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Stable large-scale CO_2 storage in defiance of an energy system based on renewable energy - Modelling the impact of varying CO_2 injection rates on reservoir behavior

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Abstract

The IPCC Report 2014 strengthens the need for CO_2 storage as part of climate change mitigation options. The further expansion of electricity generation by solar and wind and its preferential usage in Germany is leading to strong fluctuations in the CO_2 output from former base load coal fired power plants. This study takes a look at the feasibility of large scale industrial CO_2 injection into a saline aquifer structure with the main focus on varying injection rates. By means of simulation the influence of the most important parameters is analyzed.

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Keywords: CO_2 storage; numerical simulation; varying injection rates; industrial size project

1. Introduction

In 2014, electrical power generation in Germany from renewable energy sources accounted for 26.2% [1]. Wind power had a share of 9.1% and solar power of 5.7%. A total of 11.4% came from other renewable sources like

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hydropower or biomass. The growing share of wind and solar power in the energy mix makes the weather becoming the controlling factor for electricity production for fossil fuel power plants.

Despite the current legal situation in Germany, that gives each federal state the possibility to ban CO_2 sequestration on its territory and the general non-acceptance of Carbon Capture and Storage (CCS) by large parts of the German population, there seems to be no other solution than storing CO_2 in the deep underground, if the ambitious climate goals by the German government until 2020 (20% less CO_2 output compared to 1990), 2030 (40% less CO_2 output compared to 1990), and 2050 (self-sufficient by renewable energy) want to be achieved, with coal still playing a substantial role in the energy mix and also to avoid emissions from industrial sources. The Federal Institute for Geosciences and Natural Resources (BGR) has developed a special catalog and map-based information system containing all relevant storage horizons suitable for CO_2 storage as well as cap-rock horizons, necessary to hold the injected CO_2 within the structures [2]. According to BGR there is a total storage capacity between 6.3 and 12.8 billion t for CO_2 in saline aquifers in Germany [3]. Total CO_2 emission according to the Federal Environmental Agency (UBA) amounted to 822 million t in 2012 [4]. Annually, about 375 million t of CO_2 come from large point sources like power plants and industrial facilities. The figures suggest that the storage capacity in Germany would be sufficient for several decades applying CCS preferably at some selected large power plants.

The study presented here simulates the geological storage for a cluster of coal fired power plants, emitting in total 11.7 million t of CO_2 per year. The figure is derived from a study on the CO_2 transport structure in Germany by 2050 [5]. The CO_2 emission of this cluster is heavily influenced by renewable energy sources that have a volatile production pattern (wind and sun) and accounts as well for the demand driven changes in conventional power generation. In this study it was anticipated that the fluctuating CO_2 output is injected into one on-shore geological structure large enough to hold the entire CO_2 released during a time interval of 10 years, i.e. 117 million t of CO_2.

A simulation model for the large structure was set up to test the general feasibility of the storage operation. Starting from a base-case, different parameters and well patterns were modified within realistic ranges that limit the storage of CO_2. Every simulation run is providing an injection potential that is different and changing over the operational lifetime of the storage.

A model of a structure used for commercial natural gas storage which lies in the vicinity of the large structure is used for plausibility checks and comparison of simulation results in the first year of CO_2 storage operation. The model has the advantage, that it is qualified for simulation being history-matched over a storage period of more than 35 years. However, its volume capacity, is by far too small for storing the amount of CO_2 coming from the considered cluster.

