R&D project CLEAN in the context of CO_2 storage and enhanced gas recovery

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Anthropogenic emissions of carbon dioxide (CO_2) into the atmosphere have a significant impact on the Earth's carbon cycle. While efforts are made to reduce the release of greenhouse gases via reduced energy consumption, more efficient energy production, and a shift to renewable energy supplies, it is generally expected that fossil fuels will continue to provide a major part of the world's energy portfolio during the 21st century (IPCC 2005). This is particularly true for coal which is relatively inexpensive and abundantly available in existing or emerging industrial power houses such as the United States, Brazil, Russia, India, and China. Carbon Capture and Storage (CCS) has been developed as an interim measure to allow energy production from coal without CO_2 emissions. This currently available technology entails capturing CO_2 from large-scale industrial sources such as coal-fired power plants or cement, steel and petrochemical factories. The captured CO_2 gas is then compressed to a smaller volume, hence higher density, transported in pipelines, and eventually injected for long-term storage into deep geologic formations, such as deep saltwater-bearing aquifers or depleted oil and gas fields (IPCC 2005).

Extensive research is currently carried out to (1) improve the technology and efficiency of capturing CO_2 and (2) to ensure the long-term safety of storing CO_2 underground. This volume of "Environmental Earth Sciences" is a *Thematic Issue* (TI) focusing on the geologic storage aspect of CCS. The idea of a TI as a new type of publication within this series is to assemble manuscripts dealing with a specific topic comprising its state-of-the art, providing recent research results, and discussing future work from an international perspective. This TI is dedicated to the recent progress made in Germany's CO_2 storage R&D programme GEOTECHNOLOGIEN funded by the Federal Ministry of Education and Research (BMBF) and the German Research Foundation (DFG)

(GEOTECHNOLOGIEN 2006, 2007, 2009). A specific focus therein was the joint research project CLEAN - CO_2 Large-Scale Enhanced Gas Recovery in the Altmark Natural Gas Field (Germany), which was conducted by 16 German institutions from academia and industry within the period from July 2008 until December 2011 (Kühn et al. 2012, Kühn et al. 2011). In order to place the findings into a broader context, the TI also covers other related CO_2 storage R&D in Germany and provides an international point of view with contributions from the United States (Mukhopadhyay et al. 2012), Korea (Park et al. 2012) and Norway (Mykkeltvedt and Nordbotten 2012). The 24 individual contributions are structured into four major topical areas: (i) Introduction of Joint Initiatives for Field-Based Research; (ii) Laboratory Experiments and Field Tests; (iii) Monitoring Concepts, and (iv) Modelling Studies.

Under the topic *Introduction of Joint Initiatives for Field-Based Research*, the current issue collates research results from several CO_2 joint research projects, directly connected to test sites. Most of the material is provided by the CLEAN project (Kühn et al. 2012) which aimed to inject around 100.000 t of CO_2 into the depleted gas field in the Altmark, Germany. Another pilot site on the same scale is "Europe's longest-operating on-shore CO_2 storage site at Ketzin, Germany" (Schilling et al. 2009, Würdemann et al. 2010) which is presented in this TI by Martens et al. (2012). A small scale injection test was performed to study the geochemical impact of CO_2 on shallow groundwater through an injection test in Northeast Germany (Peter et al. 2012). A virtual test site is modelled in the CO_2-MoPa project, which concentrates on basic research independent from a specific test site in order to develop generic theoretical and experimental methods (Bauer et al. 2012).

Laboratory Experiments and Field Tests are in integral part to deepen the understanding within the framework of CO_2 storage and enhanced gas recovery (EGR). Pudlo et al. (2012) show results about "The impact of diagenetic fluid-rock reactions on Rotliegend sandstone composition and petrophysical properties (Altmark area, central Germany)", Huq et al (2012) investigate "Chemical changes in fluid composition due to CO_2 injection in the Altmark Gas Field" and Hou et al. (2012a) present a developed long-term wellbore sealing concept which was tested in-situ in the Altmark natural gas field.

A major factor for the success of any CO_2 storage project is that the subsurface response to CO_2 injection and storage can be reliably and efficiently monitored. This TI introduces several studies describing development and application of *Monitoring Concepts*. Schütze et al. (2012) study natural analogues to develop reliable monitoring methods to understand subsurface CO_2 migration processes. Park et al. (2012) present "A pressure-monitoring method to warn CO_2 leakage in geological storage sites". Lempp et al. (2012) outline "Methodological approaches in the laboratory with respect to the in-situ conditions of the Altmark Gas Field". Lamert et al. (2012) test the "Feasibility of geoelectrical monitoring and multiphase modelling for process understanding of gaseous CO_2 injection into a shallow aquifer". Baumann and Henninges (2012) focus on well logging for injection and saturation profiling with special emphasis on the CO_2 injection in depleted gas fields. Becker et al. (2012) conclude this section with their work on stable isotope applications with regard to CCS and EGR.

Modelling Studies are an important tool to improve the fundamental understanding of subsurface processes related to CO_2 storage but also to support more practical investigations of CO_2 migration, risk assessment, and reservoir management. The challenges for modelling lie in both describing the complexity of coupled *thermo-hydro-mechanical-chemical processes* and capturing the structural geology and heterogeneity of real systems (Nordbotten and Celia 2012). First step for any dynamic simulation model is the development of a static geological model. With regard to the CLEAN project, Norden et al. (2012) outline the basis to do that, the "Geological and thermal structure of the larger Altensalzwedel area". Böttcher et al. (2012) evaluate in this TI the thermal equations of state for CO_2 in numerical simulations. Singh et al. (2012a) conducted a "Thermal analysis of the Altmark gas field for carbon dioxide injection with enhanced gas recovery". *Hydraulic processes* are the focus of Mykkeltvedt and Nordbotten (2012) as they study convective mixing in response to commercial-scale injection. Singh et al. (2012b) describe "Numerical simulation of tracer transport in the Altmark gas field". Hou et al. (2012b) focus their modelling on *mechanical processes* with special emphasis on enhanced gas recovery technology. The *chemical processes* of CO_2-induced fluid-rock interactions are evaluated in the modelling studies by De Lucia et al. (2012) and Beyer et al. (2012).

Benchmarking by code or model comparison is an important strategy for demonstrating the accuracy and predictive capability of models. Benchmarks with special emphasis on CO_2 storage have been discussed by Class et al. (2009) and Kempka et al. (2010). In this TI, Kolditz et al. (2012a) suggest "A systematic benchmarking approach for geologic CO_2 injection and storage" and Mukhopadhyay et al. (2012) present "A model comparison initiative for a CO_2 injection field test". In order to better deal with the complexity of simulating coupled processes in complex systems, an on-going effort is to develop modelling platforms allowing efficient cooperation of distributed developer groups (Flemisch et al. 2011, Kalbacher et al. 2011). Here, Kolditz et al. (2012b) present one such effort introducing "OpenGeoSys: an open-source initiative for numerical simulation of thermo-hydro-mechanical/chemical (THM/C) processes in porous media".

Keywords*: CCS, CO_2 storage, EGR, depleted gas fields, Altmark, test sites, saline aquifers, laboratory experiments, monitoring, modelling, benchmarking*

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