Martens, S., Liebscher, A., Möller, F., Henninges, J., Kempka, T., Lüth, S., Norden, B., Prevedel, B., Szizybalski, A., Zimmer, M., Kühn, M., Ketzin Group (2013): CO2 Storage at the Ketzin Pilot Site, Germany: Fourth Year of Injection, Monitoring, Modelling and Verification. - Energy Procedia, 37, 6434-6443

DOI: 10.1016/j.egypro.2013.06.573

CO_2 storage at the Ketzin pilot site, Germany: Fourth year of injection, monitoring, modelling and verification

Sonja Martens[a]*, Axel Liebscher[a], Fabian Möller[a], Jan Henninges[a], Thomas Kempka[a], Stefan Lüth[a], Ben Norden[a], Bernhard Prevedel[a], Alexandra Szizybalski[a], Martin Zimmer[a], Michael Kühn[a] and the Ketzin Group

[a]GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Abstract

At Ketzin, located west of Berlin, the GFZ German Research Centre for Geosciences operates Europe's longest-running on-shore CO_2 storage site. The Ketzin pilot site has been developed since 2004 and comprises three wells to depths of 750 m to 800 m and one shallow observation well, an injection facility and permanently installed monitoring devices. Since June 2008, CO_2 is injected into 630 m to 650 m deep sandstone units (Upper Triassic Stuttgart Formation) in an anticlinal structure of the Northeast German Basin. Until mid of May 2012, about 61,400 t of CO_2 have been stored safely. One of the most comprehensive monitoring concepts worldwide is applied and capable of detecting the behaviour of the CO_2 in the subsurface. The Ketzin project demonstrates safe CO_2 storage in a saline aquifer on a research scale and effective monitoring. This paper summarizes the key results obtained after four years of CO_2 injection.

Selection and/or peer-review under responsibility of GHGT

*Keywords:*carbon dioxide storage; Ketzin pilot site; saline aquifer; CO_2 injection; drilling; monitoring; modelling

1. The Ketzin Pilot Site

1.1. Site Setting

The Ketzin pilot site is located about 25 km west of Berlin and Potsdam in the Federal State of Brandenburg in Germany (Fig. 1.a). It is a pure research facility which has been developed and where multidisciplinary research activities on geological storage of carbon dioxide (CO_2) have been conducted

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

since 2004 [1]. Experiences gained from the first three years of injection were summarized in several publications [2] [3] [4]. The present paper provides a comprehensive overview of the status of the Ketzin project after four years of CO_2 injection.

1.2. Boreholes and CO_2 injection

The Ketzin site comprises an injection facility with a pipeline as well as three deep wells with depths of 750 m to 800 m and one shallow well (Fig. 1.b). One deep well (CO_2 Ktzi 201/2007; abbreviated as Ktzi 201) serves as a combined injection and observation well, while the other two (CO_2 Ktzi 200/2007, CO_2 Ktzi 202/2007; abbreviated as Ktzi 200 and Ktzi 202) are only used for observation [5]. The infrastructure was complemented by a shallow observation well (Hy Ktzi P300/2011; abbreviated as P300) in summer 2011. This 446 m deep well reaches into the sandstones of the first aquifer above the Stuttgart Formation, thus enabling an above-zone monitoring of the CO_2 storage [4].

For the upper part of the P300 well the airlift drilling technique (Fig. 2) originating from the construction business was for the first time deployed at the Ketzin site. This technique requires the usage of a modified rock bit equipped with a center nozzle and a double wall drill pipe for the air injection into the inside of the pipe. Mud is injected into the borehole annulus and enters the drill pipe internal at the drill bit. Compressors at the surface push air into the internal drill pipe creating a pressure differential from the borehole annulus to the inner side of the drill pipe. This enables the flow of drill mud at the bit face towards the bits center nozzle and transportation of the drilled rock cuttings through the bit and inside the double wall drill pipe to the surface. Due to its low differential pressure at the bit, airlift drilling ensures a minimum of drilling mud rock invasion and therefore maximum borehole wall stability.

