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THEMATIC ISSUE

Energy storage in the geological subsurface: dimensioning, risk analysis and spatial planning: the ANGUS+ project

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Abstract New techniques and methods for energy storage are required for the transition to a renewable power supply, termed "Energiewende" in Germany. Energy storage in the geological subsurface provides large potential capacities to bridge temporal gaps between periods of production of solar or wind power and consumer demand and may also help to relieve the power grids. Storage options include storage of synthetic methane, hydrogen or compressed air in salt caverns or porous formations as well as heat storage in porous formations. In the ANGUS+ project, heat and gas storage in porous media and salt caverns and aspects of their use on subsurface spatial planning concepts are investigated. The optimal dimensioning of storage sites, the achievable charging and discharging rates and the effective storage capacity as well as the induced thermal, hydraulic, mechanical, geochemical and microbial effects are studied. The geological structures, the surface energy infrastructure and the governing processes are parameterized, using either literature data or own experimental studies. Numerical modeling tools are developed for the simulation of realistically defined synthetic storage scenarios. The feasible dimensioning of storage applications is assessed in site-specific numerical scenario analyses, and the related spatial extents and time scales of induced effects connected with the respective storage application are quantified. Additionally, geophysical monitoring methods, which allow for a better spatial resolution of the storage operation, induced effects or leakages, are evaluated based on these scenario simulations. Methods for the assessment of such subsurface geological storage sites are thus developed, which account for the spatial extension of the subsurface operation itself as well as its induced effects and the spatial requirements of adequate monitoring methods.

Keywords Geotechnical energy storage · Parameterization · Numerical simulation · Geophysical monitoring · 3D spatial information · Subsurface spatial planning

Introduction

The transition of energy supply from fossil sources to renewable energy sources is essential for mitigating climate change effects and for preparing a future of sustainable energy supply (IEA 2013; Moomaw et al. 2011). In Germany, this transition from fossil to renewable energy sources, termed "Energiewende", is further accelerated by the phase out of nuclear energy until 2022. Core strategies of the German Federal Government are the increased use of

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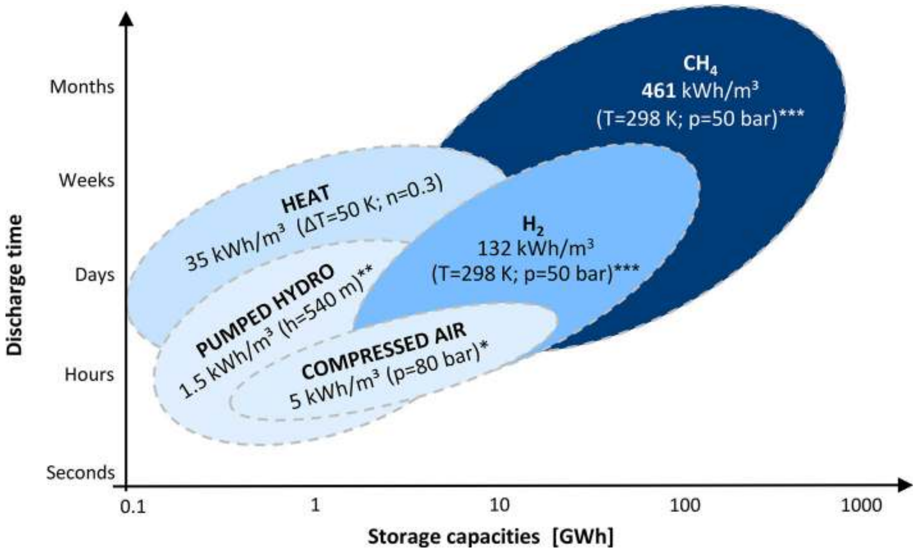

Fig. 1 Coverage of storage capacities and discharge times by different energy storage options with indication of energy densities at specified conditions. Color fill intensities reflect energy density levels. *h* elevation, *n* porosity, *p* storage pressure, *T* temperature, *energy density from Succar and Williams (2008), **energy density from Sterner and Stadler (2014), ***energy densities derived from gravimetric energy densities in Boundy et al. (2011)

renewable energies and a strongly enhanced energy efficiency. The Federal Ministry of Economics and Technology (BMWi) defines a target of covering 60% of the final energy consumption (BMWi 2010) and 80% of the final electricity consumption (Jain et al. 2015) by renewable energies by the year 2050. In 2014, the production of renewable energies in Germany reached 13.5% of the final energy consumption and 27.4% of the final electricity consumption (BMWi 2015). Shares of 30 and 50%, respectively, are aimed at for the year 2030. In the Northern German state of Schleswig–Holstein, the renewable energy production already reached 24.1% of the state's final energy consumption and 78.4% of the state's final electricity consumption (Statistisches Amt für Hamburg und Schleswig–Holstein 2016).

However, energy supply from renewable sources like wind or solar power is subject to strong natural fluctuations and does therefore frequently not match the instantaneous energy demand. In times of high renewable power production, the existing power transmission lines are not sufficient and therefore power-generating plants are frequently taken off the grid (MELUR 2015; Bundesnetzagentur and Bundeskartellamt 2015). Conversely, in times of low production, power shortages may occur, which have to be filled by backup energy. To bridge the gap between periods of excess wind or solar power, energy can be stored in periods of over production and retrieved when the demand exceeds production (VCI 2013). The operation of energy storage utilities can thus contribute to security of energy supply and to the economically viable use of renewable energies at high shares (70–90%) of the energy production (DENA 2014; Deutsche Akademie der Technikwissenschaften et al. 2016; Agora Energiewende 2014; Pape et al. 2014; Klaus et al. 2010; Purr et al. 2014). The estimated storage demand is yet subject to large uncertainties connected with the development of the energy system: In scenarios of an 80% share of renewable energies in the gross electricity consumption ("Energiewende" goal by 2050, BMWi 2015), the projections of storage demand range from around 1 TWh to 50 TWh (IEC 2011; Klaus et al. 2010; Weiß and Schulz 2013).

The production of renewable electricity as well as the energy demand fluctuates on frequencies varying from less than hourly over daily to seasonally, requiring flexible storage options on all of these timescales (IEA 2009; Luo et al. 2015). For a reliable energy supply from renewable sources also periods of insufficient wind and solar energy production have to be considered. The geological subsurface may provide the large storage capacities needed to compensate the residual load in these periods on the daily, weekly or seasonal scale [Crotogino et al. 2010; Bauer et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2883-0)]. Converted to compressed air, hydrogen (H_2), synthetic methane (CH_4) or heat, excess energy can be stored in underground salt caverns (gas) or porous geological formations (gas and heat) in the subsurface. Geological storage options can be differentiated by the storage environment and the storage medium: Sensible heat storage is typically applied into the shallow subsurface up to depths of a few hundred meters. Gas storage sites for hydrogen, methane or air use porous formations or salt caverns in the deeper subsurface at depths ranging from a few hundred meters to about two kilometers. Very large storage capacities can be realized in geotechnical storage sites due to the vast sizes of subsurface geological formations. The achievable cycle times depend on the type of storage used and can range from hours up to seasons (Fig. 1). The North German Basin provides a large potential of storage sites in both porous sandstone formations and salt caverns (Burges et al. 2014;

Kaufhold et al. 2011; Reinhold and Müller 2011; Thomsen and Liebsch-Dörschner 2007). Saline aquifers constitute potential porous storage formations, and Zechstein as well as Rotliegend diapirs are potential hosts for salt caverns especially in the North German Basin but also in the south of Germany (Gerling 2010). This potential is already tapped by 51 gas storage sites in Germany, which host a total of 24.3 billion Nm^3 of natural gas (LBEG 2015). Worldwide a total of 715 gas storage sites (including caverns and porous formations) exist, hosting 396.8 billion Nm^3 of natural gas, and the number of sites is increasing (LBEG 2015).

