Introduction

The shift from carbon-based fuels towards renewable energy production is a viable pathway to reduce greenhouse gas emissions and thus minimize the human made impact on the global climate (IPCC 2014). Renewable energy production relies on the presence of wind or solar irradiation, which show natural fluctuations in intensity depending on the location and the given weather conditions. Thus, energy storage is required in systems primarily based on renewable sources (Heide et al. 2011). Storage systems can also reduce the overall cost of the energy system by reducing the demand for conventional power-plants as black start reserve (Steinke et al. 2013).

Underground gas storage (UGS) is one of the large-scale energy storage options discussed for providing the storage requirements in future energy systems. Technology options for UGS are either mechanical energy storage in a power-to-power scheme, typically through compressed air energy storage (CAES), or chemical energy storage by storing synthetic hydrogen or synthetic methane in a power-to-gas scheme (Sternberg and Bardow 2015). Both options are investigated for grid-scale energy storage, e.g. for the case of hydrogen storage in Spain (Sainz-Garcia et al. 2017) and Germany (Pfeiffer et al. 2017) as well as CAES in the UK (Mouli-Castillo et al. 2019), Germany (Wang and Bauer 2017) and Sweden (Sopher et al. 2019).

The limiting conditions for a storage plant design are given by the geological setting and the load profiles, i.e. the charging and discharging rates which the storage plant must support. However, these load profiles are not known a-priori, as they strongly depend on the development of and the interactions within the future energy system. Assessing individual load profiles of specific components in an energy system, e.g. power- and storage-plants could be done using modelling frameworks such as oemof (Hilpert et al. 2018). However, the computed load profiles must be tested for their validity since the modelling frameworks typically only consider a simplified storage behaviour. For this validation an integrated modelling approach has been developed for a coupled power-plant and geostorage simulator, capable of considering limitations of the plant design and the geostorage at runtime (Pfeiffer et al. 2019). The hydraulic properties and their distribution within a potential geological storage formation directly affect the storage performance as shown e.g. for a synthetic hydrogen storage scenario in Pfeiffer et al. (2017). The distribution of hydraulic properties in the subsurface is inherently uncertain to some degree (e.g. Durlofsky 2005), which can be accounted for by running ensemble simulations to estimate the storage performance for a feasibility analysis. However, in combination with uncertainties regarding the technical boundary conditions, i.e. the target load profiles of a storage operation, a very large number of individual simulations is required to evaluate the feasibility of a specific storage and power-plant design in a future energy system. Due to the high demand on runtime these simulations may not be feasible.

The aim of this work is to demonstrate an approach for a fast(er) analysis of the feasibility of a CAES operation in a future energy system. For this approach first a coupled power plant & geostorage simulator is developed to allow for feedback processes during operation. In a second step, homogenous replacement models are derived from a heterogeneous ensemble for the use in simplified reservoir simulations. In combination these two approaches provide the basis for an assessment of the operation of a realistic porous media CAES system under various operational schedules.

Simulator development

For the investigation of CAES and potentially also hydrogen and methane gas storage, a coupled power-plant and geostorage simulator was developed (Pfeiffer et al. 2019), which enables the consideration of power-plant and geostorage constraints during the storage operation and allows for feedback between both components. This is achieved by coupling the scientific open source modelling software TESPy (Witte 2019) to the ECLIPSE reservoir simulator package (Schlumberger 2018) through a python-based interface (Figure 1). The primary variables which are exchanged in each coupling loop are the storage pressure and the mass flow into or from the storage formation, which for a CAES system define the power the system is providing or taking up. Since constrains in pressure...
and flowrate exist, e.g. through turbine or formation pressure limits, the calculation of the target mass flow is done iteratively in each timestep depending on the actual storage pressure.

**Figure 1** Coupling schematics of the integrated power-plant & geostorage simulator for an adiabatic CAES application (Pfeiffer et al. 2019).

In the case of a CAES system an alternating correlation of power on the one hand and mass flow and pressure on the other hand exists when charging or discharging. During charging, the increasing storage pressure results in a decrease in the required mass flow for a constant power input, showing a negative feedback (Figure 2). Conversely, the mass flow required to provide a defined power output increases as the storage pressure decreases during discharging, resulting in a positive feedback.

**Figure 2** Evolution of storage pressure and mass flow during constant charging (a) and discharging (b) of a porous media CAES system. Modified after Pfeiffer et al. (2019).

**Homogenous replacement models**

One option to minimize simulation runtimes for the validation of storage load profiles is to reduce the model complexity by homogenising the flow property model of the storage simulation. Pfeiffer and Bauer (2019) tested the applicability of several homogenous replacement models for a heterogeneous ensemble investigated for hydrogen gas storage (Figure 3). For this, equivalent permeabilities, porosities as well as capillary pressure and relative permeability data were derived from the parameter distributions of the heterogeneous ensemble. Examples to determine effective permeabilities examples are using simple arithmetic and harmonic means, which should provide accurate effective properties for single phase flow parallel or perpendicular to rock strata (e.g. Bear 1972) or provide bounds of the true effective permeability if these conditions are not satisfied (Renard and de Marsily 1997).
Methods used to obtain average or effective multiphase flow data for capillary pressures and relative permeabilities are typically differentiated into static (or steady state) and dynamic methods (Barker and Thibeau 1997, Christie 2001), of which only static upscaling using the gravity equilibrium method (e.g. Pickup and Stephen 2000, Christie 2001) was applied in the cited work. To test the effect of the shape of the capillary pressure functions also a linearized dataset based on the respective saturation endpoints obtained through the upscaling was tested in addition to the upscaled non-linear dataset.

It was found that estimating the horizontal permeability using a simple arithmetic mean and the harmonic mean for the vertical permeability yielded the best fit to the median of the heterogeneous ensemble in terms of the storage pressure during operation and the achievable gas flow rates. Neglecting the anisotropy provided a good approximation of the 5th percentile of the ensemble in terms of storage performance but provided a less accurate fit in terms of the storage pressure. Using a geometric mean of arithmetic means calculated along all vertical columns in each formation layer provided simulation results which are in good agreement with the 95th percentile of the heterogeneous ensemble. Thus, using only a couple of simulation runs instead of the full ensemble allowed the estimation of the lower bounds and the median of the storage performance, reducing the required runtime for this analysis.

Conclusions

The described coupled power-plant and geostorage simulator allows to accurately consider interactions and feedback processes occurring during the operation of e.g. CAES in porous formations. This enables a detailed analysis and validation of load profiles for such storage systems in future energy systems. Besides the definition and description of the power plant design, also a (full scale) reservoir model is required for the analysis. Given the uncertainties of the geological setting, such an assessment benefits from ensemble simulations to estimate the uncertainty of the storage flow rates and the achievable capacity. Simulation runs based on homogeneous replacement models derived from such a parameter ensemble can be useful to determine the median and the lower bounds of the storage performance using less computational resources. The combination of such an integrated modelling approach with simplified reservoir simulations using effective hydraulic properties could thus be a viable approach for the assessment of PM-CAES in future energy systems primarily based on renewable power generation.

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References