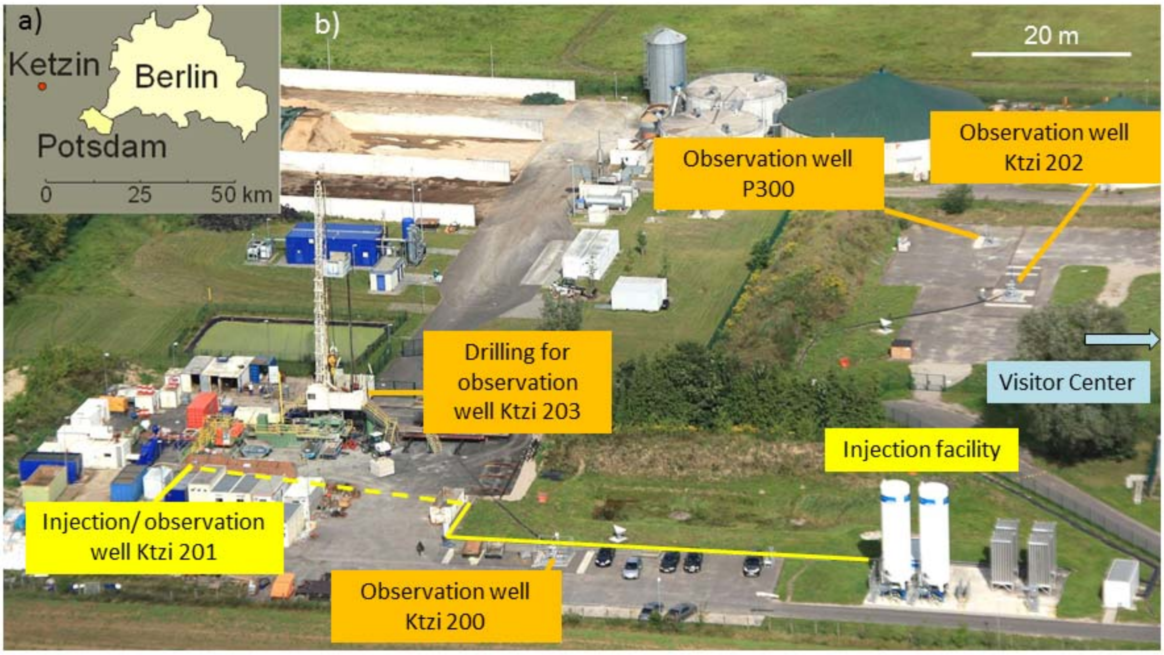

Fig. 1. Ketzin pilot site (a) location; (b) aerial photograph with infrastructure and drilling for well Ktzi 203 (September 2012)

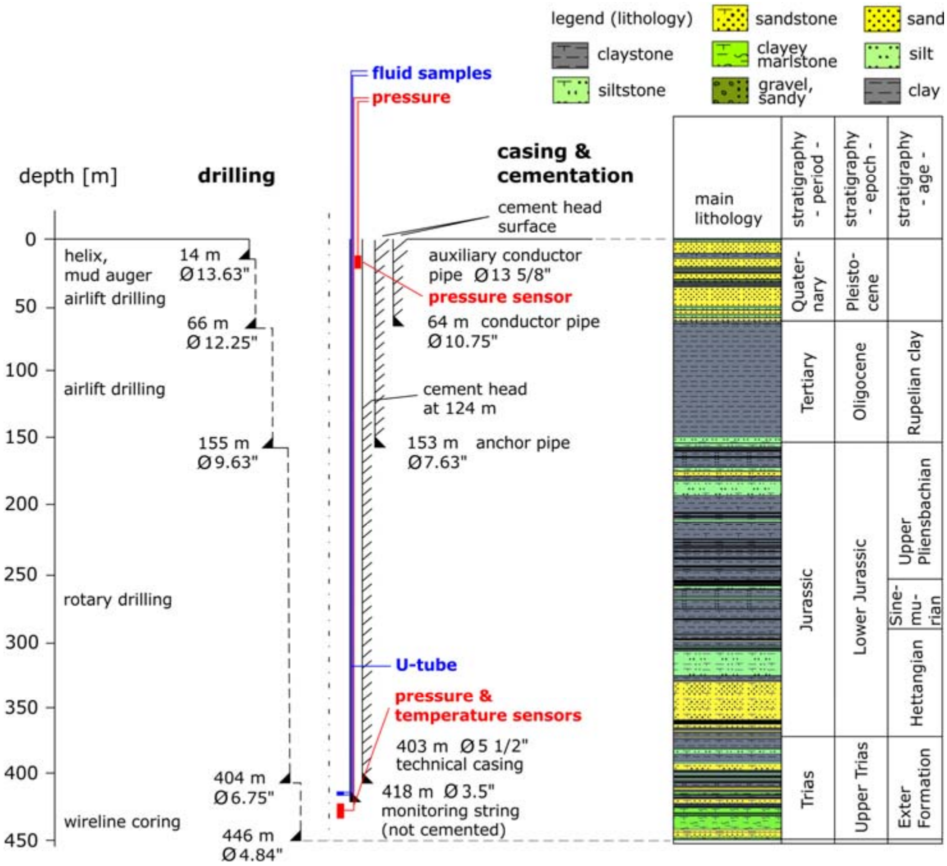

Fig. 2. Observation well Hy Ktzi P300/2011 (a) drilling design and well completion; (b) simplified geological profile

With standard rotary drilling the top hole well sections at the Ketzin location suffered in former campaigns from hole caving problems due to swelling shales and reversed circulation. Airlift drilling solved this problem successfully. On the downside, this technique is limited in drilling depth to a few hundred meters and the achieved penetration rates at Ketzin were reduced by approximately 50 % compared to classic rotary drilling. Additional rental of specialized drilling hardware is also somewhat defeating the advantage of this method. Below 155 m depth, classic rotary drilling technique was deployed at borehole P300 as with the previous Ketzin wells.