Along with its large storage capacities, the geological subsurface also constitutes a sensitively balanced environmental system. To explore geotechnical energy storage options sustainably, their possible induced effects on other subsurface uses need to be considered in planning and monitoring schemes yet pending [Bauer et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2883-0)]. In the context of CO$_2$ storage, Schäfer (2011) pointed out a need for the delineation of three-dimensional monitoring zones around subsurface storage operations. This is especially applicable, if possible impacts on protected entities such as groundwater used for drinking water purposes are considered.

In the competition for subsurface resources under the current German Federal Mining Act, a mining permission can only be denied if the reasons for a denial first occurred after a successful prospection. A regional planning procedure will only take effect if a proposal is evaluated as being of regional significance, i.e., at a late stage within the framework of licensing procedures for drilling and production or storage operations. At that advanced stage, a spatial regulation in the form of a denial of mining permissions is almost impossible in practice (Bovet 2014). Initiating regional planning procedures already prior to the issuance of prospection permits for industrial purposes could provide regulation opportunities at an earlier stage (Penn-Bressel and Weber 2014). Furthermore, an extension of the scope of the regional planning regulation for mining by the case of spatial significance could add the criterion of space occupied by the respective development as a decisive threshold triggering a regional planning procedure. The Federal Spatial Planning Act already provides for the designation of spatial planning areas with a defined priority or exclusion of specific types of use or entities, and it allows for a conceptual transfer to the subsurface as a three-dimensional space (Bartel and Janssen 2016). The German mining law, in contrast, provides for a horizontal but not for a vertical delimitation of licensing areas (Weyer 2013). Consequently, a stronger link between the regional planning law and the mining law in Germany is needed (Schulze et al. 2015). Legal clarifications are necessary to facilitate vertically adjacent subsurface operations in different geological formations (Schulze et al. 2015; Weyer 2013). To meet the challenges of a prospective sustainable spatial planning scheme for the subsurface, not only the site-specific dimensioning of subsurface (storage) operations, but also the quantified prediction of their induced effects and the derivation of appropriate monitoring schemes are crucial (Kahnt et al. 2015).

The ANGUS+ project therefore addresses the requirements of a sustainable subsurface spatial planning scheme and the necessity of profound scenario analyses to predict the total space claimed by geotechnical energy storage operations, their induced effects and appropriate monitoring methods.

The ANGUS+ project

Concepts of subsurface spatial planning

The current status of the German laws concerning the use of the deeper subsurface is a first-come first-serve approach, in which the first applicant for a specific location is granted exclusive prospection and, in a second step, utilization rights. This implies that a geological formation, which is well suited for subsurface energy storage, may be used for other purposes or may be blocked by other types of use in intermediate formations, which inhibit access to the intended storage formation. Right now, no mechanism is in place which allows to reserve certain locations in the subsurface for specific types of use. Due to the limited transmission capacities of the power grids, geotechnical storage sites will have to be found close to large producers of renewable electric power. Therefore, a planning of the use of the geological subsurface is required to ensure that storage capacities remain available where needed, and are not blocked by other types of use. This would also require a prioritization of common public interests over private company interests (Bovet 2014).

The competition for subsurface space occurs in two distinct forms: Firstly, in the form of a direct competition for an individual storage formation, where different use options apply but the formation can accommodate only one. Secondly, in the form of an indirect blocking, where a certain subsurface space may be unavailable for energy storage due to the induced effects of other types of use (e.g., pressure rises, temperature increases or induced brine movement). Access to an intended storage formation may also be blocked indirectly through operations in shallower formations which, e.g., prohibit drilling. In the case of direct competition, a mechanism is sought, which allows to prioritize individual types of use. Here, tools are required to assess the benefits of the individual storage options in

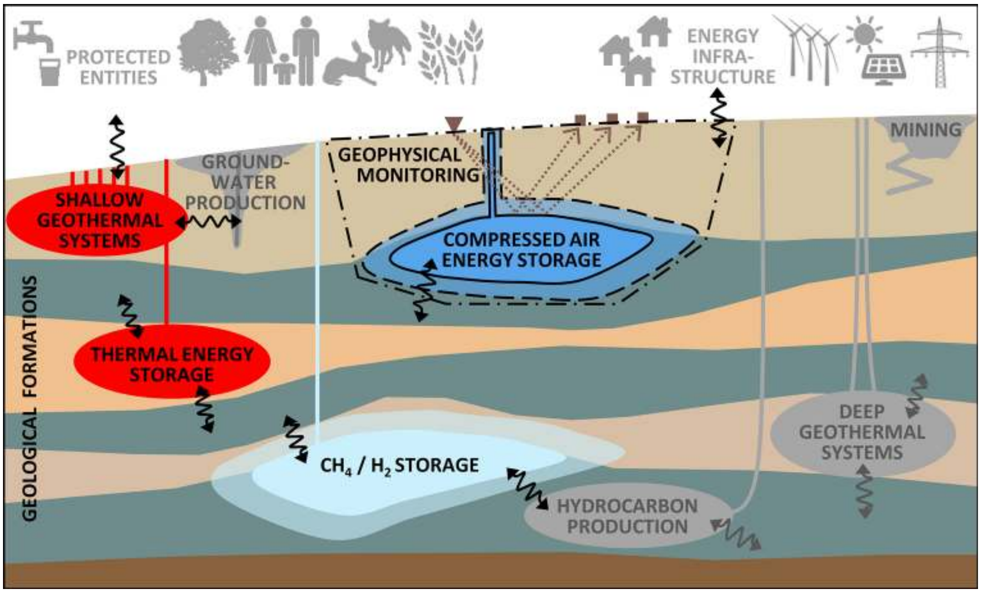

Fig. 2 Scheme of use options in the subsurface, protected entities and energy infrastructure. Entities depicted in *colored shades* are subjects of scenario analyses within the ANGUS+ project. Entities displayed in *gray shades* are implicitly considered. *Black solid line* operational space, *black dashed line* affected space, *black dash-dot line* monitoring space, *black curved arrows* mutual interactions

terms of achievable extraction or injection rates and capacity. In the case of indirect competition, a quantification of the mutual effects of individual storage operations on each other and on other types of use in the subsurface is required. In both cases, a delineation of the space required for an individual storage option is needed to be able to reserve and assign subsurface locations for this specific type of use. Three categories of used subsurface space have been identified and developed in the ANGUS+ project in the context of geotechnical energy storage: firstly, the "operational space" (Fig. 2), i.e., the space directly used by the storage operation, which comprises the technical installations and the space taken up by the injected gas or heat. Secondly, the "affected space" (Fig. 2), i.e., the surrounding space where effects of the storage operations are induced, such as zones of elevated pressure, induced brine movement, elevated temperatures, etc. And, thirdly, the "monitoring space" (Fig. 2) that needs to be free of other types of use due to monitoring requirements of the energy storage. Here, for instance, pressure monitoring of a porous medium gas storage site prohibits other types of use close by which also influence the formation pressure and thus disturb the monitoring signal. Typically, volumes affected by induced effects will be larger than volumes occupied by the direct use, and the volumes reserved for monitoring will typically again exceed the affected space. The monitoring space may extend to the land surface, if, for example, geophysical monitoring methods are used. A similar, less physically based approach was postulated by Kahnt et al. (2015), who suggested the definition of a project space as the volume taken up by the actual subsurface operation of concern and a used space around the project space as a buffer zone where induced effects exceed a certain threshold. All concepts of space in the subsurface, however, require the definition of boundaries. Thus, the definition of, for example, threshold values for pressure increases and temperature changes is required in order to delimit the operational, affected and used space. This will always imply the use of modeling tools, as delimiting these spaces by measurements only is not feasible in the geological subsurface. The process-based simulation of the governing processes on a site-specific basis and based on site-specific observation data can be a means to delimit these subsurface spaces.