2. Model description

The potential of suitable structures for CO_2 sequestration is high in northern Germany. For this study the structures illustrated in Fig. 1 were used. The small model is the existing gas storage, where the Volpriehausen sandstone (Middle Bunter) with an average thickness of 16 m is used as storage horizon. This is also used as storage horizon of the large structure. The geological model (structure and property distribution) is based on logging data from 17 wells and a time-laps seismic interpretation. The structural map for the large model was taken from the base Upper Bunter map of the Geotectonical Atlas of Northwestern Germany [6] and shifted by -360 m to adapt to the known top of the Volpriehausen sandstone. The tops of both structures are at a distance of approx. 40 km. As reservoir properties for the large structure are not exactly known it was assumed that reservoir thickness and property distribution are similar to the Volpriehausen sandstone in the nearby gas storage. Therefore in a generic modelling approach a property modelling workflow for the large model using the well logs from the small model was applied. The structural models of the small and the large structure are shown in Fig. 2.

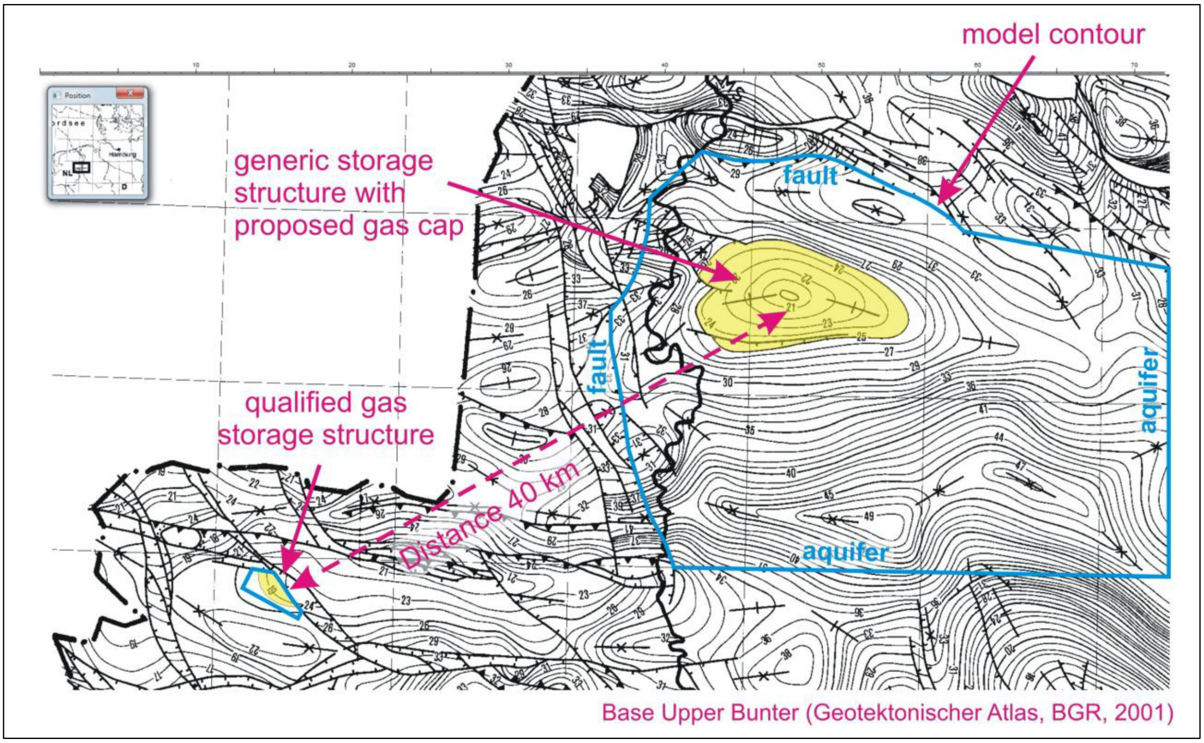

Fig. 1. Geological structures for large and small model.

