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Proxy Model Development and Application for Coupled Power Plant and Geostorage Simulations of Compressed Air Energy Storage

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ABSTRACT

Porous media compressed air energy storage (PM-CAES) is a viable option to compensate expected fluctuations in energy supply in future energy systems with a 100% share of renewables. However, the design and evaluation of operational conditions for a PM-CAES require an efficient coupled power plant – geostorage model. In this study, therefore, a proxy model for the geostorage is developed and evaluated with respect to two scenarios representing realistic energy system load profiles. Results show, that the proxy model represents a consistent approximation, yielding storage pressure, rates and capacity within 98% of the full-scale reservoir model, while reducing runtimes to about 6%.

Keywords: compressed air energy storage, proxy model, model coupling, renewable energy systems

NONMENCLATURE

Abbreviations	
PM-CAES	Porous medium compressed air energy storage
TESPy	Thermal engineering systems in python
BHP	Bottom hole pressure
Symbols	
M	Motor
G	Generator
p_{BHP}	Well BHP
M_{gas}	Gas in place mass
Q_{surf}	Flow rate at standard condition
ρ_{surf}	Fluid density at standard condition
μ_{res}	Fluid viscosity at reservoir condition
k	Formation permeability
h	Formation thickness

1. INTRODUCTION

Currently, countries worldwide transit from conventional hydrocarbon-based to renewable energy sources, in order to mitigate climate change effects by reducing greenhouse gas emissions and to diversify electricity production [1]. However, the fluctuating weather-dependent nature of renewable power generation can negatively impact the stability of the energy system [2]. Therefore, large scale energy storage is required to mitigate these fluctuations. Porous medium compressed air energy storage (PM-CAES) can provide the required large storage capacities as well as high charging/discharging rates and thus help to compensate the periods of reduced power generation [3]. Recent studies show that PM-CAES can be employed on scales up to the grid-scale [4], [5].

CAES is a mechanical energy storage option, whereby energy is stored in form of pressurised air during times of surplus renewable power generation and released during times of peak demand, or of insufficient renewable power generation. A PM-CAES consists of a power plant on the land surface, containing the machinery for gas compression and expansion, i.e., a compressor drive train and a generator connected to a turbine, and a geologic porous formation in the subsurface, providing the storage space for the compressed air. For this, compressed air is stored in the pore space of the formation, which additionally requires a tight overburden to contain the gas in the formation. Injection and withdrawal of the compressed air is performed using boreholes with open screen sections.

The charging and discharging power of a CAES-system strongly depend on the storage pressure and the achievable mass flow rates. In case of a PM-CAES, pressure and flow rate are strongly linked to the flow processes within the porous storage formation [6] and thus geological factors. During operation, both power plant and geostorage impose limitations through safe pressure and mass flow rate limits of the individual components. To accurately represent all the relevant processes, as well as limitations of PM-CAES, a coupled power plant – geostorage simulation tool is therefore required [6]. To this end, a dedicated power plant simulation code (TESPy, [7]) and a proprietary reservoir simulator (ECLIPSE, [8]) have been combined and connected through a coupling interface [6]. While the developed tool provides an accurate representation of the storage operation of any PM-CAES, its application for scenario simulations or assessment studies, which typically require the performance of hundreds of individual simulations with varying power plant and geostorage settings, is extremely time-consuming or even unfeasible, given the high numerical burden posed by the three-dimensional and transient storage reservoir simulation conducted on large spatial scales. Moreover, the coupled simulation tool requires access to the proprietary ECLIPSE reservoir simulator and a corresponding licence package.

In this work, therefore, a lower dimensional proxy model for the geostorage part of the coupled power plant – geostorage simulator is developed, in order to decrease simulation runtimes significantly to the short execution times required for scenario analysis and optimization studies. The coupled simulator has to provide accurate predictions of reservoir pressure, achievable mass flow rates and storage capacity, at the same time providing the required computational efficiency. To this end, the storage reservoir is conceptually simplified so that analytical and semi-analytical solutions for gas flow in porous media can be applied and combined with a storage gas mass balance. The suitability of the newly developed proxy geostorage model is evaluated by comparing the results of the new model to those obtained using the full-scale reservoir model for two PM-CAES storage scenarios.

2. METHODOLOGY

In order to accurately simulate compressed air energy storage in porous formations, the intricate and strongly coupled processes occurring within the surface power plant and the subsurface geostorage facilities have to be adequately represented for the wide variety of expected operational modes. Therefore, in a prior paper [6], a suitable coupled simulator has been developed and verified, which is based on an explicit representation of the relevant mass and energy flow rates in the power plant and the porous geological storage formation (Fig. 1).