ANGUS+ project structure

An enhanced knowledge of the induced effects and monitoring requirements of subsurface energy storage and its interactions with other types of subsurface use (e.g., waste disposal, gas storage vs. heat storage, water supply and distribution) needs to be made available to authorities and policy makers, and requires consolidation in a subsurface spatial planning scheme in order to serve as beneficial information to planning procedures. Informed decisions can prevent interferences and can avoid wasting of subsurface space by implementing less efficient types of subsurface use. In view of the demands on a future sustainable subsurface spatial planning scheme comprising the concept of operational, affected and monitoring spaces of prospective storage sites, the overall objectives of the ANGUS+ project are to develop

- methods and databases for the assessment of prospective storage capacities in geological formations,
- methods for the prediction and monitoring of induced effects connected with these storage operations and

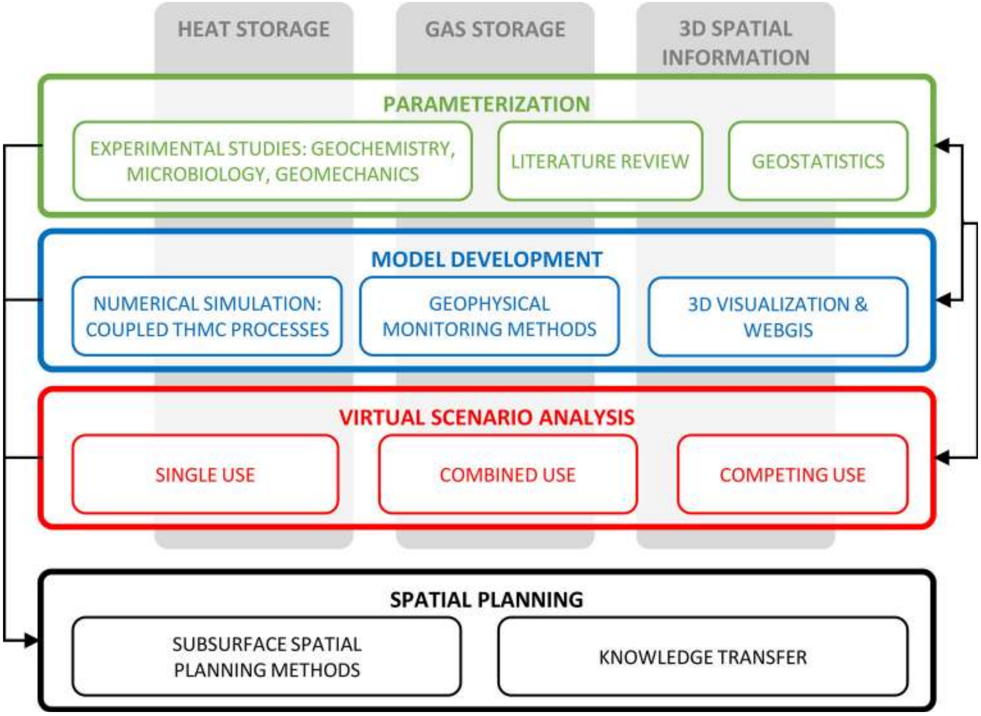

Fig. 3 ANGUS+ project structure with cross-cutting themes (*boxes in gray shades*) and work packages (*boxes with colored frames*)

- tools and first concepts for a sustainable subsurface spatial planning.

The coordination of subsurface use options, environmental protection and surface infrastructure is crucial for an economically and ecologically feasible exploration of the subsurface as a spatial asset. A sustainable approach to subsurface use therefore requires spatial planning for minimized competition and maximized synergies (ARL 2012; Gerling 2010; Bovet 2014). Bauer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2883-0)] qualitatively demonstrated the expectable mutual effects of different subsurface applications on each other and identified a need for site-specific process quantifications. With heat storage, gas storage and 3D spatial information as cross-cutting themes of the ANGUS+ project (Fig. 3), this aim is pursued by using numerical simulations of synthetic, however, realistically defined energy storage scenarios. The literature research, laboratory experiments and numerical modeling contribute to the parameterizations preceding the realistic scenario definition of geological formations and induced processes. Enhanced numerical tools enable the computation of coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes (THMC-processes) induced by geotechnical energy storage operations for realistically parameterized sites on the field scale. This simulation of virtual storage site operations allows a generic approach to storage environments, as the quantification of occupied subsurface space can be used in the permitting process for all storage types considered. The identification of spatial extents and magnitudes of induced processes subsequently also allows for the evaluation of monitoring schemes. Comprehensive data on geological parameters, energy infrastructure and protective areas in Schleswig–Holstein are compiled in a newly developed, web-based 3D spatial information system.

Heat storage

The conversion of excess wind and solar power to heat, also termed Power-to-Heat (Sterner and Stadler 2014), provides the option of heat storage as a contribution to the heating supply of buildings. The suitability of the different types of heat storage, however, is highly site specific (Schmidt and Müller-Steinhagen 2005). Therefore, a resource efficient and environmentally sustainable thermal use of the subsurface requires the parameterization of geological and hydrological conditions connected with the site exploration as well as cost-efficient methods for long-term monitoring of the thermal application (Vienken et al. 2016). In particular, low-temperature heat storage in the shallow subsurface and high-temperature heat storage in depths below about 500 m are considered, as here installation costs may still be reasonable in connection with residential or office buildings (Koenig 2015; Raymond et al. 2015). High-temperature heat storage would allow an increased storage efficiency compared to the lower temperatures usually applied at present. However, environmental concerns restrict heat storage with injection temperatures of up to 90 °C to formations not used for drinking water purposes (Griebler et al. 2015). High-temperature heat storage is typically considered as a seasonal storage option, but may contribute to shorter time scales as well. Depending on the geological setting, heat can be exchanged with the subsurface in either aquifer thermal energy storage (ATES) or borehole thermal energy storage (BTES) systems.

Gas storage

Natural gas can be stored in salt caverns, in deep saline permeable porous formations or in former hydrocarbon reservoirs. Excess power from wind or solar energy plants can be stored chemically by conversion to hydrogen (via electrolysis, Götz et al. 2016; Walker et al. 2016) or synthetic methane (via methanation of hydrogen and carbon dioxide, Götz et al. 2016; Rönsch et al. 2016), or it can be stored physically as compressed air in caverns or porous media (Oldenburg and Pan 2013; Succar and Williams 2008).