The geological succession encountered by the P300 borehole is very similar to the geology observed at the other Ketzin boreholes [6]. From 404.0 m to 446.1 m below ground level, 40.9 m of best quality cores were retrieved, allowing a detailed analysis of the mineralogy and geochemical properties of the Triassic Exter Formation. The sedimentary succession of the cored section consists of marly mudstones, siltstones, and sandstones. The mudstones show dark reddish brown to very dark red colors. At the upper part of the cored interval, two sandy units with high porosities and a thickness of about three meters each were encountered (from 407 m to 410 m and from 415 m to 418.5 m, respectively). In the lower part of the interval, a 5 m thick sandy but less porous interval was cored (438 m to 443 m). The sandstones are fine-grained to middle-grained with a variable content of silty to clayey components. In contrast to the mudstones the colors of the sandstones are more diverse, ranging from dark grayish colors, dominating the upper two sandstones, to light grayish to grayish blue-green and reddish-orange colors of the lower less-porous sandstones.

A U-tube system is installed in well P300 for sampling of formation water and gas from a depth of 417 m in order to detect any potential leakage through the first caprock of the storage horizon at an earliest stage possible. The water samples which are analyzed for their dissolved cations, anions, gases and $^{12}C/^{13}C$ isotope ratio of CO_2 have revealed no impact of the injected CO_2 on the Exter Formation. Additionally, well P300 is equipped with high resolution pressure/temperature sensors at two depth levels.

Drilling of a fifth well (Ktzi 203) near the injection point is underway in summer 2012. This new observation well will have a final depth of ~ 700 m. It will also be equipped with permanent devices for temperature and pressure monitoring. In addition, well Ktzi 203 will provide an opportunity to gain rock cores from the storage reservoir which have been exposed to the CO_2 for about four years.

Injection of CO_2 commenced at Ketzin on June 30, 2008. Thus Ketzin is the longest-operating on-shore CO_2 storage project in Europe and still the only storage site in Germany. The target saline aquifer is the Upper Triassic Stuttgart Formation situated at about 630 m to 710 m depth [7]. Since June 2008, 61,402 t CO_2 were stored without any safety issues until mid of May 2012, when the injection was temporarily interrupted due to the drilling operations for the well Ktzi 203.

2. Multidisciplinary Monitoring

A unique and multidisciplinary monitoring concept is applied and operated at the Ketzin pilot site [8]. In this contribution, we focus on borehole monitoring, active seismic methods and gas monitoring.

In well Ktzi 201, the downhole pressure is continuously monitored via an optical pressure-temperature gauge. This sensor is installed at a depth of 550 m directly above the end of the injection tubing. Fig. 3 shows the results of the pressure monitoring with the increasing amount of CO_2 injected. In situ data show a positive correlation between the injection rate (cf. change in slope of cumulative mass curve in Figure 3) and the reservoir pressure which is well below the pressure limit for the Ketzin project as defined by the mining authority. The CO_2 injection stop in May 2012 was accompanied by a decrease in reservoir pressure.

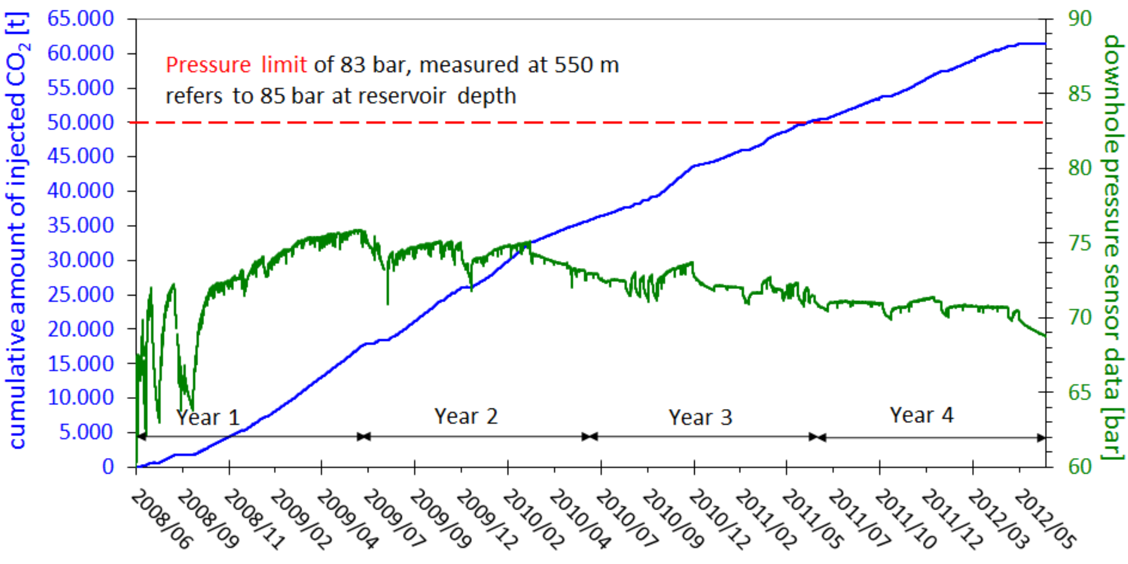

Fig. 3. Evolution of downhole pressure and cumulative mass of injected CO_2 over four years of operation

Fluid saturation changes and the vertical CO_2 distribution at borehole scale are determined using a combination of pulsed neutron-gamma (PNG) and pressure-temperature wireline logging as well as distributed temperature sensing (DTS). The temperature distribution along the wells is continuously monitored using fiber-optic DTS cables which are permanently installed downhole. New PNG repeat logging runs were recorded in March and October 2011 (Table 1) with simultaneous acquisition of downhole pressure and temperature logs.