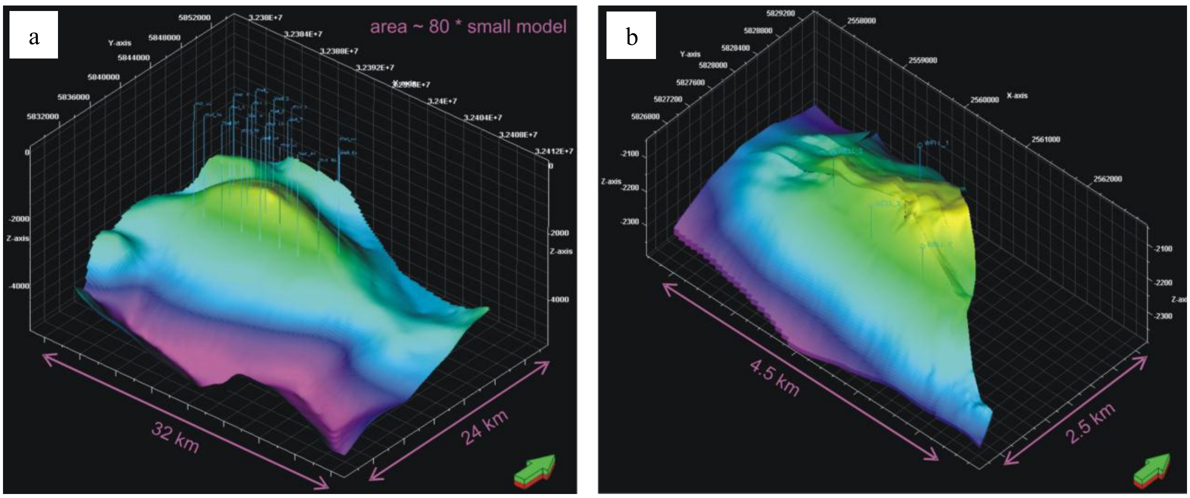

Fig. 2. (a) Large generic reservoir model; (b) Small qualified reservoir model.

3. Varying CO_2 injection rates

The injection rates come from a study on the CO_2 transport structure in Germany by 2050 [5]. The study is based on real data CO_2 output in Germany considering the year 2013 and presents a week CO_2 output profile (Fig. 3) from power plants with the strongest variation (peaks) above a base load.

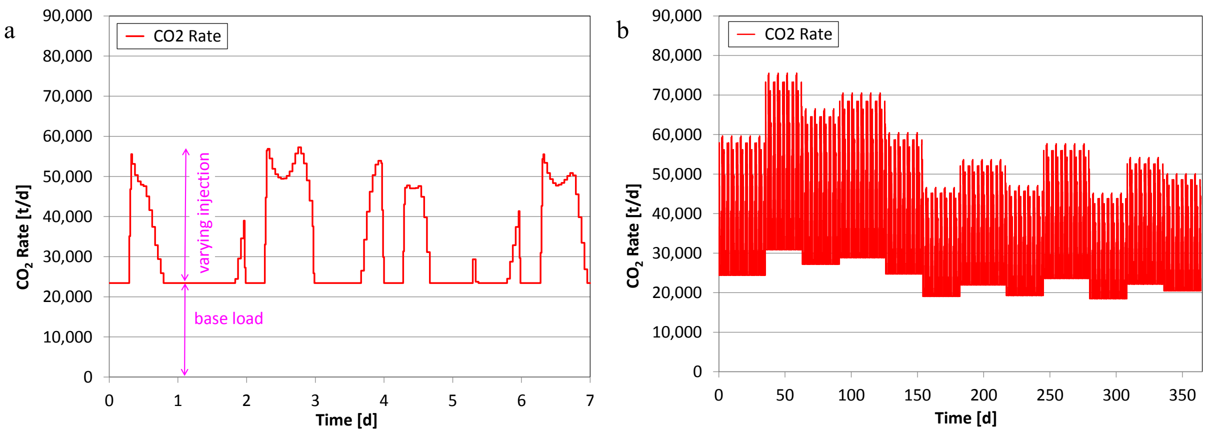

Fig. 3. Varying CO_2 injection rates; (a) week schedule; (b) year schedule.