Caverns for gas storage operate in depths between about 500 and 2500 m, determined by the subsurface pressures needed to match the operational requirements (Kepplinger et al. 2011; Kushnir et al. 2012). The leaching of caverns in salt structures causes a need for disposal of the dissolved material in the form of brine. The disposal by injection into deep formations may affect drinking water resources if faults or fracture networks in the sealing cap rocks permit brine to rise into shallower aquifers. Methods for the assessment of induced brine movement and reliable monitoring methods are needed.

Porous formations provide very large potential capacities and therefore typically serve for seasonal gas storage. As in the case of cavern storage, operational pressures in the storage formation have to match the requirements of the surface installations. The injection and extraction rates are limited by the storage formation's permeability and pressure restrictions to guarantee formation integrity. The constraining permeability and pressure ranges of the storage formations differ depending on the storage medium (hydrogen gas, methane gas, compressed air). To counterbalance buoyancy effects, a sealing cap rock is required. In accidental cases of gas leakage from the reservoir through faults or fractures, an early detection of the gas phase distribution is crucial and requires the application of geophysical monitoring schemes. Therefore, depleted oil and gas fields may also offer porous media storage options since tightness of the cap rock is given, but the well installations and sealings have to be carefully considered (e.g., Kühn and Münch 2013).

3D spatial data for public outreach and participation

Three-dimensional data visualization in online spatial information systems can make data of the subsurface, including geological structures, protected entities, but also electric power infrastructure, accessible for regional planning purposes. Data availability in turn contributes to the transparency of subsurface uses. As the public concern over and involvement in subsurface operations has become a major issue (e.g., Bleicher and Gross 2015), public information and participation are increasingly required (Ashworth et al. 2010; Friedl and Reichl 2016; Schweizer et al. 2014). To this end, communication and visualization tools (e.g., Zehner et al. 2010) are valuable media for knowledge transfer in energy infrastructure projects.

The ANGUS+ project structure accounts for the demands on a sustainable planning and operation of geotechnical energy storage sites outlined by Bauer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2883-0)] and supports the development of the concepts of subsurface space management outlined above. The project structure is schematically shown in Fig. 3. The following sections present an overview of the preliminary research results achieved by the ANGUS+ research consortium.

Heat storage

Development of a data base: parameterization of the shallow subsurface through literature survey and experimental process studies

For the assessment of heat storage capacities and associated implications, scenarios of daily and seasonal storage are designed to represent typical operation modes for residential or office buildings. These scenarios are investigated with respect to the coupled thermal, hydraulic, mechanical and geochemical processes induced by the imposed temperature changes. Competition for subsurface space can also occur with unintentional types of subsurface use. As typical examples, interactions with preexisting contaminations in the formations affected by heat storage, and accidental leakages of heat transfer fluid from borehole heat exchangers (BHE) are investigated experimentally and numerically. The definition of realistic virtual scenarios for the assessment of heat storage operations requires geostructural, hydraulic, hydrogeochemical and mineralogical parameterizations of the subsurface formations involved. However, Dethlefsen et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5626-1)] characterized the availability of these data as at least partly affected by scarcity, value uncertainty and process knowledge uncertainty.

Within the same study, consequently, a categorization of process knowledge and concepts for the quantification of prediction errors were developed: Process knowledge is categorized here based on the uncertainties of process parametrization and their resulting impacts on simulation results. Prediction errors are quantified by sensitivity analysis with regard to statistical data uncertainty and by experimental studies with regard to scenario uncertainty. This work thus also shows where further characterization efforts yield the largest effect on reducing uncertainty. In a deficit analysis of the data availability for the parameterization of the shallow subsurface in Schleswig–Holstein with respect to energy storage, Dethlefsen et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6343-5)] found that information on geostructures and hydraulic properties is typically available on the regional scale, but detailed information exists only patchy and locally. Near-surface groundwater is found to be well characterized concerning the main constituents, but data on trace elements and dissolved gas concentrations are sparse, as well as sediment properties and mineral compositions. Often, results are available for typical ambient or laboratory temperatures, but not for higher temperatures as expected in heat storage applications. Also, the temperature dependencies of individual geochemical or mechanical processes are often poorly investigated. Near-surface geophysical exploration, sediment characterization and geostatistical description of shallow subsurface parameters in cooperation with federal authorities and federal states are identified as requirements for reliable prognoses of the effects on drinking water aquifers [Dethlefsen et al. 2015; Dethlefsen et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6343-5)].

As an effect of larger temperature changes due to thermal energy storage, gas phases can form in shallow aquifers. A gas phase is bypassed by the groundwater flow and hinders the heat transport in ATES or BTES sites due to a reduced heat conductivity of the gas phase compared to the groundwater. These alterations reduce the system performance and induce changes in groundwater flow and chemistry. Experimental work using Pleistocene sands as typical aquifer sediments from Northern Germany and atmospherically equilibrated groundwater shows that gas phases may develop and accumulate, when temperatures are increased to 40 °C or up to 70 °C [Lüders et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6181-5)]. The same study shows with the help of geochemical equilibrium calculations that the gas phase formation in a water saturated aquifer is limited to the upper 12 m at temperatures up to 70 °C, assuming atmospheric equilibrium, due to the rising pressure, but extending somewhat deeper if H_2S, CO_2 or CH_4 are present as dissolved gases in higher concentrations.

Temperature increases may affect the mobility of potential inorganic groundwater contaminants. Trace elements of geogenic origin can potentially be released to the groundwater if shallow aquifers are exposed to temperature changes. The sorption behavior of arsenate in goethite sand under cyclic thermal loading was studied in circulating column tests and through titration of goethite surface charges. A temperature increase of 60 °C resulted in a reversible 70% increase in the arsenic concentration at the column outlet compared to the column inlet, which was not fully explained by a simple sorption transport model. Titrations showed a decrease in the pH_{PZC} (pH value of the point of zero charge) with increasing temperature, connected with a decrease in anion sorption sites at elevated temperatures and constant pH values. This effect resulted in a release of arsenic through the reduced sorption of arsenate anions at elevated temperatures. The experimental results shall contribute to the development of a transfer function to combine sorption isotherms at different temperatures for the description of the sorption-limited mobility as a temperature-dependent parameter (M. Ebert, pers. comm.).

In connection with thermal applications in the subsurface, changes in the microbial biocenosis are indicators for ecosystem changes and can be the cause for microbiologically induced operational disorders. Geochemical and microbiological analyses of thermally induced changes in bacterial diversity and abundance of aquifer sediments by Lienen et al. [at http://angusplus.de/en/publications/journal-articles (submitted)] accompanied the column experiments conducted by Lüders et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6181-5)]. The observed temperature-related biocenosis changes indicated a potential for bacterial decomposition of harmful substances like hydrogen sulfide or sulfuric acid at elevated temperatures of up to 70 °C [Lienen et al. at http://angusplus.de/en/publications/journal-articles (submitted)]. Temperature increases to up to 70 °C induced aerobic organic matter degradation, sulfate reduction and biomass formation as the most important processes in acetate-enriched aquifer sediments. Methanogenesis was observed only within a narrow temperature range around 25 °C and coincided here with the most efficient acetate conversion, compared to lower temperatures [Westphal et al. at http://angusplus.de/en/publications/journal-articles (submitted)].