Table 1. Overview of PNG and pressure-temperature wireline logging campaigns between 2008 and 2011

	Baseline (BL)	**Repeat 1 (R1)**	**Repeat 2 (R2)**	**Repeat 3 (R3)**	**Repeat 4 (R4)**	**Repeat 5 (R5)**
Well fluid	Brine	Brine	CO_2	CO_2	CO_2	CO_2
Ktzi 200	10.06.2008	21.07.2008	25.06.2009	22.03.2010	01.03.2011	13.10.2011
Ktzi 201	09.06.2008	-	24.06.2009	23.03.2010	03.03.2011	14.10.2011
Ktzi 202	09.06.2008	-	26.06.2009	22.03.2010	02.03.2011	12.10.2011

The temperature conditions in well Ktzi 201 are controlled by the injection regime, i.e. the injection temperature and rate. Changes of the injection regime and resulting short-term temperature changes of the injected CO_2 at depth enable a localization of the injection intervals. Within the observation wells, the temperature conditions are dominated by a heat-pipe process with condensation and evaporation of CO_2 in the upper and lower sections of the wells, respectively [9]. In 2011, the two-phase interval expanded further down into the reservoir interval. The pressure differences along the wells depend on the phase conditions and the corresponding CO_2 density within the wells. Due to the observed heat-pipe process the fluid column in the well is comprised by variable amounts of liquid- and vapor-phase CO_2.

During PNG logging, the macroscopic thermal capture cross section SIGMA is determined. The data of repeat 4 (Figure 4) shows a continued development towards decreasing CO_2 saturations in the lower injection intervals, which can be observed at Ktzi 201 since 2010 due to the decreased injection rate.

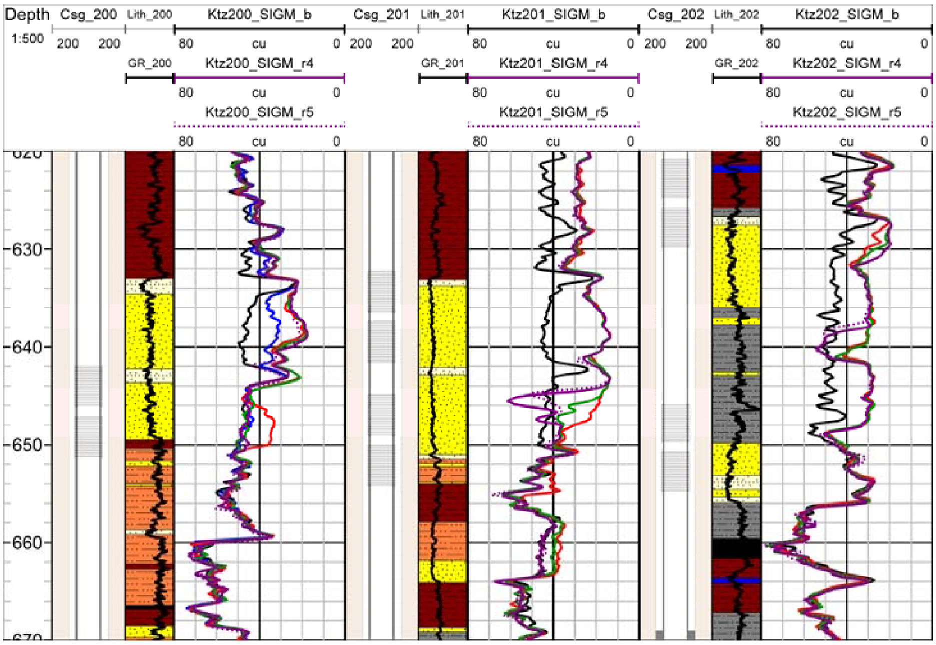

Fig. 4. SIGMA formation curves recorded during PNG wireline logging in well Ktzi 200, Ktzi 201 and Ktzi 202 (from left to right). Black: baseline, blue: repeat 1, red: repeat 2, green: repeat 3, purple: repeat 4, purple (dotted): repeat 5. Geology after [7]

At the Ktzi 202 observation well, a small but continuous decrease of SIGMA in the upper part of the sandstone layer at approximately 630 m depth indicates increasing CO_2 saturation within this interval. The SIGMA curves of repeat 5 recorded in October 2011 are almost identical to repeat 4 indicating that no significant changes of the saturation conditions have occurred during this time. During both repeat runs the recorded SIGMA curves have remained constant at depths of shallower aquifers above the storage interval, indicating that no changes of the saturation conditions, which could be caused e.g. by migration of CO_2 along the wells, have occurred. Based on the PNG results, a quantitative evaluation of the total CO_2 mass based on seismic data has been performed [10] (see below) and important implications for the evaluation of the surface-downhole electrical resistivity tomography measurements could be gained [11].