This week's profile represents the "worst case scenario" in terms of fluctuations [5] and can happen any time during the year and therefore will be applied throughout the entire year to generate a maximum stress for the storage reservoir. As there is also a seasonal variation observed in electricity production by wind and solar in 2013, a seasonal variation was added to the schedule, having the highest CO_2 output in February and the lowest during summer and autumn.

4. First-up appraisal calculations

With the objective to test the volume capacity and injection rates of the large reservoir, simulation runs were realized using 10 injection wells and applying a constant injection rate. The runs showed that the volume capacity would be sufficient to hold approx. 120 million t of CO_2. However, due to the given flow dynamics, especially the limited permeability capacity, only one third of the required average constant rate was possible to be injected, no matter how many more injection wells were applied in the top of the structure. With this limitation in flow dynamics a base-case for simulations with varying injection rates and parameter variations was developed considering only 25% (approx. 3 million t/a) of the initially required injection rate. As for the base-case with a constant injection rate, four similar structures like the selected large structure would be needed to accommodate the yearly CO_2 output of almost 12 million t.

5. Configuration of simulation runs

In total 8 simulation categories were set up, each category specifying the range of one parameter. The parameters, shown in Table 1, are very diverse considering reservoir properties, structural features, number and position of well locations as well as aquifer size. The base-case was given reservoir parameters that are expected to be favorable for large scale gas injection. The parameter range is within realistic limits.

Table 1. Variation categories and parameters (large model).

Variation category		base-case configuration	parameter variation	
			from	to
1) Permeability capacity	k*h=	4000 mD	1000 mD	4000 mD
2) Distance of wells	d=	2000 m	1000 m	3000 m
3) Number of top structure wells	n=	10	4	10
4) Top wells vs. wells on structural flank	depth=	-2360 m	-2360 m	-3500 m
5) Well bore injection (perforation interval)		entire reservoir section	upper reservoir section	lower reservoir section
6) Impact of hysteresis		no hysteresis	no hysteresis	hysteresis
7) Impact of aquifer size	V_{Aqu}=	500 billion m³	5 billion m³	500 billion m³
8) Impact of bordering faults		no boundary	no boundary	two boundaries

The maximum injection pressure for the top wells is set to 1.4 times the initial pressure allowing a pressurization of the reservoir of 40%. This is done in accordance to the storage operation of the gas storage (small model). The maximum injection pressure for the wells positioned at the structural flank is set as such that the reservoir pressure in the top of the structure is not reaching higher values than 40% above the initial pressure in order to remain well below the formation breakdown pressure in this geological setting.

6. Evaluation of simulation results

The model results are evaluated in terms of pressure range utilization. Fig. 4 shows the bottom hole pressure behavior of an injection well for the base-case (blue line) ranging from the initial pressure to the maximum injection pressure.