The temperature signals induced by seasonal or shorter term heat storage with cyclic thermal loading can be used for geophysical monitoring of the heat storage site, due to the temperature dependency of propagation parameters such as seismic velocities. Oedometer tests on over-consolidated Tertiary clay as a typical sediment in Northern Germany were run to validate the representation of thermally induced alterations in the mechanical state by the velocity of elastic waves. The clay responded to the cyclic temperature changes with similar cyclic changes of the void ratio and, correspondingly, the longitudinal wave velocity. Along with the cyclic property changes, first results showed a gradual reduction of the void ratio (i.e., thermal hardening) with an increasing number of temperature cycles (V. Feeser, pers. comm.).

Development of numerical coupled process-oriented simulation tools

Simulations of thermal effects in the subsurface have been conducted for decades in the context of geothermal energy projects (Florides and Kalogirou 2007; Mielke et al. 2014; Yang et al. 2010) or thermal site remediation (Illangasekare et al. 2006). As open systems (well doublets) typically are considered for deep geothermal energy production, significant experience exists considering the availability of high-temperature data and the simulation of these systems. The representation of the technical installations in BTES systems (i.e., borehole heat exchangers in the form of single U-tubes, double U-tubes or coaxial tubes) by a numerical model, however, is challenging. Models so far use analytical solutions embedded as source terms for simplified cases, or double porosity. Computationally efficient OpenGeoSys dual-continuum models of BHE systems were applied to simulate BHE-coupled ground source heat pump systems (Zheng et al. 2016; Hein et al. 2016), where the BHE is represented as 1D domain in the surrounding 3D soil model. For high-temperature heat storage, however, a process-based detailed representation of the near borehole effects of the BHEs is required, which also allows for a representation of the coupled induced processes. Aiming for efficient but fully discretized OpenGeoSys models of multi-BHE heat storage sites representing all BHE components, Boockmeyer and Bauer [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5773-4)] developed geometrically simplified but volumetrically accurate numerical representations of BHE components. Reductions of the computational runtime by factors of up to 50 were achieved while allowing a heat balance deviation of maximum 1% compared to the geometrically accurate representation. This development now allows the fully discretized representation of real scale BTES sites in numerical models for the simulation of coupled induced processes.

The most likely place for the application of heat storage is the urban environment, which at the same time is the most likely place for the presence of soil contaminations. To be able to assess and predict adverse or beneficial thermal effects at contaminated sites, Popp et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5743-x)] and Beyer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5976-8)] extended the OpenGeoSys code (see Kolditz et al. 2016; Kolditz and Bauer 2004) for the non-isothermal simulation of heat storage in the shallow subsurface in the presence of dense non-aqueous phase liquids (DNAPL) as contaminants (Beyer et al. 2006). The process of temperature-dependent NAPL-dissolution was implemented and verified against a dedicated two-dimensional flow cell experiment [Popp et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5743-x)]. This extended model can be applied to simulate the induced hydraulic, chemical and microbiological effects in scenarios of seasonal heat storage in a trichloroethene (TCE)-contaminated aquifer (Popp et al. 2015).

Heat storages in specified normal operation

Fully discretized and process-oriented OpenGeoSys models of BHE systems allow to investigate the influences of individual component design, BHE array design and subsurface parameters on the performance and induced effects of a BTES site [Boockmeyer and Bauer 2014; Boockmeyer and Bauer at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5773-4)]. Using the developed modeling approaches, an increase in the recovered heat to 80% was achieved for a BTES setup with a few tens of BHEs. Single BHEs, in contrast, yielded a heat recovery of only 30%, due to a lack of mutual influence among individual BHEs (Bauer et al. 2015).

Failure in operational storage

First results of simplified numerical simulations of heat storage in TCE-contaminated shallow aquifers by Popp et al. (2015) showed slightly elevated TCE emissions due to increases in groundwater flow and TCE solubility, but also increases in contaminant biodegradation caused by a widening of the TCE plume. Besides interaction with existing groundwater contaminations, a BTES site may, in cases of accidental leakage, pose a threat in itself, since the circulating heat transfer fluid typically contains ethylene glycol or propylene glycol as anti-freezing compounds and benzotriazole as corrosion inhibitor. To protect groundwater resources, heat storage sites in shallow aquifers are therefore subject to a restrictive licensing policy in Germany (Haehnlein et al. 2010). The reactive transport behavior and degradation potential of the compounds mentioned above in a typical Northern German aquifer is therefore studied by both numerical simulations and flow-through column experiments. Results indicate that a compound- and site-specific regulation of the minimum distances between BHEs and water supply wells could significantly improve the compatibility of groundwater protection with an optimized use of shallow aquifers for heat storage and geothermal applications, since substantially shorter distances could be applied if degradation reactions were taken into account (C. Bendtfeld, pers. comm.).

Characterization of heat storage sites

To ensure the environmental and economic sustainability of an increasingly intensive geothermal use of the shallow subsurface especially in urban areas, Vienken et al. (2016) identified the consideration of thermal interactions among thermal subsurface uses as a planning and exploration requirement. Accordingly, Schelenz et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6331-9)] developed and tested a coordinated site investigation approach on the neighborhood scale. Results clearly show that a detailed site characterization allows an enhanced prediction of heat extraction capacities. This in turn can be used for a site-specifically optimized and cost-efficient system design and for a reliable assessment of changes in soil and ground water temperatures induced by the geothermal use. Therefore, novel site characterization approaches and techniques are needed (Vienken et al. 2015). Accordingly, Seibertz et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1016/j.jhydrol.2015.12.013)] developed a new methodology for high-resolution vertical characterizations of the heat storage potential in the saturated zone. Fiber optic distributed temperature sensing was used to provide depth dependent measurements of temperature dissipation after thermal excitation. This approach allows the use of existing groundwater monitoring wells and thereby avoids the necessity of BHE installations for the purpose of geothermal characterization. Seibertz et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1016/j.jhydrol.2015.12.013)] additionally showed that small changes in lithology, composition and state of compaction have a strong impact on the thermal storage potential, stressing the need for reliable high resolution in situ measurement techniques. A quantitative assessment of established and emerging methods for vertical soil water content profiling and the connected determination of total porosity in the saturated zone was conducted by Vienken et al. (2013). The yet little established direct push-based water content profiling method was identified as beneficial in terms of a high vertical resolution, time efficiency and a possible coupling with other direct push-based sensor probes.

Gas storage: Porous media and salt cavern storage

Development of a data base: Parameterization of formations and processes in the deep subsurface

Potential gas storage reservoirs require porous formations with a tight cap rock counteracting a buoyant rise of the stored gases. In the North German Basin, these characteristics are typically present in the sandstones of the Dogger, Rhaetian, Middle Buntsandstein and Rotliegend Formations. The simulation of realistic subsurface energy storage scenarios requires detailed parameterizations of these storage sites and formations. The availability of data is a major issue, as numerous (coupled) parameters on the involved fluid and solid phases are required for the respective temperature and pressure range. Dethlefsen et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2627-1)] assembled a thematic geological database with geological, hydrogeological, and geochemical parameters of reservoirs in the North German Basin at depths > 500 m, using well data from the exploration and production industry and geostatistical analyses. Although being able to determine correlation lengths for a number of variables, a lot of the required data, especially on multiphase flow parameters, is still unknown or not publicly available. The geological model and facies definitions for the North German basin could be based on previous studies by Gaupp (1991) and Hese (2012).