Repeated seismic and geoelectrical measurements are performed at Ketzin in order to monitor the propagation of the injected CO_2 in the reservoir. Crosshole, surface-downhole and surface-surface surveys are combined in order to image the reservoir at high resolution and to provide a comprehensive overview of the reservoir as a whole. The active seismic surveys are complemented by continuous passive monitoring in a dedicated borehole receiver array in shallow wells close to the injection well [12]. For imaging the complete CO_2 reservoir, 3D seismic surveys were acquired in 2005 (baseline), 2009 (first repeat) and 2012 (second repeat). The first 3D repeat survey was acquired while between 22 and 24 kilotons of CO_2 had been injected into the reservoir. The time-lapse signature of the injected CO_2 could be identified by increased reflectivity at the top of the storage formation and by increased two-way-travel time of reflectors below the reservoir due to a P-wave velocity reduction in the storage formation [10]. An integrated interpretation of the seismic signature was performed using petrophysical laboratory experiments and PNG results. This allows for quantifying the amount of stored CO_2 imaged by time-lapse seismics. According to this quantification, approximately 93 % to 95 % of the stored CO_2 were imaged by the first repeat 3D survey in autumn 2009 [10].

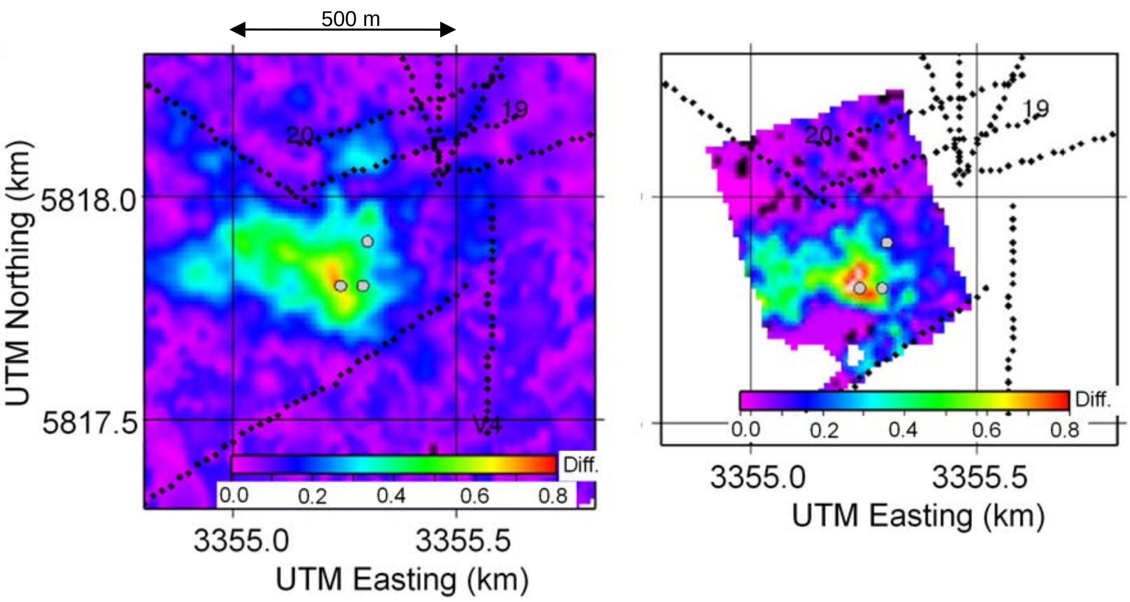

Fig. 5. Map view with comparison of difference amplitude signatures of CO_2 in the Stuttgart Formation, derived from the 2009 full 3D seismic repeat (left panel), and from the second repeat of the sparse profile acquisition (2011); modified from [13]. Grey dots indicate the location of the injection well Ktzi 201 and the observation wells Ktzi 200 and Ktzi 202

Full surface 3D seismic surveys are logistically demanding and mean, particularly in densely populated or farming areas, invasive and disturbing operations. It is therefore desired to avoid these operations and restrict the acquisition to easily accessible tracks. This approach, which is particularly attractive for the long-term monitoring of large storage sites and for the post-injection phase, was tested at Ketzin by the repeated acquisition of surface-surface data on sparse profiles. This resulted in 2D sections with high subsurface coverage along the profiles and a 3D volume with low and irregular subsurface coverage at the location of the injection well. In spite of the irregular subsurface coverage it was possible to provide a qualitative image of the CO_2 propagation in the storage formation [13]. Two repeat surveys were acquired (2009 and 2011), where the second revealed a significantly stronger anomaly compared to the first repeat. The results indicated, consistently with those of the full 3D repeat survey, a preferential propagation direction of the stored CO_2 towards the northwest (Figure 5).

