Subsurface energy storage: geological storage of renewable energy—capacities, induced effects and implications

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The transition of energy supply from mainly fossil sources to renewable energy sources is essential for mitigating climate change effects and preparing for a future of sustainable energy supply not relying on finite fossil resources. In Germany, this transition from fossil to renewable energy sources is termed “Energiewende” (energy transition) and further accelerated by the phase-out of nuclear energy until 2022 (BMW 2015). However, energy supply from renewable sources like wind or solar power is subject to strong natural temporal fluctuations and therefore frequently does not match the instantaneous energy demand and energy base load. Energy storage is thus required, to dampen these fluctuations and to compensate for times of low power production. By taking up surplus power, energy storage also contributes to grid stability in times of high renewable energy production. The estimated yearly storage demand for Germany, assuming a large contribution of renewable energy, varies considerably, but may reach 50 TWh of electrical energy (Klaus et al. 2010). Due to the fluctuating nature of renewable power production, storage is required on a wide range of time scales, ranging from seconds to months, as well as storage sizes, ranging from tens of kWh to tens of GWh (Luo et al. 2015).

For long-term storage of large amounts of energy that arises from longer periods with excess energy provided by wind or sun, the geological subsurface may potentially provide the large storage capacities required for storage on daily to seasonal scales (Bauer et al. 2013). Suitable subsurface renewable energy storage options include compressed air energy storage (CAES), which may also be a short-term storage option on the hourly time scale; hydrogen gas, generated from electric power by hydrolysis; or synthetic methane gas, generated in turn from hydrogen. These gases can be stored in very large amounts of hundreds of millions of m³ STP (LBEG 2016) either in caverns or in porous formations. Energy in the form of heat may be stored in the subsurface using methods from geothermal applications (Kolditz et al. 2013). This includes near surface storage of heat (or cold) from residential or industrial areas, especially in urban settings, as well as high-temperature storage at up to 100 °C in the subsurface, which may provide also daily to seasonal heat storage. Experience from both open well systems and using borehole heat exchangers exists, however mainly in the lower temperature range (e.g. Mielke et al. 2014).

Although the geological subsurface offers large potential storage capacities, large achievable loading and unloading rates and a variety of suitable settings, also other ways of using the subsurface are already in place. These include shallow or deep geothermal applications for climatization of buildings, groundwater abstraction for drinking water purposes, mining of ores, coal or geomaterials, hydrocarbon production or disposal of hazardous materials or waste. Also protected entities, such as groundwater reservoirs, flora and fauna, and ultimately humans, have to be safeguarded when utilizing the geological subsurface, which may put restrictions on the implementation of certain types of subsurface use. In

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addition, competition for subsurface space, i.e. suitable geological formations, may impair their use as storage sites, as other types of use may already be in place or prohibit the use as storage site due to induced effects. Thus, methods are required for determining achievable storage capacities as well as charging and discharging rates of subsurface energy storage sites. Also, methods for assessing induced effects of geotechnical storage operations on other types of subsurface use and on protected entities are required. The ANGUS+ project is dedicated to contributing to these topics, in order to support the implementation and regulation of such geological storage sites. An overview of the ANGUS+ project results (Kabuth et al. 2017) is part of this topical collection.

The German government has acknowledged the demand for energy storage and initiated a research initiative for energy storage—“Forschungsinitiative Energiespeicher” (Energy storage research initiative (BMW i et al. 2011)—as a joint effort of the Ministry of Education and Research (BMBF) and the Ministry for Economic Affairs and Energy (BMW i), which covers all types of storage methods and facilities. Within this priority research initiative, the ANGUS+ project is funded as one of the three geoscientific research projects working on geological storage options. Also funded are the InSPEE project (e.g. Horváth et al. 2016), assessing storage capacities in salt caverns for Germany, and the H2STORE project (e.g. Feldmann et al. 2016), assessing hydrogen gas storage in former gas fields.

This topical collection presents first results of the ANGUS+ project and connected relevant research from other research projects.

Contributions to geological subsurface use and storage research can be structured into the main categories: (1) Parameterization of subsurface formations and induced processes for energy storage use; (2) development of process-oriented simulation tools; and (3) scenario simulations for specific storage options.

1. Assessing the opportunities and risks of subsurface use requires structural information on subsurface formations in terms of their occurrence and prevalence as well as their properties and induced effects regarding the use as potential storage sites. Here the papers by Dethlefsen et al. (2016, 2017) describe the parameterization required as well as a geostatistical analysis of available spatially distributed values for North Germany. Lüders et al. (2016) study induced gas phase evolution and Popp et al. (2016) temperature-dependent mass transfer. Berta et al. (2016), Westphal et al. (2017) and Lienen et al. (2017) study microbial-mediated geochemical effects due to temperature changes and Kasina et al. (2017) and Pellizzari et al.

