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Assessment of CO_2 Storage Capacity in Geological Formations of Germany and Northern Europe

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Abstract

CCS is discussed in a broad sense throughout Europe. In this paper a cautious, conservative estimate of CO_2 storage capacity for Germany and its neighbouring countries where CO_2 emissions from Germany could possibly be stored (Netherlands, France, Denmark, Norway, UK and Poland) is presented. Such a lower limit calculation is necessary for orientation purposes for potential investors and political decision-makers.

Conservative CO_2 sequestration capacity in deep saline aquifers for Germany is derived by the volumetric approach where parameters such as efficiency factor, CO_2 density, porosity of the geological formation are of interest. It is assumed that every geological system is closed and thus an efficiency factor of 0.1 per cent (based on maximum pressure increase and total compressibility) for saline aquifers is applied. The capacity of German depleted oil and gas fields is based on cumulative recovery data and a sweep efficiency of 75 per cent.

The storage capacity in the other considered countries, adjacent to Germany, are based on a critical review and adjustment of the results of the European reports JOULE II, GESTCO and GeoCapacity.

The conservative capacities for all countries together amount to 49 Gt CO_2, from which Norway and the UK provide 36 Gt, all offshore in the North Sea. Compared to the emissions from large point sources in these countries during 40 years (47.6 Gt of CO_2), a virtual balance is achieved. This can only be reached, if a large scale CO_2 pipeline system is installed to connect these countries, especially Germany, to the large sinks in the North Sea. If additional restrictions like source-sink matching, acceptance issues and injection rates constraints are taken into account, the available storage space gets increasingly scarce.

Keywords

CCS; storage capacity; conservative assessment; Europe; Germany

1. Introduction

CCS is a technology that is discussed intensively within the political and scientific community. The European Union sees this technology as one important step to reach CO_2 emission reductions. It is acknowledged as a mid-term climate mitigation technique, a bridge towards a mostly renewable energy world in 2050. But it is still uncertain whether CCS works on large-scale application. One crucial limiting factor is the storage space for CO_2 because suitable geological formations are not indefinite. In this paper the limits and constraints of geological carbon dioxide storage are investigated. A cautious, conservative estimate of CO_2 storage capacity is presented, for Germany and its neighboring countries where CO_2 emissions from Germany could possibly be stored (Netherlands, France, Denmark, Norway, United Kingdom of Great Britain and Northern Ireland (UK) and Poland). Such a lower limit calculation is necessary for orientation purposes for potential investors and political decision-makers. If the capacity of one of those countries is limited or acceptance issues prohibit most of the storage projects, adjacent countries could import CO_2 from neighbours, depending on their geological potential to store CO_2.

First of all, the concepts and methods used to estimate the capacity for CO_2 sequestration in deep saline aquifers and hydrocarbon fields in Northern Europe are explained (chapter 2). Next, this is applied to conservatively assess the capacities (chapter 3). The results are discussed in chapter 4, and finally, a conclusion is drawn in chapter 5.

2. Methodology

To provide a reliable number of storage capacity, every possible formation has to be analysed specifically through well bores and seismic surveys, and interference between storage sites has to be estimated and modelled. While such a bottom-up approach was applied to the estimation of storage capacity in depleted German gas and oil fields, it was not possible for saline aquifer structures, due to lack of data and time. Instead, a much broader top-down methodology was selected to derive a conservative assessment of CO_2 storage capacity for Germany and adjacent countries.

Both concepts, the bottom-up as well as the top-down approach, are based on the pyramid concept [1]. The *theoretical capacity* is the entire pore volume of a formation, including uneconomic and unrealistic pore space, and can thus be modelled as the total volume of a pyramid. If physical, geological and engineering cut-off limits are applied, the smaller *effective capacity* is derived, moving up the pyramid. This capacity was intended to be estimated herewith. Adding technical, economic and legal barriers, an even more realistic *practical capacity* might be received, filling a much smaller part of the pyramid [2].

The authors' assessment for Germany is based on a comprehensive analysis of previously published CO_2 storage volume estimates [1]. The main result of this analysis is that the methods and selected assumptions vary to a large degree. Many authors arrive at unrealistically high theoretical predictions for CO_2 sequestration capacity due to overly optimistic selection of parameters. Therefore, a detailed scenario analysis is performed with a typical "what-if" examination in which cautious estimates and assumptions are pooled. The methodologies applied are described below.

Existing capacity estimates of the other countries are compared mainly based on the European storage assessment reports of JOULE II, GESTCO and GeoCapacity [3,4,2]. These calculations are analysed, critically discussed and adjusted in order to derive a conservative storage capacity.

It is worth to say that the authors' analysis is not based on new geological data, but instead uses the findings available in the literature and new calculations.