A comprehensive gas monitoring network at Ketzin has been in operation since 2005 in order to acquire a solid baseline and to monitor upward migration of CO_2 with potential leakage to the surface. This network consists of 20 sampling locations for soil gas flux, soil moisture and temperature measurements distributed across an area of approximately 2 km x 2 km. Since the start of the injection in 2008, no change in soil CO_2 gas flux could be detected in comparison to the pre-injection baseline from 2005 to 2007 [14]. In 2011, this network was expanded with the installation of eight permanent stations with automated soil gas samples in the direct vicinity of the injection and observation wells. The data do not give any indication for CO_2 leakage and highlight the in-between station variability of CO_2 soil gas fluxes. The variability of the fluxes between the stations can be attributed to different organic carbon contents [14]. Figure 6 shows the CO_2 soil gas fluxes for two stations which are only about 20 m apart from each other. CO_2 soil gas fluxes at station 2 are up to 10 times higher than those measured at station 8 from April 2011 to May 2012 (interruption due to system failure in early 2012). These data highlight the need for a detailed and robust baseline for any surface CO_2 soil gas flux monitoring. Without knowing the overall background flux and its detailed spatial and temporal variability any statement on CO_2 leakage based on singular CO_2 soil gas flux measurements is at best questionable.

In-reservoir gas monitoring is performed with a riser tube installed in observation well Ktzi 202 since autumn 2011. Fluids are produced from a depth of 600 m with a flow rate of 5 l/min and continuously analyzed with a mass spectrometer. In this way, any change during the storage process can be registered immediately. The gas composition, dominated by CO_2 (> 99 vol. %) with traces of N_2, H_2, He and CH_4, as well as the $\delta^{13}C$-values of CO_2 were constant during the monitoring period.

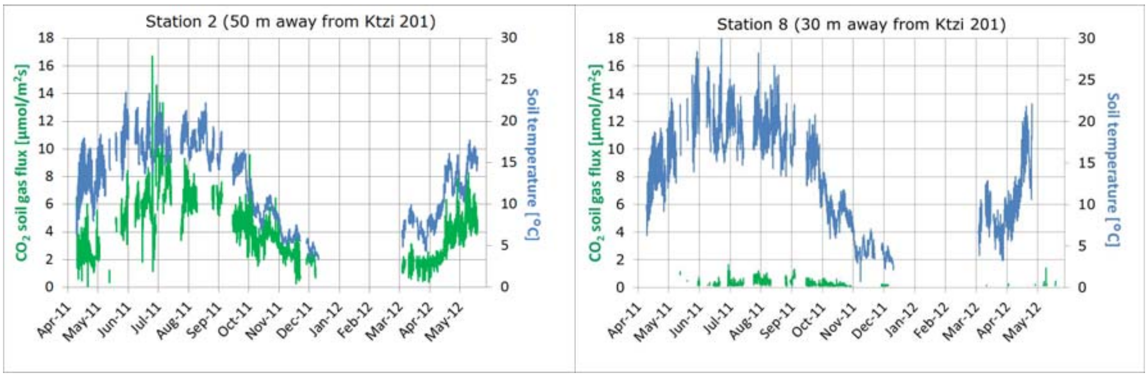

Fig. 6. Seasonal trend of CO_2 flux (green) and soil temperature at 40 cm depth (blue) from two stations (50 m and 30 m away from Ktzi 201). Difference in the CO_2 flux is explained by the organic carbon content of the soil (Station 2 = 0.91 %, Station 8 = 0.31 %)

3. Geological Modelling and Dynamic Simulations

Geological modelling of the Stuttgart Formation and dynamic simulations are regularly updated and accompany the entire lifetime of the Ketzin project. In advance of the first dynamic simulations, a reservoir model [15] using PETREL was developed taking into account all available geophysical and geological data including the heterogeneous lithology of the Stuttgart Formation [16]. Based on this geological model, reservoir simulations were conducted [17] and the first history matching for the injection period from June 2008 to April 2009. Although the simulated CO_2 arrival time at the observation well Ktzi 200 was in good agreement with the monitoring results, the arrival time at the observation well Ktzi 202 could not be matched together with the reservoir pressure, indicating that the geological model at that time did not represent the actual conditions at the Ketzin site.

Subsequently, the 3D geological model of the Stuttgart Formation was revised by integrating new monitoring data obtained from a 3D seismic (re-)interpretation, electrical resistivity tomography and well logging. The revised geological model formed the base for further reservoir simulations with the simulators ECLIPSE 100 [18] and TOUGH2-MP/ECO2N [19] [20] and a successful history matching for the period June 2008 to December 2011 [4]. The simulated CO_2 arrival times are in excellent agreement with the monitoring data for the well Ktzi 200 and in good agreement for the well Ktzi 202. Furthermore, a very good pressure match could be achieved for the injection well Ktzi 201 and the observation well Ktzi 202. Results from both simulators show almost identical spatial and temporal migration of the CO_2 plume and of average residual gas saturation [4]. Consequently, the validated reservoir model of the Stuttgart Formation enables us to predict pressure development and CO_2 distribution in the storage formation by dynamic flow simulations. Figure 7 shows the progressing of the gaseous CO_2 plume over a period of six years (2009 to 2014) where results from 2012 on are predictive. According to the simulations and in accordance with the seismic monitoring, the CO_2 plume moves further upward towards the top of the anticline structure, mainly in northwestern direction. The CO_2 migration is strongly determined by reservoir heterogeneity.