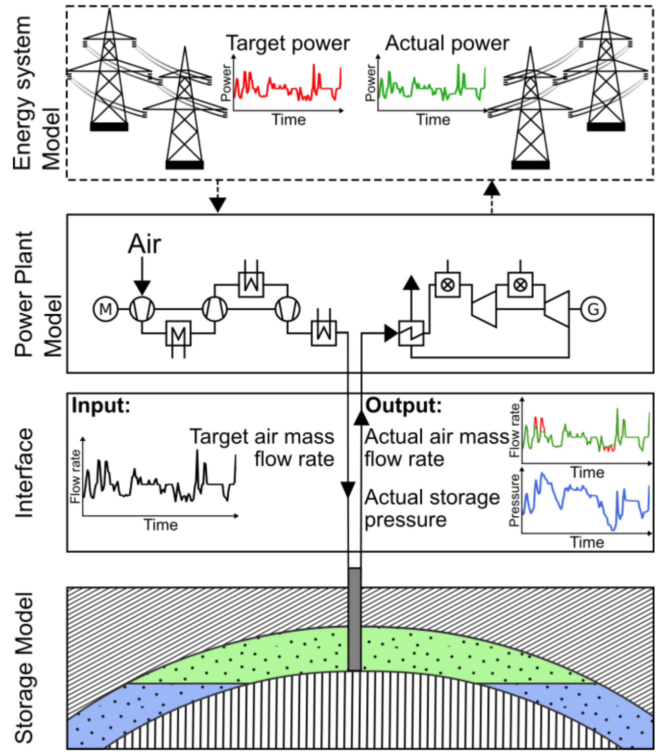

Fig. 1 Schematics of coupled power plant – geostorage models with energy system model for diabatic PM-CAES with heat recuperator (after Pfeiffer et al. 2021 [6]).

To model the surface power plant, a set of nonlinear equations based on the power plant topology are generated and solved, thereby providing the target mass flow rate, as well as system pressure required to meet a specific power load. The geostorage model then provides the actual mass flow rate, which can be supported by the geological storage formation, as well as the pressure response of the geostorage by solving the corresponding three-dimensional and transient balance equations based on an extended Darcy's law and mass conservation. Mass flow rates and pressures are coupled at the boreholes and made consistent by iterating between the power plant and the geostorage models. This model has been shown to be accurate and be able to handle basically all occurring operational situations even during strongly fluctuating loading and unloading situations [see 6], so that it will be used in this paper as a reference to assess the performance of the proxy model. However, this approach requires significant computational efforts and long simulation times, making it impractical for design studies and parameter variations. As the main computational burden of the coupled model was found to be caused by the geostorage model, the development of a more efficient simulator has to be based on an efficient representation of the subsurface storage processes.

2.1 Proxy storage simulation

The basic assumptions for the development of a simplified and thus more efficient proxy-model for the geostorage are based on observations of the typical conditions in the storage required to meet the energy demands. From detailed prior work ([4], [9]) it was found that a large gas phase is required, which supports the large mass flow rates required mainly by expansion and compression, as opposed to moving the gas – water contact in the porous formation. It could thus be assumed, that the volume of the gas phase in the storage formation is constant and the mass flow rates are supported by varying storage pressure and thus varying compressed air density [10]. Due to the physical laws governing fluid and gas flow in porous formations, the pressure at the boreholes will differ from the storage pressure, due to the pressure gradient required to drive the gas through the formation towards the borehole.

The proxy model uses a gas mass balance calculation based on PVT data for the compressed air [11], thus linking gas density and viscosity to the storage gas pressure. From the gas mass injected or withdrawn through the boreholes, the gas density can thus be calculated and used to determine the pressure boundary condition p_{res} at the outer boundary of the gas phase assuming a stable gas-water contact level and isothermal conditions:

$$\rho_{res} = \frac{M_{gas}(t-1) + Q_{surf}(t)\,\Delta t\,\rho_{surf}}{V_{gas}} \qquad (1)$$

with M_{gas} the total mass of gas within the storage formation (kg), V_{gas} the initial gas in place volume (m^3) and Q_{surf} the flow rate of gas (m^3/s) at surface conditions of 293.15 K and 101325 Pa (NTP).