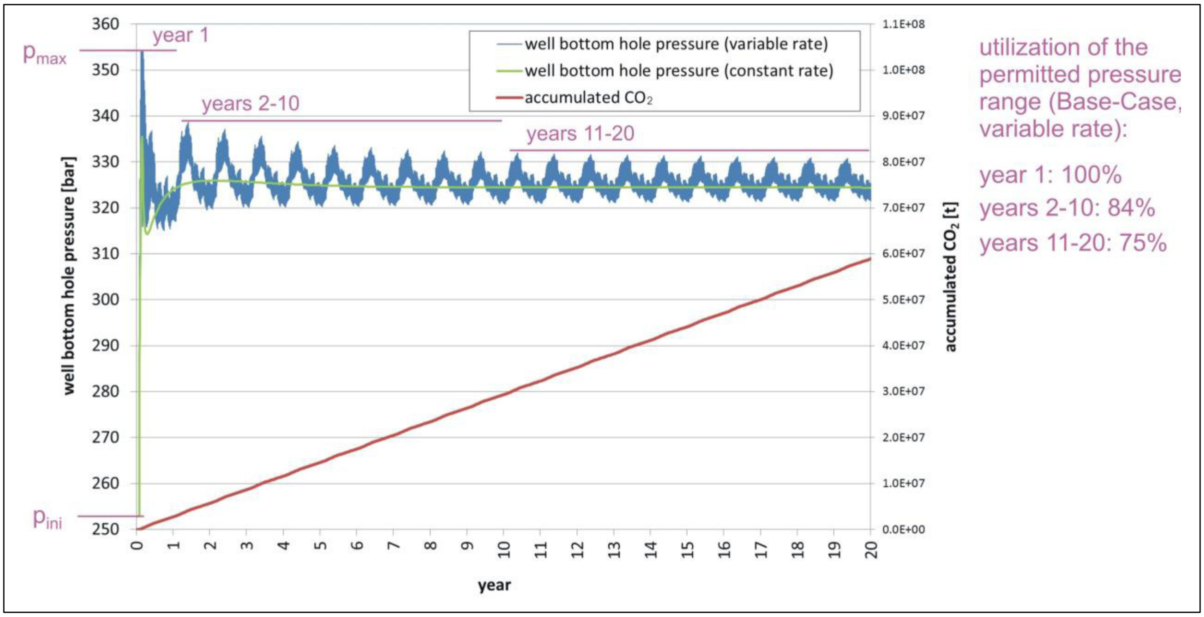

Fig. 4. Pressure range utilization.

After the maximum injection pressure is reached the injection rate is automatically reduced in order not to violate the maximum pressure limit. With respect to the pressure response a division of the timeline in first year, 2-10 years and 11-20 years is appropriate. During first year of injection the available pressure range is used up to 100% resulting in substantial injection rate reduction. In the years 2-10 the pressure range is used up to 84% and in the years 11-20 only up to 75%. For comparison, the pressure response from an averaged constant injection profile is shown as green line in Fig. 4. As for the base-case with the variable injection profile, the injection pressure range above the initial pressure is between 25% (first year) and 10% (later years) higher compared to the scenario with an averaged constant injection rate.

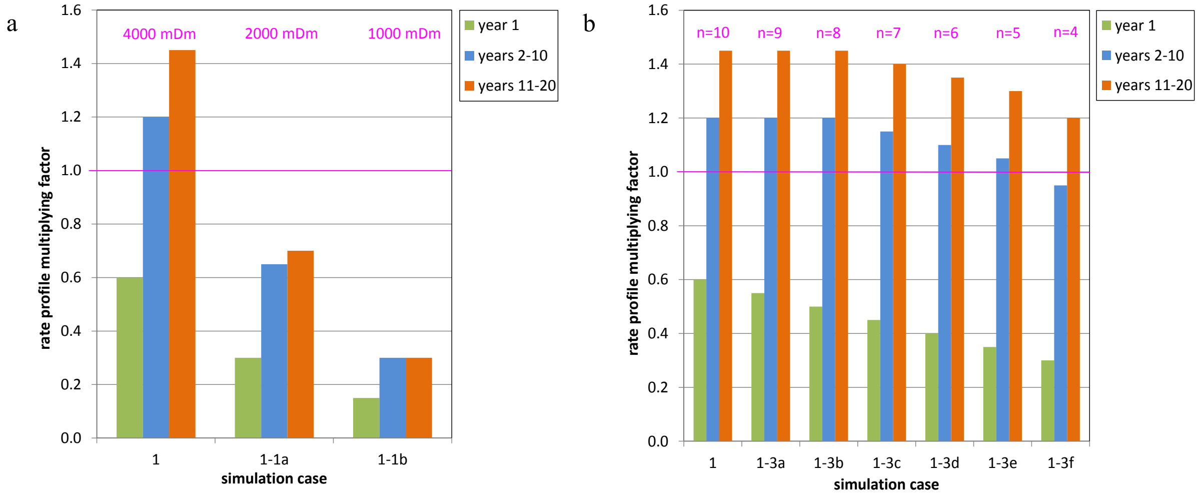

Fig. 4. (a) Impact of permeability capacity on injectivity; (b) Impact of number of wells on injectivity.