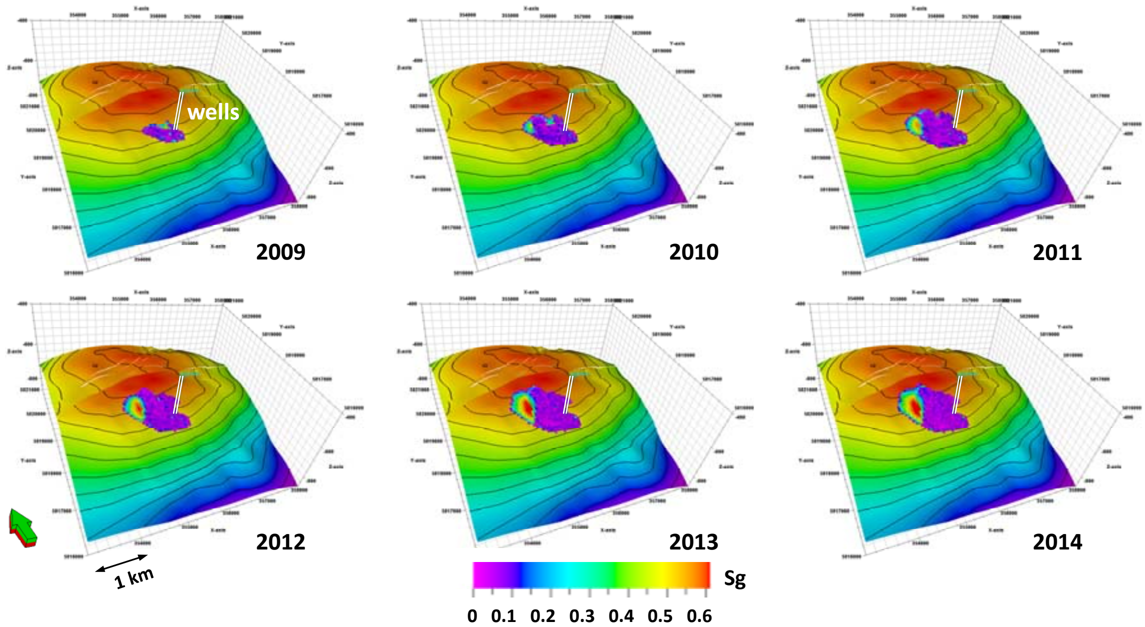

Fig. 7. Simulated gaseous CO_2 plume migration from 2009 to 2014 based on 5 km x 5 km geological model

4. Public Outreach and Communication

Public outreach is a main aspect of the Ketzin research project. Since the start, a key principle of the communication activities is to ensure an open and transparent dialogue with all stakeholders. During the course of the project, it turned out to be of particular importance to provide up-to-date information and keep the dialogue with the public. The visitor center at the Ketzin site is the most important contact point.

Activities during the fourth year of CO_2 storage encompassed: (i) weekly guided tours on-site and an Open House Day in June 2012, (ii) close contact to the nearby town of Ketzin/Havel including meetings with the mayor and the city council, the local fire brigade and the tourist office, (iii) off-site educational efforts, e.g. talks at nearby schools and public events in Berlin and Potsdam, (iv) project status and progress are covered and disseminated in leaflets and the comprehensive website (www.co2ketzin.de).

In all, our way of communication is reflected by mainly positive resonance and media coverage, the openness of the local community and about 800 visitors from all over the world at the pilot site in 2011.

5. Verification and Outlook

Four years of CO_2 injection, scientific investigations and communication at the Ketzin pilot site have been a success. Fundamental knowledge about the geological storage of CO_2 in deep saline formations are obtained and it is shown that:

- the geological storage of CO_2 at the pilot site Ketzin runs safely with no indication for CO_2 leakage,
- geophysical and geochemical monitoring methods are effective in detecting small quantities of CO_2 and can be used to image the spatial CO_2 distribution and to quantify the amount of stored CO_2,
- dynamic simulations are capable of describing the temporal and spatial distribution of the CO_2, and underline their suitability to predict the pressure development and the CO_2 behavior in the reservoir.

The results from the Ketzin pilot site show the feasibility of CO_2 storage on the research scale and emphasize the requirement to employ demonstration sites on the industrial scale in Germany and Europe as a next and consequent step.

The final stop of the CO_2 injection with a total amount of about 70,000 t CO_2 is scheduled at Ketzin for 2013. Although the injection will cease, research activities on CO_2 storage will continue in order to complement the contributions to the entire life cycle of a storage site. Thus, well abandonment and post-injection monitoring will be major parts of the final phase of the Ketzin project.

Acknowledgements

The authors gratefully acknowledge the interdisciplinary team working on the Ketzin project and all partners for their continued support. The Ketzin project received funding by the European Commission (6th and 7th Framework Program), two German ministries - the Federal Ministry of Economics and Technology and the Federal Ministry of Education and Research - and industry since 2004. The on-going research at Ketzin is funded within the project CO_2MAN (CO_2 Reservoir Management) by the Federal Ministry of Education and Research within the GEOTECHNOLOGIEN Program (this is publication GEOTECH-2045). Further funding and support is received by VNG Gasspeicher GmbH, RWE Power AG, Vattenfall Europe Technology Research GmbH, Statoil Petroleum AS, AG of Dillinger Hüttenwerke, Saarstahl AG as well as OMV Exploration and Production GmbH.