Rock salt caverns used for Compressed Air Energy Storage (CAES) or Power-to-Gas storage (Sterner and Stadler 2014) of hydrogen or synthetic methane are subject to cyclic changes of pressure and temperature due to gas compression and expansion during injection and production, respectively. Numerical models require an accurate representation of the coupled thermal and mechanical effects on the behavior of rock salt under cyclic loading. Khaledi et al. [at http://angusplus.de/en/publications/journal-articles (doi: 10.1016/j.ijrmms.2016.04.010)] used the results from experimental triaxial compression tests to calibrate an elasto-viscoplastic creep constitutive model of rock salt, accounting for temperature effects, dilatancy and damage progress. An extension of this constitutive model has been utilized by Mahmoudi et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5850-8)] to integrate the experimental investigations with the obtained results from the numerical analyses and to update the calibration procedure iteratively. In addition, the effect of uncertainties in the considered values of input parameters on the computational responses is investigated by applying global sensitivity measurements [Khaledi et al.

at http://angusplus.de/en/publications/journal-articles (doi:10.1016/j.cam.2015.03.049)].

Development of numerical tools

Numerical tools for the simulation of gas storage in porous media or salt caverns and its induced effects need to be able to represent the governing coupled thermal–hydraulic–mechanical and geochemical processes. These tools are the basis for the dimensioning of storage sizes, determining operation conditions and quantifying induced effects. Due to the large variety of possible subsurface situations, a flexible and versatile model approach is required. The ANGUS+ project provides for this requirement by developing appropriate models and by using different coupling schemes.

Pfeiffer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6168-2)] coupled the THMC simulator OpenGeoSys (Kolditz et al. 2015) with the multiphase-multicomponent simulator ECLIPSE (Schlumberger NV 2015), to make use of the high computational efficiency of the industry simulator ECLIPSE for large-scale grids as well as the thermal and reactive mass transport capabilities of OpenGeoSys. This coupling allows for fully coupled non-isothermal multiphase flow and multicomponent reactive transport simulations, making also use of the geochemical modules described in Li et al. (2014) and Beyer et al. (2012). The coupling scheme was successfully validated using a set of dedicated benchmark simulations [Pfeiffer et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6168-2)].

As a further improvement to the OpenGeoSys framework, Böttcher et al. [at http://angusplus.de/en/publications/journal-articles (submitted)] developed a staggered coupling scheme for the governing thermal and mechanical processes which accounts for the thermodynamic behavior of the stored gas in the cavern. Nagel et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5429-4)] introduced Kelvin mapping for the simulation of deformation processes, as this method preserves the tensor character and provides a numerical matrix notation directly corresponding to the original tensor notation.

For the integration of large-scale geological data into numerical models, Wang and Bauer [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6138-8)] implemented a consistent mapping from corner point gridded heterogeneous geological structures and data to finite element grids. This allows the use of these grids in any THMC model based on the Finite Element Method, and facilitates the coupling between OpenGeoSys and ECLIPSE, which requires a joint computational grid. The conversion concept was shown to be able to successfully convert a reservoir scale geological model with multiple layers, pinch-outs and faults, thus accounting for the major features encountered.

A modeling scheme for the safety assessment of gas storage in salt caverns is suggested by Khaledi et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1016/j.ijrmms.2016.04.010)]. This approach encompasses a literature-based material parameterization and numerical simulation of the excavation and the subsequent operational cyclic loading. The numerical computation of stress paths, volume convergence, damage propagation and permeability changes simulated in the numerical scenarios allows the derivation of safety limits for the cavern operation.

Gas storage in normal operation: Storage dimensioning and induced effects

The actual technical and economic significance is a precondition for the meaningful evaluation of subsurface gas storage scenarios in connection with Power-to-Gas schemes. To achieve this, load curves are required, considering the excess power production from wind or solar power plants as well as the power demand. To this end, Pfeiffer and Bauer (2015) and Pfeiffer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5958-x)] estimated the amount of 129×10^6 m^3 of hydrogen gas (at surface conditions) as amount necessary to secure the electricity demand of 0.82×10^6 GJ in Schleswig–Holstein during one week of a shortfall in both wind and solar power production. Injection and extraction rates were determined taking into account the efficiency of hydrogen re-electrification and assuming an array of five wells in a Rhaetian sandstone reservoir formation in a dome-shaped anticline site. They found that 0.186×10^6 GJ could be supplied by the storage site during a production period of 1 week, which corresponds to about 22% of the required power. Therefore, either more storage sites or, preferably, an increased number of wells would have to be used to cover the storage demand. The anticline site considered would allow a corresponding extension (Pfeiffer and Bauer 2015). To assess the hydraulic impacts of such a large storage site, Bauer et al. (2015) quantified the pressure changes after each injection cycle compared to the initial hydrostatic pressure and the gas phase distribution by means of gas saturation in the reservoir formation around the wells. Pressure changes of more than 1 bar occurred at distances $\leq$ 7.5 km from a well, resulting in an area affected by pressure increases of about 88 km^2. The gas phase, however, was found to extend over an area of only about 4.5 km^2. Hydrogen storage could thus be an option for energy storage on the time scale of days.

Wang et al. (2015) derived a storage scenario from existing gas turbine technical data and daily operation cycles at the operational cavern of the Huntorf CAES power plant in Lower Saxony, Germany, and transferred it to a virtual CAES application in an idealized anticlinal structure. With an estimated production rate of 208.5 kg/s of air for 30 h, equivalent to about 10% of the total air stored in the porous formation, the observed fluctuations of the bottom-hole pressure are within the limits of minimum turbine inlet pressure and maximum safe operation pressure. This hypothetical CAES storage in a porous formation with a permeability of 1 Darcy (equal to 9.86923×10^{-13} m^2) and 20 m thickness could thus provide about 320 MW for up to 41 h. This shows that under favorable reservoir conditions, porous media CAES could provide short-term storage capacities on the order of hours to days.

In a numerical study of the long-term stability of rock salt caverns as energy storage sites, Khaledi et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5970-1)] simulated the stress–strain behavior of rock salt under extreme loading conditions of an operational CAES cavern. A scenario of high-temperature operating conditions showed that an increased creep rate led to accelerated cavern closure, while a scenario of low-pressure operating conditions induced severe effects of dilatancy, damage propagation, and tensile failure in addition to a likewise increased rate of cavern closure.