There is additional potential for higher injection rates in years 2-20 with respect to the base case. For each simulation run either the rate reduction within each time interval or the higher injection rate potential relative to the base case is determined.

In the first variation category the impact of permeability capacity (k*h) on the realization of the variable injection rate was analyzed (Fig. 4a). As for the base-case, using the full pressure range between initial and maximum reservoir pressure a steady increase in the injection rate can be identified. On the y-axis in Fig. 4a the multiplying factor 1 denotes the 25% initial rate schedule. In first year of the base-case scenario for example, applying the multiplying factor of 0.6, only 15% of the initial rate schedule can be realized. In the years 2-10 and 11-20 the injection rate can be increased, because after the first year the pressure range in the 25% rate schedule scenario is not entirely used.

At lower permeability capacity scenarios (runs 1-1a and 1-1b) we still see the general tendency to higher injection rates with progressive storage filling, however, compared to the base-case the injection rates decrease significantly. A cut of 50% of the permeability capacity is roughly equal to injection rate reduction of 50%. At lower permeability capacity no further increase in injection rate can be realized in later years.

Variation category 3 is dealing with the number of top structure wells (Fig. 4b). Starting with the base-case the number of wells is continuously reduced from 10 to 4 wells. In first year we see a strong correlation in number of wells and injection rate. This is because the effective pressure radius of each well is comparatively small and wells do not much interfere with each other or the reservoir limit. With respect to the defined time intervals we can see that the situation, i.e. the increase in injection rate from first year to years 2-10 and years 11-20, is not significantly changing compared to the base-case. We do however see that the injection rates in the years 2-20 fall when less than 8 wells are applied. The use of more than 8 wells on the other hand will not result in higher injection rates, as we encounter restrictions in the flow dynamics from the top of the structure to the surrounding reservoir.

In variation category 4 the impact of the well location (top vs. flank) on the realization of the injection rate was analyzed (Fig. 5a). Whereas in the base-case all wells are placed in a triangular pattern at equal distance of 2000 m from each other in the top of the structure, the wells in the cases 1-4a and 1-4b are placed at isobaths of -3000 m and -3500 m, respectively, keeping also a distance of 2000 m between neighboring wells. When we look at the simulation results we see some minor increase in injection rate in first year. Due to the near wellbore water-gas replacement injection rates get not much higher than in the base-case, even though the maximum injection pressure is higher because of larger depth. In years 2-20, injection rates for the injection scenarios at larger depth increase significantly compared to the base-case. One reason for that is the higher maximum injection pressure. More important however is the fact that the wells are placed in a slightly bended line along the isobaths, as opposed to the base-case, where the interference between wells is much stronger due to their triangular pattern. The stronger influence of the well pattern can be deduced from the injection rate increase between base-case and case 1-4a and between cases 1-4a and 1-4b. In summary, approx. 40% higher injection rates can be realized when CO_2 is injected at the flank of the structure.

