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TEST CASES FOR A COUPLED POWER-PLANT AND GEOSTORAGE MODEL TO SIMULATE COMPRESSED AIR ENERGY STORAGE IN GEOLOGICAL POROUS MEDIA

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ABSTRACT

CAES using porous geological formations such as sandstones could provide the large storage capacities required in future energy systems largely based on renewable sources. In such systems storage pressure, achievable mass flow and power output have strong interdependencies. Thus, an integrated assessment of the power plant and the geostorage is required, for which a coupling approach is presented. Three generic test cases are constructed, demonstrating an accurate representation during all operational modes.

Keywords: compressed air energy storage, geological porous media, renewable energy systems, model coupling, numerical simulation

NONMENCLATURE

Abbreviations	
BHP	Bottom Hole Pressure
CAES	Compressed Air Energy Storage
G	Generator
M	Motor
PV	Photovoltaic
TES	Thermal Energy Storage

1. INTRODUCTION

Increasing the share of renewable sources in power generation to mitigate climate change could result in a significant storage demand to compensate natural fluctuations in wind and solar availability [1]. Underground gas storage is typically seen as a large-scale energy storage option in such systems, either for mechanical energy (power-to-power) [2] or for storing an energy carrier like hydrogen (power-to-gas) [3].

Underground natural gas storage in porous formations such as sandstones can provide large capacities over long discharge periods [4]. More recently, research has focused on using the vast storage potential the subsurface for CAES [2], as the systems can provide MW-scale power outputs, show good partial-load performance and moderate response times [5]. In combination with underground gas storage, also discharge cycles of multiple days are possible [6].

Modelling frameworks capable of simulating future energy system dynamics, such as oemof [7], can provide storage load profiles for a feasibility analysis, e.g. using power plant simulations. When using porous geological formations to store the gas, also the flow in the storage formation must be accounted for, as the power the system can provide is strongly dependent on the storage pressure, which varies spatially and temporally due to the geologic properties and the history of the injection and withdrawal periods.

For a detailed assessment an integrated simulation approach is required, accounting for the processes occurring in the power plant and the storage formation as well as their interdependencies.

2. MODEL COUPLING

To enable such assessments, a CAES power plant model generated with the scientific open-source modelling software TESPy [8] is coupled to the reservoir simulator package ECLIPSE [9].

2.1 Power plant simulation model

A CAES power plant is defined by its topology as well as the parametrization of the respective components and connections. The component based power plant simulation software TESPy provides pre-defined components, for example different types of turbomachinery, heat exchangers and combustion chambers. Each component comes with built-in basic equations (e.g. mass flow balance) and optional equations (e.g. specification of isentropic efficiency).

To simulate the operation of a specific power plant an individual model is created by connecting the respective components to form a topological network. TESPy automatically generates a set of nonlinear equations based on the components applied. Using the multi-dimensional Newton-Raphson method the system of equations is solved to calculate mass flow as well as fluid properties such as pressure, enthalpy and fluid composition at every point of the network.

2.2 (Geo)-Storage simulation model

Gas storage in porous geological formations represents a multiphase system, e.g. of gas and water. Flow within the storage formation is not trivial due to the distribution of the geologic properties, the geometry of the formation and the history of the storage formation, i.e. the exact pressure distribution in the storage formation prior to injection or withdrawal.

The mathematical description of flow in porous media has been covered extensively [e.g. 10]. Based on a mass balances and using the generalized Darcy's law (assuming laminar flow), a set of partial differential equations is obtained, which are typically solved using numerical methods. In the developed model coupling this is done with the ECLIPSE [9] reservoir simulator package, which was previously used for e.g. simulating hydraulic effects during CAES in sandstone formations [6] and hydrogen gas storage [6, 11].

2.3 Simulator coupling

The simulators are coupled time step wise through an interface that controls the execution of both TESPy and ECLIPSE (Fig 1). The primary exchange variables are the air mass flow and the storage pressure. The operation of the CAES is constrained on the power plant side by the minimal and maximal values of mass flow and pressure. On the storage side, the flow rate applied at the storage wells may not result in a violation of the lower and upper BHP limits to ensure geomechanical integrity of the storage formation and the caprocks. Thus, reductions in mass flow and consequently power output can occur due to limitations in both primary components of the system. An iterative coupling was implemented ensuring neither the power plant nor the storage is operated outside their respective limitations.