Failure in operational storage

Pressure increases in the deeper subsurface, induced by large-scale gas storage operations in porous structures or by other types of use, as, for example, fluid injection, may mobilize the resident formation brine. If permeable leakage pathways are present, brine may also be displaced into overlying formations. Rising saline formation water may, in the worst case, reach shallow fresh water aquifers and deteriorate drinking water resources. Studies so far looked at horizontal pressure propagation (e.g., Birkholzer et al. 2009) or vertical brine migration across one sealing formation (e.g., Zhou and Birkholzer 2011). Delfs et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6245-6)] used numerical simulations to assess brine ascent through a series of alternating reservoir and barrier formations. The reservoirs were connected by a permeable vertical pathway, representing a fault. If permeability in the vertical pathway was high, brine rose into the overlying formation, expelled the brine from there further into overlying formations and thereby drove a gradual upward displacement. In the absence of intermediary permeable reservoirs, upward brine movement was reduced or even stopped by the higher density of brine from deep saline reservoirs [Delfs et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6245-6)]. The spreading of a brine leakage once intruded into a shallow fresh water aquifer was investigated by Wiegers and Schäfer (2015) in realistically parameterized 3D simulations. At groundwater flow velocities larger than 0.5 m/d, the effect of aquifer bottom topography on the simulated brine spreading was minor compared to the effect of the groundwater flow. Numerical simulations on realistically parameterized virtual sites were also used to derive possible gas phase distributions after an accidental gas leakage in order to design adequate monitoring methods [al Hagrey et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5784-1)]. Wiegers and Schäfer (2015) worked out that the detection of such plumes is highly reliant on the monitoring setup employed. As has been shown by, for example, Bauer et al. (2006), Beyer et al. (2007) or Rein et al. (2009), monitoring setups for these cases can be adapted to heterogeneous as well as transient conditions and be used to quantify the expected measurement uncertainty.

Leakage of air from a CAES storage site into a shallow aquifer with reducing conditions will typically fuel geochemical reactions due to high oxygen availability. As one case of the possible reactions, Berta et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5985-7)] experimentally characterized pyrite oxidation in dependence of oxygen partial pressure and observed low reaction rates, explained by surface passivation of the pyrite grains. Gas leakages from methane or hydrogen gas storage sites into shallow aquifers can also impair groundwater quality. Hydrogen as a very reactive electron donor will likely induce the reduction of nitrate, sulfate and carbonate, if available (M. Berta, pers. comm.). Methane, in contrast, seems to require an established initial methane oxidizing microbial community to trigger biogeochemical reactions after a comparably long adaption phase following the gas intrusion (Berta et al. 2015a, b).

Geophysical monitoring of gas storage operations

Geophysical monitoring has been shown to be a successful and promising tool for the control of subsurface gas storage operations (Dethlefsen et al. 2013). Specifically adapted seismic inversion codes, which use full waveform inversion methods (FWI) were shown to be able to resolve small structures with high resolution. To this end, an advanced FWI code was developed by Köhn et al. (2015a, 2015b). In combination with geoelectric and gravimetric methods, an integrated approach was devised, which combines the specific strengths of the individual methods to yield an improved representation of gas distributions in the subsurface, for cases of either porous medium storage or cavern storage. This integrated approach was assessed in synthetic case studies by al Hagrey et al. (2014a) and Benisch et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-014-3603-0)], and subsequently applied to numeric scenarios of gas storage operations and accidental leakages to test for the geophysical monitoring options.

The scenario simulations of hydrogen storage in porous media conducted by Pfeiffer and Bauer (2015) and Pfeiffer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5958-x)] were accompanied by a numerical assessment of geophysical monitoring methods. Seismic FWI, electrical resistivity tomography (ERT) and gravity monitoring were tested virtually on the fully parameterized, synthetic scenario. Seismic FWI and ERT were shown to be able to identify the thin (order of meters) gas phase in the storage reservoir. P-wave velocities from seismic FWI in a cross-well geometry with a spacing of less than 500 m distance and frequencies up to 1000 Hz were found to allow the resolution of gas phase saturation in the storage reservoir. Optimized data acquisitions and constrained inversions using the highly resolved structures mapped by FWI enhanced the ERT mapping [Pfeiffer et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5958-x)].

The detectability of gas and brine leakages by the integrated geophysical monitoring approach was investigated in a sensitivity study by al Hagrey et al. (2014b). While gravity mapping and seismic FWI performed better in monitoring air leakages in the defined scenario, ERT and transient electromagnetic induction (TEM) were observed to perform most sensitive in the detection of brine intrusions and allowed for the detection of brine leakages in larger depths, compared to air leakages (al Hagrey et al. 2014b). The integrated geophysical monitoring approach using seismic FWI, ERT and gravity monitoring techniques to detect the altered geophysical properties and reduced density caused by the presence of a gas phase was also applied by al Hagrey et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-5784-1) to virtual CAES leakage scenarios: The case of air leakage from a simulated CAES site into a shallow aquifer was considered in a fully parameterized numerical scenario with an accumulating gas phase resulting from a leakage rate of 1 kg/s. While seismic FWI and ERT resolved the anomalies caused by the air leakage 3 years after intrusion into the freshwater aquifer, including gravity mapping improved the detectability to 4 months after start of the leakage.

An early detection of induced cracks can help to identify possible pathways for gas leakages. A seismic monitoring strategy for cavern gas storage in complex salt structures using crack-induced microseismic events was developed by Köhn et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6032-4)]. The improved spatial resolution of the FWI method as compared to standard methods allows for a localization of these events, which can be used in cavern inspection surveys.

3D spatial data in web-based and visual information systems

To technically support the integration of subsurface energy storage applications into spatial planning, a web-based 3D spatial information system is developed within the ANGUS+ project. The setup includes parameterizations of energy related surface infrastructure like electric power lines on different voltages, residential areas for heat demand quantification, gas pipeline networks, current spatial planning areas and protective areas in Schleswig–Holstein as a demonstration area. Surface data and structural geological models of this area are transformed into a consistent voxel data model and integrated into the newly developed 3D spatial information system, allowing for exploration of the combined data sets by 2D and 3D visualizations, user-defined queries and export of the results as georeferenced data [Nolde et al. 2015; Nolde et al. at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-016-6089-0)].

Interactive 3D visualization is an important native tool to assist data analyses of heterogeneous and complex subsurface spatial data and to support knowledge transfer to government agencies, involved companies and public, etc. Complete workflows are required for the analysis of complex data and model sets in order to gain the maximum information for a better system understanding and for the development of reliable planning tools (Rink and Fischer 2012; Helbig and Bilke 2015). The preparation of process analyses involves integration of geoinformation data from heterogeneous sources, e.g., GIS maps and 3D hydrogeological data. The OGS^{DataExplorer} software has been developed for this purpose and is also able to integrate simulation results from different modeling tools (Rink 2015; Fischer et al. 2015). For the present study, integrated data and simulation results have been embedded into a Unity3D framework. Figure 4 depicts different stages of the analysis workflow, starting from the structural geological model (a) and structural analysis (b). Figure 4c shows the embedded simulation results for an individual cavern. The full data and model set can be displayed in a Virtual Reality (VR) environment, such as the visualization center VISLAB at the Helmholtz Centre for Environmental Research (UFZ) (Fig. 4d). Those workflows have been implemented for different geoscientific applications already, e.g., CO_2 storage (Krawczyk et al. 2015), shallow