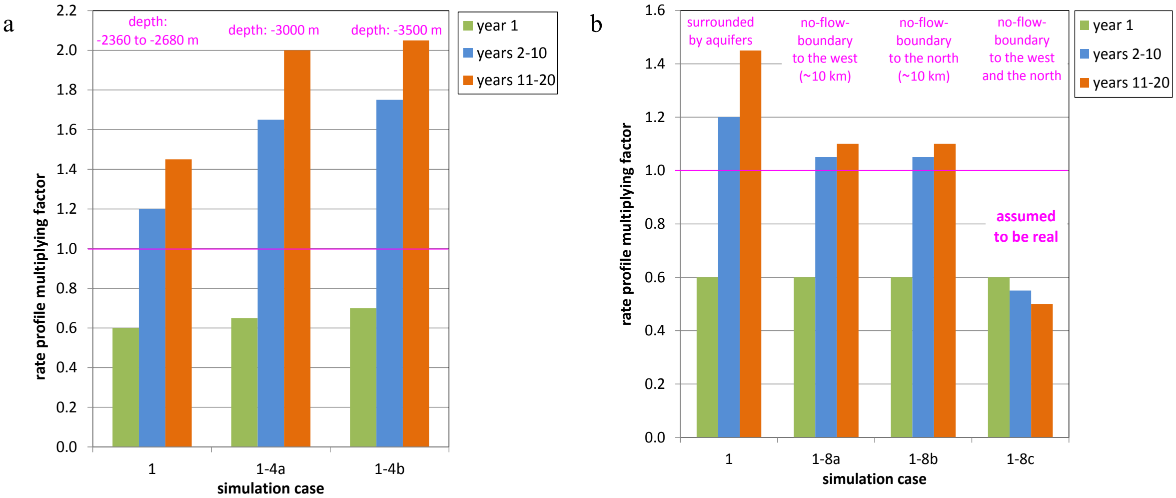

Fig. 5. (a) Impact of well location (top vs. flank) on injectivity; (b) Impact of bordering faults on injectivity.

In variation category 8 the impact of bordering faults on the realization of the injection rate was analyzed (Fig. 5b). This was done in view of the structural situation of the used large structure. The structure is in fact limited to the west end the north by faults at distances of approx. 10 km from the structural top. As for the generic base-case, aquifer regions are defined at the model edges extending the reservoir laterally to all sides. In first year, according to the simulation results, we do not see any influence due to the bordering faults, because the pressure radius is not extending that far yet. In years 2-20 however, we see a strong influence of the bordering faults. Each fault on its own (runs 1-8a and 1-8b) gives a similar reduction in injection rates compared to the base case. In the years 11-20 the injection rate reduction is about 25%. Both faults in combination (run 1-8c) give an even stronger reduction of about 66% in the years 11-20.

7. Comparison of simulation results from large and small model

Having similar vertical setups (reservoir thickness and property distribution) the large generic model covers an area that is approx. 80 times larger than the small qualified model. If the maximum injection rate is to be applied, both models can only be compared for the first year of injection, as the volume capacity of the small model is relatively small. The simulation of the CO_2 injection in the small model is realized with either 3 or 4 wells and either injection into the structural top or the flank. In combination these are four simulation runs that are compared to the simulation run of the large model with the corresponding variation case (run 1-1a).

In Fig. 6 the multiplying factors for the injection rate schedules are shown. Regarding the maximum injection rate, the simulation results from both models are quite similar. In the first year of injection only 20%-30% of the base-case varying injection rate can be realized independent from the size of the model. The simulation with 10 top-structure wells of the large model is about equivalent to the simulation with 4 wells on the structural flank of the small model. A higher number of wells in the small model would, due to restrictions in the flow regime, not result in significantly higher injection rates. The general differences in the simulation results between the large generic model and the small qualified model, used for predicting reservoir behavior in a natural gas storage, come from differences in depth, number of wells, and model adaptations to the small model as a result of the history match.

The general good match between the maximum injection rates in both models gives us an indication that the large model can be applied with good confidence. Long-term experience in gas storage operation can therefore be used to secure the prediction results of similar geological settings even if the extent of the reservoir is significantly smaller.