References

[1] Schilling F, Borm, G, Würdemann H, Möller, F, Kühn M, CO_2SINK Group. Status Report on the First European on-shore CO_2 Storage Site at Ketzin (Germany). *Energy Procedia* 2009; 1: 2029–2035, doi:10.1016/j.egypro.2009.01.264.

[2] 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.

[3] Martens S, Liebscher A, Möller F, Würdemann H, Schilling F, Kühn M et al. Progress Report on the First European on-shore CO_2 Storage Site at Ketzin (Germany) - Second Year of Injection. *Energy Procedia* 2011; 4: 3246–3253, doi:10.1016/j.egypro.2011.02.243.

[4] Martens S, Kempka T, Liebscher A, Lüth S, Möller F, Myrttinen A et al. Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany: A progress report after three years of injection. *Environ Earth Sci* 2012; 67: 323–334, doi: 10.1007/s12665-012-1672-5.

[5] 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.

[6] Förster A, Giese R, Juhlin C, Norden B, Springer N, CO_2SINK Group. The Geology of the CO_2SINK Site: From Regional Scale to Laboratory Scale. *Energy Procedia* 2009; 1: 2911–2918.

[7] Förster A, Schöner R, Förster HJ, Norden B, Blaschke AW, Luckert J et al. Reservoir characterization of a CO_2 storage aquifer: The Upper Triassic Stuttgart Formation in the Northeast German Basin. *Mar Petrol Geol* 2010; 27 (10): 2156–2172.

[8] Giese R, Henninges J, Lüth S, Morozova D, Schmidt-Hattenberger C, Würdemann H et al. Monitoring at the CO_2SINK Site: A Concept Integrating Geophysics, Geochemistry and Microbiology. *Energy Procedia* 2009; 1 (1): 2251–2259. doi:10.1016/j.egypro.2009.01.293.

[9] Henninges J, Liebscher A, Bannach A, Brandt W, Hurter S, Köhler S et al. P-T-rho and two-phase fluid conditions with inverted density profile in observation wells at the CO_2 storage site at Ketzin (Germany). *Energy Procedia* 2011; 4: 6085–6090, doi:10.1016/j.egypro.2011.02.614.

[10] Ivanova A, Kashubin A, Juhojuntti N, Kummerow J, Henninges J, Juhlin C et al. Monitoring and volumetric estimation of injected CO_2 using 4D seismic, petrophysical data, core measurements and well logging: a case study at Ketzin, Germany. *Geophysical Prospecting* 2012; 60: 957–973. doi:10.1111/j.1365-2478.2012.01045.x.

[11] Bergmann P, Schmidt-Hattenberger C, Kiessling D, Rücker C, Labitzke T, Henninges J et al. Surface-downhole electrical resistivity tomography applied to monitoring of CO_2 storage at Ketzin, Germany. *Geophysics* 2012; 77 (6): B253–B267.

[12] Arts RJ, Meekes JAC, Brouwer JH, van der Werf M, Noorlandt RP, Paap B et al. Results of a monitoring pilot with a permanent buried multicomponent seismic array at Ketzin. *Energy Procedia* 2011; 4:3588–3595, doi:10.1016/j.egypro.2011.02.288.

[13] Ivandic M, Yang C, Lüth S, Cosma C, Juhlin C. Time-lapse analysis of sparse 3D seismic data from the CO_2 storage pilot site at Ketzin, Germany. *Journal of Applied Geophysics* 2012; 84: 14–28, doi:10.1016/j.jappgeo.2012.05.010.

[14] Zimmer M, Pilz, P, Erzinger, J. Long-term surface carbon dioxide flux monitoring at the Ketzin carbon dioxide storage test site. *Environmental Geosciences* 2011; 18: 119–130.

[15] Norden B, Frykman P. Geological modeling of the Stuttgart Formation at Ketzin, Germany. *IJGGC (*submitted).

[16] Förster A, Norden B, Zinck-Jørgensen K, Frykman P, Kulenkampff J, Spangenberg E et al. Baseline characterization of the CO_2SINK geological storage site at Ketzin, Germany. *Environ Geosciences* 2006; 13 (3): 145–161. doi:10.1306/eg.02080605016.

[17] Kempka T, Kühn M, Class H, Frykman P, Kopp A, Nielsen CM et al. Modeling of CO_2 arrival time at Ketzin - Part I. *Int J Greenh Gas Control* 2010; 4 (6): 1007–1015. doi: 260 10.1016/j.ijggc.2010.07.005.

[18] Schlumberger. Eclipse Technical Manual. 2009.

[19] Zhang K, Wu Y-S, Pruess K. User's Guide for TOUGH2-MP - A Massively Parallel Version of the TOUGH2 Code. *Report LBNL-315E* 2008; Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California.

[20] Pruess K. ECO2N: A TOUGH2 Fluid Property Module for Mixtures of Water, NaCl, and CO_2. *Report LBNL-57952* 2005; Lawrence Berkeley National Laboratory, Berkeley, California.