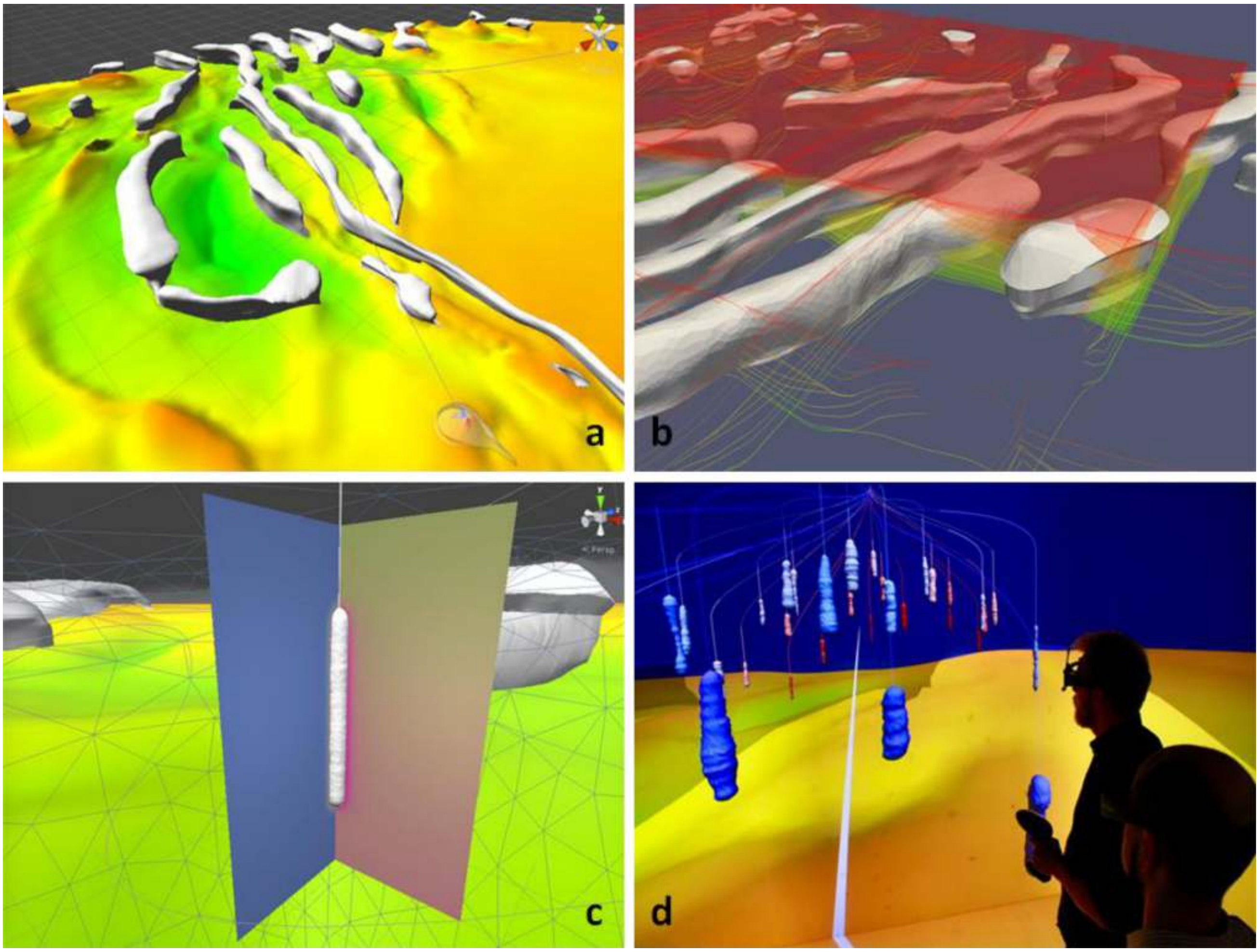

Fig. 4 3D stereoscopic visualization of different facets of geoenergy storage: salt layer representation in the North German Basin (more specific) (**a**), *lines* indicate cross sections of hidden layers (**b**), numerical models of individual cavern utilization in the full geological context (**c**), intuitive data exploration in VR frameworks (VISLAB) (**d**). Figure by Lars Bilke, Helmholtz Centre for Environmental Research (UFZ)

and deep geothermal energy resources and hydrology. The ANGUS+ visual framework for interactive applications is available on different VR systems, VISLAB, PCs or online. The 3D interactive visualization tool allows the user to navigate through the visualized geological model, toggle the visibility of data sets and control the display of time-dependent data sets.

Conclusions

Currently, the permission of subsurface use in Germany is subject to market forces (Bovet 2014). Without the identification of priority and reserved areas for specific types of subsurface use, potential storage sites may become inaccessible despite their qualification as a storage site and despite not necessarily interfering effects of operating applications in different geological formations. A future sustainable subsurface planning will rely substantially on the quantified knowledge of the subsurface operation itself, the magnitudes and spatial extents of the potentially induced effects and mutual effects with other subsurface operations at a specific site.

Bauer et al. [at http://angusplus.de/en/publications/journal-articles (doi:10.1007/s12665-013-2883-0)] identified the need for site-specific evaluations of a scenario-based research approach as a basis for a sustainable subsurface planning scheme. Following that work, the conceptual distinction of an operational space, an affected space and a monitoring space in connection with subsurface operations is proposed in this study, in order to enable the identification of direct or indirect competitions for subsurface space. The delineation of these areas or volumes in the subsurface requires adequate prognosis tools, which will typically be numerical, spatially distributed parameter models accounting on a physical base for the processes involved. Thus, the quantification of thermal, hydraulic, mechanical and chemical (THMC) process magnitudes and spatial extents is crucial in the assessment of such subsurface operations. The ANGUS+ project therefore provides the data collections for parameterizations, as well as the methodologies and tools required for site-specific assessments of geotechnical energy storage options. These are demonstrated and tested on realistic, albeit virtual, scenarios of specified normal operation and cases of accidental failure. Studies within the framework of the ANGUS+ project also show that the assessment of subsurface energy storage operations is highly specific for each site and type of storage application: It depends on the geological setting, the storage capacities and the deliverability rates (discharging rates) required by the surface infrastructure and the given storage option. Following an interdisciplinary ANGUS+ project concept, integrated geophysical monitoring approaches combining seismic full waveform inversion (FWI), electrical resistivity tomography (ERT), gravimetry and geomagnetic methods were virtually applied to the simulation of fully parameterized numerical storage scenarios. In this context, the integrated geophysical monitoring approaches were evaluated as suitable methods for gas storage monitoring and for the early detection of gas and brine leakages. The 3D spatial information system developed within the ANGUS+ project gathers data on energy infrastructure, protected entities and subsurface geology, aiming at query-based 3D visualizations of parameterized subsurface formations as potential storage sites in the context of energy production and demand. Future efforts for 3D data visualization shall be directed toward the further formalization of specific workflows for the analysis of complex data and models sets and toward the development of so-called Environmental Information Systems. For the further improvement of energy storage scenarios in step with actual practice, linking the storage demand to accurate energy system models will be crucial.

The parameterization of the geological subsurface is yet in progress. Here, we presented complete parameterizations of potentially suitable storage sites. A further parameterization of the subsurface with a geostatistical description especially of the fluid phase on a wider spatial scale is necessary to improve the chances for a future subsurface spatial planning scheme. Experimental test site validations of the numerical methods presented in this study are the next step to enhance prediction methods in an iterative experimental–numerical process. From this process, the tools and methods for an elaborate subsurface spatial planning scheme can be derived. The profound knowledge of the subsurface geology can then provide the basis for an identification and definition of priority areas and reserved-function areas. Case-to-case simulations can predict optimal storage dimensions, the magnitudes and spatial extents of their induced effects, and the respective monitoring requirements. However, to achieve a sustainable and economically efficient pattern of subsurface use, the legal framework needs to overcome the traditional mining law principle of first-come-first-serve.

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