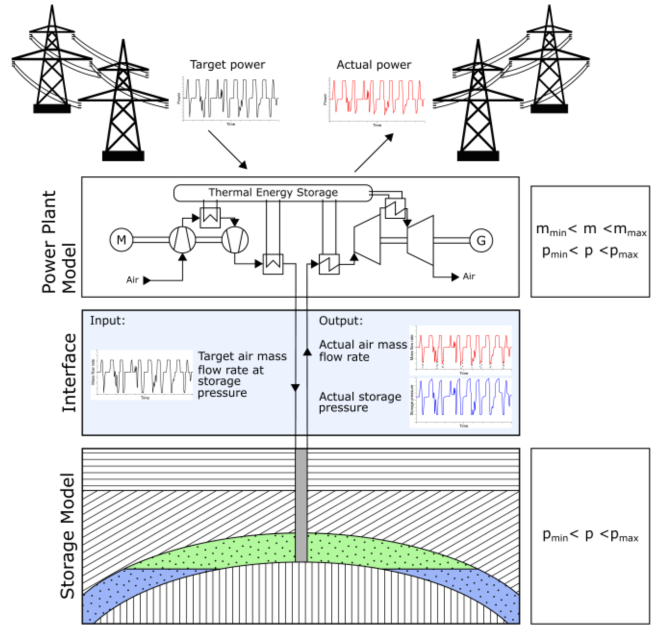

Fig 1 Schematics of the developed model coupling including the power plant design used for the presented test cases.

Based on a target load and the current storage pressure first the target mass flow is calculated using TESPy. Subsequently this mass flow is set as a boundary condition for the geostorage simulation, providing an updated storage pressure and a limitation for the achievable mass flow if the BHP limits are violated. With these updates the power plant model is re-run. The time step is accepted if the difference between the pressure in the power plant model and the geostorage model are below a threshold. If the pressure difference is not within the defined limits, the target mass flow is recalculated based on the new storage pressure, which is then again used as an updated boundary condition for the geostorage simulation. If the flow rates are limited, i.e. the storage cannot provide the required rate, the power output or input is adjusted based on the maximal flow rate and the given storage pressure.

3. SIMULATION AND RESULTS

3.1 Simulation setup

Three dedicated test cases are used to assess the coupled model behavior: An alternating load profile mimicking peak shaving of PV generation, a continuous charging case (storage feed-in) and a continuous discharging case (storage feed-out).

For the testcases an adiabatic power plant concept similar to [12] was selected (Fig 1). A two-stage compression with coolers after each stage feeding a thermal energy storage is implemented. The first stage

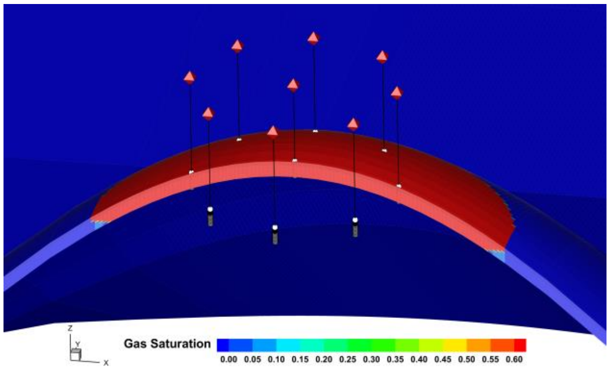

Fig 2 Slice through the storage formation showing the initial gas phase distribution.

has a fixed pressure ratio of 5 and a nominal isentropic efficiency of 91 %. The second stage nominal efficiency is at 85 %. A reheat turbine powered by the thermal energy storage represents the expansion part of the power plant. The high-pressure turbine includes a control stage for pressure regulation with a nominal efficiency of 85 %. The efficiency of the second stage is set to 90 %. The power plant is connected to the geological storage by wells, with the mass flow being equally distributed. Rated power of both compression and expansion is 100 MW. The energy balance of the heat storage is not considered in detail for the test simulations.

The geological storage formation is an anticline, representing a typical trapping geometry and is identical to what Wang & Bauer [6] used in terms of most of the parametrization, thus some detail is omitted. The storage is operated using 9 wells in depths of around 700 m, with the BHP limits set to 90 and 40 bars, respectively (Fig 2). Initially the storage pressure is hydrostatic at 72 bars. Constant pressure boundary conditions are applied at the edge of the model domain. The gas-water contact was set to 800 m, resulting in an initial gas mass of around 168 kilotons.