(2017) due to gas injection. Miao et al. (2016) investigate induced geotechnical effects.

2. A prognosis of storage dimensions and induced effects also requires adequate simulation tools, which represent the governing processes and allow for site-specific assessments. Herein, Boockmeyer and Bauer (2016) and Schulte et al. (2016) present new methods for the simulation of borehole heat exchangers, while Beyer et al. (2016) present methods for temperature-dependent phase transitions and Pfeiffer et al. (2016b) on simulator coupling. Nagel et al. (2016) present work on geomechanical coupling, while Mahmoudi et al. (2016) and Böttcher et al. (2017) simulate coupled effects for gas cavern storages. An information system, which incorporates all required surface and subsurface input data, is presented by Nolde et al. (2016).
3. Having parameterized the processes and the geological formations used and having developed suitable modelling tools, these models can be applied to assess options of subsurface energy storage, their monitoring and possible interactions with other types of use. The papers in this topical collection cover geothermal applications, site investigation and monitoring by Schelenz et al. (2017) as well as Wang and Bauer (2016), and applications to geomechanical effects during cavern storage by Khaledi et al. (2016) and monitoring aspects Köhn et al. (2016). Dimensioning and effects of porous formation gas storage are considered in Feldmann et al. (2016) and Pfeiffer et al. (2016a), who also test adequate monitoring methods in a virtual setting. Delfs et al. (2016) simulate induced brine migration, while al Hagrey et al. (2016) investigate methods for detection and monitoring of induced leakages.

As the work presented in this topical collection shows, the topic of subsurface energy storage and its implications for other types of use as well as the topic of subsurface spatial planning is a relatively new one. We therefore think that the development and provision of dedicated tools for the planning, dimensioning and impact assessment of subsurface energy storage are an imminent task for the scientific community. While prior work on gas storage techniques as well as geothermal applications provides a long-standing basis, new aspects, for example the high cyclicity of energy storage due to the intermittent nature of renewable resources, which induces mechanical, hydraulic and thermal effects, or high-temperature storage at up to 100 °C in subsurface thermal storage applications, which induce geomechanical and hydraulic changes, need to be experimentally quantified and reliable prognosis methods need to be developed. We think that only a thorough understanding of these effects and a corresponding analysis

of their long-term and short-term risks, such as integrity of confining units, land subsidence or uplift, changes of groundwater flow fields as well as groundwater composition, are a prerequisite for the implementation of these energy storage techniques on the required large scale. However, only recently dedicated sessions at, for example, the German FHDGG conference (“Wärme-, Energie- und Kohlenstoffspeicherung im Untergrund”; Bayreuth 2014) or the European Geoscience Union (“ERE5.3 Process quantification and modelling in subsurface utilization”, EGU 2016 and 2017, Vienna) have come up to specifically present this topic at international conferences. Generally, energy storage and subsurface use topics are integrated into sessions on geothermal use or larger-scale subsurface simulation approaches. We think that more dedicated conference sessions need to be established to allow for a clearer focus on these issues in the future.

In the long term, we think that treating the subsurface as a resource not only for energy production, but also for energy storage will require a subsurface planning approach. This subsurface planning approach should allocate specific types of use to individual subsurface formations and thus provide for enough subsurface space for priority uses, for example groundwater abstraction. We think that such an approach needs to be quantitative, i.e. it has to be able to assign for each type of use the corresponding subsurface spatial demand. Thus, also interactions between different types of use can be assessed, and their combination or mutual exclusion can be provided for in the planning process. Only by such an approach, a reliable and sustainable ecologic and economic use of the subsurface as a resource will be achieved. Such a quantitative approach is also transparent, as decisions on subsurface spatial needs are quantified, which we think will enhance public acceptance and thus support the installation of subsurface energy storage sites. This need becomes more obvious, as energy storage will become a central issue for the transformation of the energy system to renewable sources only. However, a further parameterization of the subsurface according to storage option needs, as well as methods for predicting and assessing the induced effects by such subsurface installations through (mainly numerical) modelling approaches, is therefore required to achieve these aims. This will be especially important when considering the linked risks and side effects, for example changes in groundwater temperature and composition or land subsidence, in relation to other options of the future energy system, as for example biomass, which is an energy technology also connected with environmental impacts such as soil compaction and high nutrient loads. Also here, we think that a transparent planning process for subsurface applications helps to

obtain public acceptance. Tackling these tasks represents an effort for the wider geoscientific community, but also beyond, as technical aspects have to be considered and dedicated regulations have to be developed and implemented.

As becomes clear from this collection of scientific research papers, we think that an integrated and interdisciplinary approach to the topic of subsurface spatial planning and assessing geological storage options is required to prepare for a both economically and ecologically sustainable use of the subsurface resources.

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