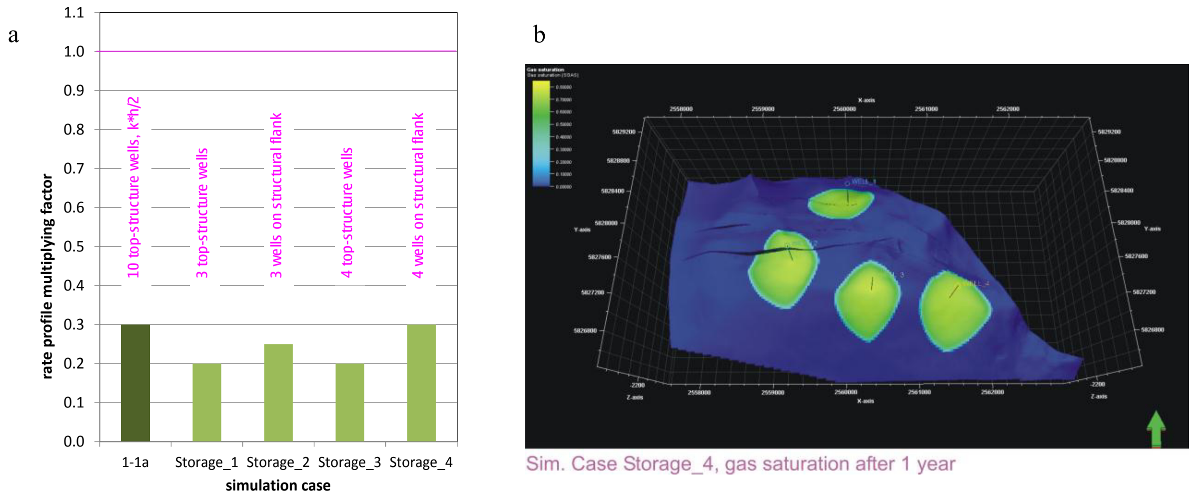

Fig. 6. (a) Comparison of large model and small model simulation results; (b) Small model gas saturation.

8. Conclusions

The objective of the project presented here was to analyze by means of simulation the feasibility of large scale industrial CO_2 injection into a saline aquifer structure with varying injection rates. For that purpose a structure large enough to hold approx. 120 million m³ CO_2 was chosen from a large number of potential structures in northern Germany. For the chosen structure and stratigraphic horizon (Volpriehausen sandstone - Middle Bunter) the same reservoir properties were applied as known from the nearby natural gas storage. The generally existing uncertainties have been addressed within a comprehensive sensitivity analysis. The variable injection rate schedule over 20 years is based on an out of one year week scenario with the highest fluctuations in CO_2 output, due to wind and solar power electricity generation, and a seasonal component.

Under the given circumstances stable large-scale CO_2 storage could be demonstrated by simulation. Permeability capacity, aquifer size and bordering faults have the largest influence on the realizable varying injection rate. Key findings have been proven by comparison to model results achieved from simulation runs with a qualified gas storage model. Varying injection rates show most significant influence on overall injectivity within the first years of operation when comparing it to respective constant injection scenarios. With increasing operational lifetime the dynamically induced pressure spread becomes more marginal.

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References

[1] Stromerzeugung 2014 nach Energieträgern; http://strom-report.de.
[2] GIS-basierte Kartenanwendung „Informationssystem Speicher-Kataster Deutschland“. http://www.bgr.bund.de/DE/Themen/ CO2Speicherung/ Downloads/Speicherkataster_Kartenanwendung.html.
[3] Knopf S, May F, Müller C, Gerling JP.: Neuberechnung möglicher Kapazitäten zur CO_2-Speicherung in tiefen Aquifer-Strukturen. Energiewirtschaftliche Tagesfragen 2010; 4: 76-80.
[4] Emissionen von direkten und indirekten Treibhausgasen und von Schwefeldioxid. http://www.umweltbundesamt.de/daten/ klimawandel/treibhausgas-emissionen-in-deutschland.
[5] Buit L et al.: CO_2-Transportinfrastruktur in Deutschland - Notwendigkeit und Rahmenbedingungen 2050. DNV GL, Groningen, 2014
[6] Baldschuhn R, Binot F, Fleig S, Kockel F.: Geotektonischer Atlas von Nordwest-Deutschland und dem deutschen Nordsee-Sektor. Geologisches Jahrbuch, Reihe A, Heft 153, 3 CDs. Hannover, 2001.