3.2 Simulation results

The target power demand defined in the simulation case mimicking a peak shaving of PV is met at all times, as no flow rate reduction occurs (Fig. 3). However, the higher mass flow required during the withdrawal periods compared to the injection phases to achieve the same absolute power output results in a slight but steady decrease of the storage pressure. Ultimately, this will result in an adapted dispatch or a reduction of flow rates once the storage pressure is approaching the lower BHP limit set for the simulation. The feedback of storage pressure on the applied mass flow rates for a given power, albeit not visually apparent, is well represented.

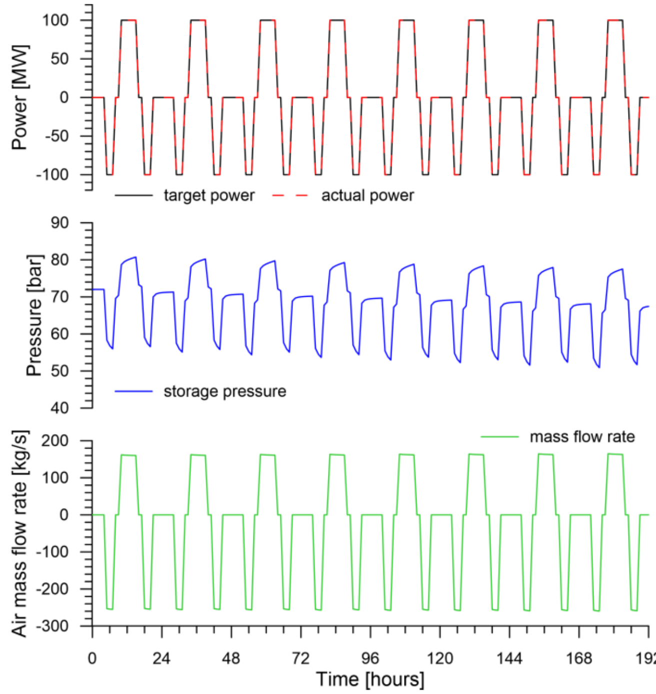

Fig 3 Simulation results for the test case approximating a storage operation for peak-shaving PV power generation.

The following two test cases allow an easier assessment of the feedback between the power plant and the geostorage model. While charging the system, the storage pressure increases as air is injected (Fig 4). This results in a decreasing mass flow as less gas can be compressed for a fixed amount of power as storage pressures increase, which can be seen in the first 106 hours of the continuous charging test case. Once the storage pressure reaches the specified upper BHP limit of 90 bars, a sharp decrease in the air mass flow and power rate is observed, as the storage formation cannot support the required injection rates from this point onwards. Thus, during this time the achievable power rate is limited by the storage behavior. Ultimately, the mass flow drops below the power plants minimum requirement at 181 hours, resulting in a shut-in of the storage. During the shut-in no flow rate is applied, which

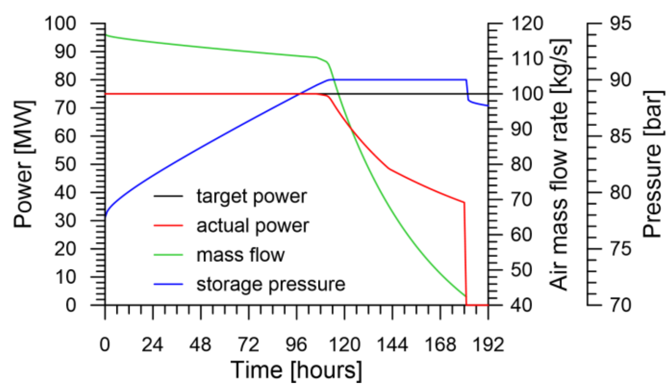

Fig 4 Storage metrics during the continous charging case.

allows the pressure gradient within the storage formation to equalize, resulting in drop in the observed storage pressure at the wells.

