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# $CO_2$ Monitoring

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## Technical and methodological requirements for a permanent downhole geoelectrical measurement system as CO2 monitoring tool – A review from the Ketzin pilot site

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At the Ketzin pilot site, Germany, electrical resistivity tomography (ERT) is part of a multi-disciplinary geophysical monitoring concept, which has been established in order to image $CO_2$ injected into a saline aquifer (Martens et al., 2015). Since more than seven years, a borehole electrode array is operated as a permanent reservoir monitoring tool for continuous ERT measurements. This so-called vertical electrical resistivity array (VERA) consists of a behind-casing installation of permanent electrodes in three Ketzin wells and is used to conduct highly frequent crosshole ERT measurements and periodic surface-downhole surveys (Schmidt-Hattenberger et al., 2014; Bergmann et al., 2012). The VERA system is deployed in the depth range of 590-735 m with 15 electrodes per well (electrode spacing of 10 m), covering the reservoir formation (depth 630-650 m) and parts of the adjacent formations. On the basis of this long-term application, the review presents the technical and methodological requirements for a ERT system in order to perform successful $CO_2$ plume imaging.

Since 2008, the VERA system has accompanied all stages of the $CO_2$ storage operation: (1) Start of injection and detection of $CO_2$ arrival at the observation wells, (2) intermediate phases of reduced injection rates as well as shutdowns due to technical operations, and, since August 2013, (3) the injection stop and its subsequent post-injection phase. In addition, ERT monitoring was also performed for a controlled $CO_2$ back-production test as well as a brine injection experiment, both of which were conducted in the context of potential remediation techniques for $CO_2$ storage sites. During all of these operational phases, ERT measurements aimed at resolving the various reservoir processes of relevance and were, therefore, demanded to provide sufficient flexibility regarding temporal and spatial data acquisition. Advanced numerical tools, which allow for an improved pre-processing, efficient time-lapse inversion, and an integration of further types of monitoring data into the imaging process, have been established. Moreover, integration with operational injection data, petrophysical relations, and well logging data has been performed, leading to valuable interpretations on ongoing reservoir processes and estimated $CO_2$ saturation levels.

From a technical point of view, the ERT array components, i.e. electrodes, multi-conductor cables, centralizers, and insulated casing pipes are discussed in view of cost aspects, capability for downhole installation, and durability under demanding subsurface conditions. Regular contact resistance checks provided useful information about the fidelity of the subsurface electrodes, particularly with regard to the detection of possible degradation effects. Given the long-term $CO_2$-brine exposition, some 7 electrodes (out of the 45 electrodes in total) have been identified to have technical issues, such as damaged or degraded cable break-outs.

Finally, we conclude the multiple benefits of using permanent ERT downhole arrays for monitoring the $CO_2$ storage operations. Experiences from further pilot-scale applications are deemed necessary in order to advance the presented ERT monitoring technology towards industrial scales.

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