Flow to or from the boreholes can be simulated using analytical solutions for stationary radial gas flow in a homogenous storage reservoir of constant thickness:

$$p_{BHP,w} = -Q_{surf}\,\frac{\rho_{surf}}{\rho_{res}}\,\frac{\left[ln\left(\frac{r_{res}}{r_w}\right)\right]\mu_{res}}{2\,\pi\,k\,h} + p_{res} \qquad (2)$$

With $p_{BHP,w}$ the bottom hole pressure at the borehole (Pa), ρ_{surf} the gas density of 1.204575 kg/m^3 at surface conditions, ρ_{res} the varying gas density in the storage formation, p_{res} the reservoir pressure at the outer boundary of the gas phase, with an initial hydrostatic reservoir pressure of 72×10^5Pa for model initialisation. k is the formation permeability (m^2), μ_{res} is the dynamic viscosity at reservoir conditions (Pa s). The radius r_w is the borehole (m) while r_{res} is the reservoir radius of the outer gas phase boundary. The proxy simulator supports both single and multiple well setups, as often required to achieve the target mass flow rates, by applying a superposition technique for the individual pressure perturbations caused by each well to obtain the storage pressure. For each borehole, the bottom hole pressure p_{BHP} is determined at each timestep, as this pressure has to be restricted to save operation values in order to prohibit reservoir damage, like fracturing. Also, storage gas density ρ_{res}, storage pressure p_{res} and storage gas viscosity are updated at each timestep using a dry gas PVT model [11].

The described proxy model is implemented in an object-oriented C++ code, which sets up and initialises the model, applies all parameters and updates the time varying gas density and viscosity. It also performs an automatic iterative adaptation of mass flow rates at the boreholes if the user-defined safe operating pressures are being violated, i.e., if the current p_{BHP} is not within the so-called bottom hole pressure limits. For a coupled power plant – geostorage simulation, the implemented proxy model wholly replaces the three-dimensional storage model ECLIPSE.

2.2 Power plant & storage design

A diabatic CAES power plant with three-stage compression and two-stage expansion and heat recuperator is employed as a realistic test case for the newly developed proxy model, which is similar as the plant in McIntosh, (USA) (Fig. 1). A total of 9 vertical storage wells with full formation perforation are used to inject or withdraw the compressed air from the reservoir with a permeability of 500 mD. All relevant input parameters for the coupled model are summarised in Table 1.

Table 1 CAES power plant and geostorage parameters

Component	Parameter	
Compressors	max power [MW]	50
	isentropic efficiency [%]	92
	isentropic efficiency control stage [%]	85
	pressure ratio at stages	5
	max. flow rate limit [kg/s]	98.8
Turbines	max power [MW]	50
	isentropic efficiency [%]	85
	isentropic efficiency control stage [%]	90
	max. flow rate limit [kg/s]	54.3
Coolers	temperature after cooling [°C]	25
Generator & Motor	efficiency [%]	97
Combustion	fuel type	CH_4
	turbine inlet temperature [°C]	1200
	outlet temperature [°C]	150
Storage	nominal pressure compression [bar]	75

nominal pressure expansion [bar]	65
permeability [mD]	500
initial air in place content [kt]	329
initial pressure [bar]	72
min/max. allowable BHP [bar]	40/90
well number	9
well radius [m]	0.125

2.3 Scenario definition

This study considers two development paths of the German energy system to a 100% renewable power generation [12]. Scenario #1 is based on a CO_2 emission price at 150 EUR/t, a shadow electricity price in 2050 and no biomass installation in Germany. Scenario #2 is based on the same scenario year with biomass potential in Germany. The full scenario description with all assumptions is provided in [12].

For PM-CAES assessment, mass balanced load profiles in hourly resolution are generated from the operator's perspective using a dispatch model developed within the ANGUS project [13]. Scenario #1 requires a total annual storage discharge of 147.713 GWh and 81.550 GWh of charging. In scenario #2 the total storage demand is only 54.1 GWh (discharging) and 28.977 GWh (charging) during the year. During discharging compressed air is delivered from geostorage that drives a generator for power generation and during charging off-peak power at the low electricity price is used for ambient air compression. The energy imbalance of load profile is compensated by an external heat source for the diabatic power plant. The numbers of charging and discharging cycles varies significantly for the scenarios. For validation purposes and performance comparison, all simulation runs were performed using both the proxy model and the full reservoir simulator in the coupled model.

3. SIMULATION RESULTS

3.1 Scenario simulation using the proxy model

The coupled simulation results show that the dispatch signals can be fulfiled by the PM-CAES facility most of the time (Fig. 3). No mismatches between the target power required by the energy system and the actual power provided by the coupled PM-CAES storage power plant occur during the discharging periods (a total of 3032 hours). The storage pressure at the well bottom hole is always within the specified BHP-limits of 40 bar and 90 bar. During the charging periods a small mismatch of target power vs. actual power occurs for a total of 1631 hours (see inset in Fig. 3). However, the total energy stored is only insignificantly lower than the target, e. g. 81.157 GWh vs. 81.550 GWh, so that this effect does not impair storage operation.