During discharging air is extracted from the storage formation, resulting in a decrease in storage pressure, which causes an increase in the required mass flow to provide the specified target power output, visible in the first 65 hours (Fig 5). As the storage pressure drops further, the maximum mass flow limit of the power plant design can be reached, resulting in a reduced power output. The withdrawal of gas ultimately results in a violation of the lower acceptable pressure limit of 40 bars set at the wells, which occurs at 76 hours. Following this, the mass flow rates the storage can provide decrease rapidly resulting in significant decrease in power output. After 175 hours, the flow rate drops below the power plants minimal requirement, triggering the shut-off of the system. The equalizing of the pressure gradient within the storage formation then causes a rebound in the storage pressure. The thermodynamic full cycle efficiency of the storage system ranges from 54 % to 59 % depending on the power plant design showing a decrease in efficiency with increasing power rating.

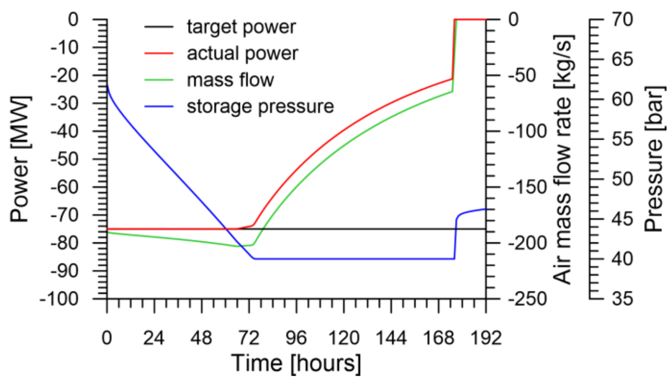

Fig 5 Storage metrics during the continous discharging case.

4. CONCLUSIONS

The developed coupled simulator provides the functionality to accurately simulate a CAES system that uses underground gas storage in porous formations. The interactions between the surface plant and subsurface storage via air mass flow, storage pressure and power are correctly represented in the model, resulting in a damping (negative feedback) of flow rates and storage pressure during injection and a self-enhancing (positive feedback) during withdrawal. As an integrated and coupled model of the power plant and the subsurface storage is available and fully functional, it can be used for detailed assessment of CAES using a porous formation to store the gas.

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REFERENCE

[1] International Energy Agency. Technology Roadmap – Energy Storage. Paris: IEA; 2014.

[2] Mouli-Castillo J, Wilkinson M, Mignard D, McDermott C, Haszeldine RS, Shipton ZK. Inter-seasonal compressed air energy storage using saline aquifers. Nature Energy 2019;4:131-139.

[3] Pfeiffer WT, Beyer C, Bauer S. Hydrogen storage in a heterogeneous sandstone formation: dimensioning and induced hydraulic effects. Petroleum Geoscience 2017;23:315-326.

[4] Plaat H. Underground gas storage: Why and how. In: Evans DJ, Chadwick RA, editors. Uunderground Gas Storage: Worldwide Experience and Future Development in the UK and Europe, London: Geological Society Special Publications 313; 2009, p. 25-37.

[5] Luo X, Wang J, Dooner M, Clarke J. Overview of current developments in electrical energy storage technologies and the application potential in power system operation. Applied Energy 2015;137:511-536.

[6] Wang B, Bauer S. Compressed air energy storage in porous formations: a feasibility and deliverability study. Petroleum Geoscience 2017;23:306-314.

[7] Hilpert S, Kaldemeyer C, Krien U, Günther S, Wingenbach C, Plessmann G. The Open Energy Modelling Framework (oemof) – A new approach to facilitate open science in energy system modelling. Energy Strategy Reviews 2018;22:16-25.

[8] Witte F. Thermal Engineering Systems in Python (v0.1.1); http://doi.org/10.5281/zenodo.2555866; 14 May 2019.

[9] Schlumberger NV. ECLIPSE Version 2018.2 – Technical Description; 2018.

[10] Bear J, Bachmat Y. Introduction to modelling of transport phenomena in porous media. Dordrecht: Kluwer Academic Publishers; 1990.

[11] Pfeiffer WT, Bauer S. Comparing simulations of hydrogen storage in a sandstone formation using heterogeneous and homogeneous flow property models. Petroleum Geoscience 2019;2018-101.

[12] Kaldemeyer C, Boysen C, Tuschy I. Compressed Air Energy Storage in the German Energy System –Status Quo & Perspectives. Energy Procedia 2016;99: 298– 313.