innermost casings. The logging campaigns prove that the wellbore integrity is given and has not deteriorated due to CO_2 injection. Logging will also continue in the post-injection phase.

The geophysical methods applied at Ketzin mainly consist of seismic and electrical techniques which play a key role for the non-invasive monitoring and the spatial and temporal characterization of the underground processes. Further monitoring includes geochemical measurements such as CO_2 flux surface measurements and fluid sampling from the wells which are done on a monthly (shallow well P300) to annual basis (deep wells). The combination of both geophysical and geochemical monitoring demonstrates that we are able to detect and image even small amounts of CO_2 and gives no indication for CO_2 leakage at the Ketzin pilot site [5, 46].

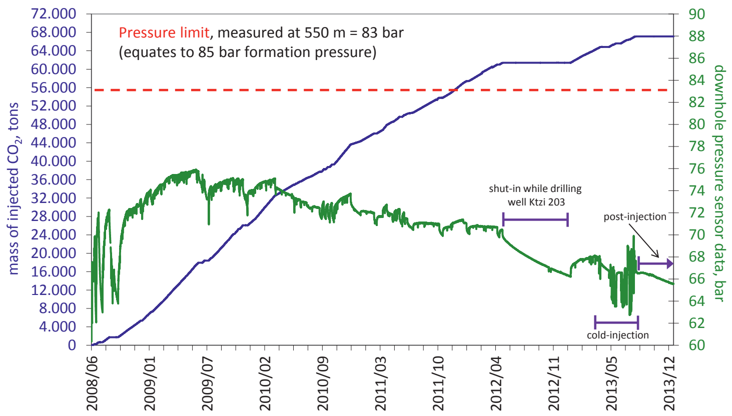

Fig. 4. Injection history showing cumulative mass of injected CO_2 (blue) and measured pressure at 550 m depth in well Ktzi 201 (green). The reservoir pressure at 630 m is about 2 bars higher than the measured pressure at 550 m. The red line refers to the maximum permitted pressure of 85 bars at reservoir depth.

3.2. Stepwise well abandonment

An essential step of the ongoing project phase is the abandonment of the five wells. As long as the wells are accessible, logging and monitoring which relies on wellbore installations, e.g. the VERA system, will continue in order to further characterize the state of the wells and assess their integrity.

The well abandonment will be done stepwise and it already started with the partial plugging of the observation well Ktzi 202 in the lower interval including the CO_2 reservoir section in September 2013. A special CO_2 resistant cement blend was used from 729 m to 521 m below ground surface which is monitored for its tightness over the using a gas membrane sensor GMS [47] and a pressure sensor in 500 m depth. The well is accessible above the cement plug and the DTS cable and the geoelectrical array are also still in operation for further monitoring.

The observation well Ktzi 202 is planned to be fully abandoned in 2015. The abandonment of the other wells is scheduled for 2016. During abandonment, materials like cement, casing and elastomers will be sampled and analysed in order to study if and how the materials have been affected by the CO_2 environment.

4. Conclusion and outlook

The Ketzin project demonstrates successful and safe CO_2 storage in a saline aquifer on a pilot scale. With the cease of injection in August 2013, the project has entered the post-closure and pre-transfer phase. The overall aim at Ketzin is to close the complete life-time cycle of a CO_2 storage site at pilot scale.

Within the post-closure phase a series of activities and further investigations are foreseen: The five wells will be successively abandoned while monitoring will continue. The partial plugging of one observation well in the reservoir section was already completed in fall 2013. The recent four-years project COMPLETE started in January 2014. Activities within COMPLETE include further R&D work on well integrity, post-closure monitoring, e.g. the third 3D seismic repeat, and two more field experiments. The one is a back-production test of the CO_2 in 2014 aiming at information on the physicochemical properties of the back-produced CO_2 and the pressure response of the reservoir. The other test will focus on a small-scale brine injection into the CO_2 reservoir in order to study e.g. the residual gas saturation and the potential as a means for wellbore leakage mitigation.

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