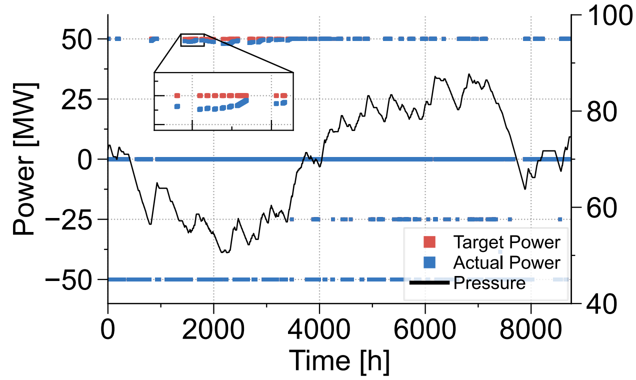

Fig. 3. Coupled simulation results for scenario #1. Actual power and pressure are provided from proxy geostorage model.

The reason for the observed mismatch during charging of the storage are the specifications of the power plant. Although the storage pressure remains within the allowable pressure range at all times, the low storage pressure (e.g., 51 bar) at the beginning of the charging period results in large target mass flow rates, which are in violation of the power plant's maximum flow rate limit of 98.8 kg/s (compare Fig. 3 and 4). Thus, the charging power is reduced so that the maximum mass flow is within the plants' specification. As the storage pressure increases, a reduced mass flow rate is sufficient to achieve a given target power, which is e.g. visible from 3000 h onward in Fig. 4.

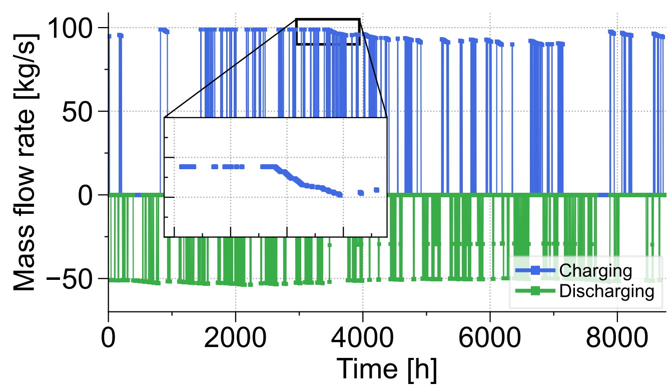

Fig. 4 Actual air mass flow rate from geostorage for scenario #1. The embedded figure shows mass flow reduction from timestep 3000 hours to 3900 hours as a result of pressure increase in storage.

The simulation results for scenario #2 show that a total of 54.098 GWh of energy is discharged from the storage and 28.718 GWh are fed-in during charging (Fig. 5). Thus, the achieved values are slightly below the target values of 54.1 GWh and 28.977 GWh, respectively. During the year-long storage operation, the storage pressure remains within a pressure envelope of 50.6 to 87.7 bars (Fig. 5), and thus within the BHP-limits of the storage formation.

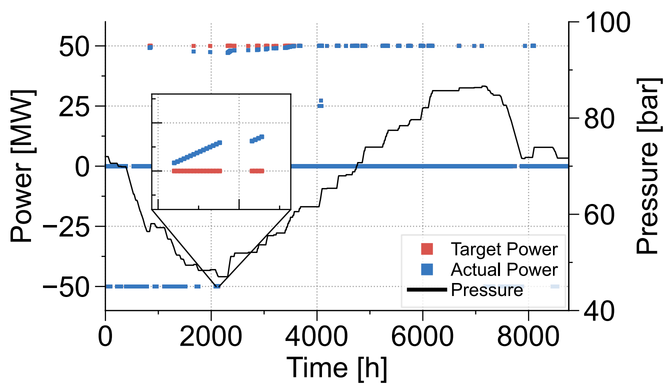

Fig. 5 Coupled simulation results for scenario #2. The embedded figure shows power mismatch during discharging.

Similar to scenario #1, the observed reductions in power rating during the simulation of scenario #2 (Fig. 5), which are observed also during discharging, are a consequence of the limitations in the power plant design. To maintain a constant target power output during discharging, the required mass flow rate increases with decreasing storage pressure (Fig. 6). Given the low storage pressures, the required mass flow rates to maintain the targe discharging power of 50 MW violates the power plants' mass flow rate between 2088 h and 2100 h (Fig. 6, embedded figure) and reaches limit of 54.3 kg/s and the power rate is thus curtailed from 2105 h to 2140 h (Fig. 5).

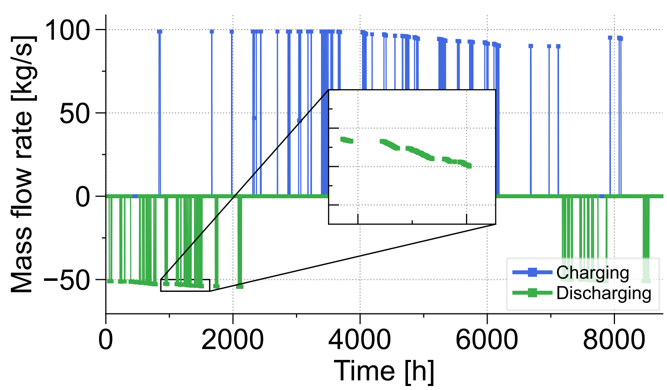

Fig. 6 Actual air mass flow rate from geostorage for scenario #2.

For both scenarios an external heat source is required during discharging as the power plant used in this study is a diabatic design. In total 173.7 GWh and 63.6 GWh of heat is required for scenario #1 and scenario #2, respectively.

3.2 Comparison of the geostorage models

To assess the proxy model performance, results are compared to the coupled simulator using the ECLIPSE code to simulate geostorage processes. Mass flow rates and storage pressures for both cases are depicted in Fig. 7. The comparison shows a very good agreement between the two simulation approaches. The actual power rate difference between the geostorage model shows a difference for scenario #1 only during the charging period up to 1 MW, for scenario #2 the actual power rate difference during discharge is less than 0.5 MW. Storage pressure is also simulated a good agreement, with both pressure curves following the seasonal cycle. However, storage pressure in the proxy model has no sharp peaks and during long shut-in periods does not tend towards the initial hydrostatic conditions.

The reason for the first effects is the stationary flow assumption inherent to equation 2 for flow to the borehole, while the second effect is due to the assumption of a constant volume of the gas phase. In reality, the gas phase volume expands slightly when pressures are higher than the hydrostatic pressure. For scenario #1, this leads to an annual average pressure difference of up to 1 bar, although pressure from the proxy model may be too high, as well as too low. Even though systematic differences exist, the effect on the storage and power plant operation are small and well within the short-term variability of the realistic load curves, so that the proxy model can be regarded as a valid approximation of the governing storage processes.

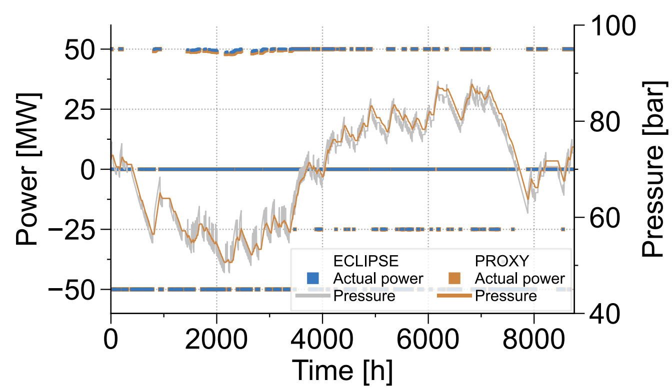

Fig. 7 Coupled simulation result comparison, using ECLIPSE simulator and proxy model for scenario #1.

Both geostorage models are compared also in terms of computational performance. All simulations were run as single-threaded processes on the same workstation using an Intel Xeon E5-1650 v4 @3.60GHz.

Total runtime for the coupled simulation for one year with hourly resolution is 2.92 h for scenario #1 and 2.55 h for scenario #2, when using the proxy model. Corresponding times using the full reservoir model

ECLIPSE are 47.7 h and 40.6 h, correspondingly. Thus, the use of a simplified reservoir model and analytical solutions for the boreholes yields a reduction of runtime to about 6%. Computational time within the power plant model and coupling routines require considerable runtime and can be a study point for further optimization.

4. CONCLUSIONS

The implemented physics-based proxy model for the simulation of the geostorage provides a reasonably accurate approximation of the storage processes occurring during PM-CAES. The storage performance metrics obtained with the proxy model are in a very good agreement with those obtained by the full three-dimensional numerical geostorage model, even when accounting for technological and geological constraints. Thus, the coupled simulator using the proxy model provides a tool to assess the feasibility of porous media compressed air energy storage for future energy system market conditions, thus allowing optimization of the power plant set-up and the storage operation. Subsequent enhancement of computational performance should be done within the power plant simulator and coupled interface code.

5. ACKNOWLEDGEMENTS

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