2.1. Deep saline aquifers

CO_2 sequestration capacity in deep saline aquifers is derived by the volumetric, top-down approach. It is based on the bulk volume of the aquifer, derived from the average available subterranean area (m^2) and the average thickness of the aquifers (m). This volume is then restricted to the fraction which can absorb CO_2, using the net-to-gross ratio. For acceptance reasons and to facilitate monitoring, CO_2 should only be stored in closed structures. This is documented in most studies and is achieved by considering *traps%*. Taking into account the density of CO_2 at reservoir conditions, equation (1) gives the gravimetric theoretical storage capacity of CO_2.

$$m_{CO_2,theoretical} = V_b \cdot n/g \cdot \phi \cdot traps\% \cdot \rho_{CO_2} \qquad (1)$$

Where

m_{CO2} = gravimetric storage capacity, theoretical or effective, $[m_{CO2}]$ = kg;
V_b = bulk volume of the potential formation, $[V_b] = m^3$;
Φ = porosity, $[\Phi]$ = %;
n/g = proportion of sediment structures with porosity and permeability suitable for absorbing CO_2 (net-to-gross ratio), [n/g] = %;
traps% = proportion of traps in the total volume, [traps%] = %;
ρ_{CO2} = density of the CO_2, $[\rho_{CO2}] = kg/m^3$.

The theoretical storage capacity calculates the pore volume of a reservoir rock. However, it is impossible to fill this total volume with CO_2 because the pores are water-saturated. For this

reason, efficiency factor E, which takes the potential water displacement and compressibility into account, is required.
Applying the efficiency factor on equation (1), gives the effective CO_2 storage capacity:

$$m_{CO_2,effective} = m_{CO_2,theoretical} \cdot E \tag{2}$$

where

E = efficiency factor, [E] = % and therefore

$$m_{CO_2,effective} = V_b \cdot n/g \cdot \phi \cdot traps\% \cdot \rho_{CO_2} \cdot E \tag{3}$$

The efficiency factor is the most widely ranging parameter in the storage calculation in deep saline aquifers. In the literature, the efficiency factor varies between 0.01% and 40% but the processes underlying its derivation are not always as clear as presented here [5-7,1].
In terms of a cautious estimate, the approach of calculating a reasonable efficiency factor is applied by making assumptions of rock and water compressibility (c_r and c_w) and maximum pressure increase (Δp) in a reservoir, which leads to equation (4):

$$E = (c_r + c_w) \cdot \Delta p \tag{4}$$

In this calculation, it is assumed that every formation is finite and that brine cannot be displaced out of the system. Potential hazards from contamination of potable ground water resources or of saline water reaching the surface are therefore minimized. The maximum pressure increase affects the entire pore space, not only the pore space of the traps, where CO_2 is injected. *Traps%* in equation (1) is therefore set to 1, which means that for calculation of E the percentage of traps is not needed. But still, CO_2 injection is limited to closed structures.

2.2. Depleted hydrocarbon fields

The potential of depleted hydrocarbon fields can be calculated from cumulative production and reserve data. The volume of ultimately recoverable gas at the surface is multiplied by CO_2 density, gas expansion factor/formation volume factor and sweep efficiency to determine the theoretical capacity estimation.
In the past, the efficiency factor (sweep efficiency) for depleted hydrocarbon fields has often been neglected and instead the assumption of total replacement was used. However, based on recent studies, only 75% replacement of original oil or gas in place is expected [8,9]. As it is unlikely that the entire amount of hydrocarbons produced will be replaced, this factor seems more reasonable. Applying this sweep efficiency reduces the capacity estimations by a quarter.

3. Assessment

3.1. Germany

The presented methodology is applied to gain an effective conservative storage capacity of *German onshore aquifers*. The estimate is based on averaged values from site-specific investigations. Lack of geological data for many formations contributes significantly to uncertainty.
A bulk area of sediment deposits in Germany is estimated to 140,000 km^2, based on [6]. This leads together with an averaged thickness of 50 m to the bulk volume of German sediment layers of 7,000 km^3. The porosity is assumed to 20% as most authors do [3,10,4]. It is further analysed that the entire bulk volume is used and the net-to-gross-ratio is set to 1. The same applies to *traps%* because the efficiency factor is based on the total pore volume, not the volume of traps as described in chapter 2.1. To determine the efficiency factor, equation (4) is applied with Δp of 1 MPa and total compressibility of 1x10^{-3}/MPa, leading to E = 0.1% (base

case). The CO_2 density is set to 600 kg/m^3 [3,10]. A conservative estimate is derived by applying these factors in equation (3):

$$m_{CO2,effective} = 7{,}000 \bullet 1 \bullet 0.2 \bullet 1 \bullet 600 \bullet 0.001 = 840 \text{ [Mt } CO_2\text{]}$$

Thus storage capacity in German onshore aquifers is estimated to 0.84 Gt CO_2.
Beside this base case, sensitivity analyses with different efficiencies are calculated. In the literature, Δp ranges from 1 MPa to 10 MPa [11,12]. The total compressibility is given with 0.5 to 1x10^{-3}/MPa. Applying equation (4) leads to efficiency factors of 0.05 and 1%, applied on the total system volume. With lower compressibility and hence an efficiency of 0.05%, a capacity of 0.36 Gt CO_2 is derived. If higher maximum pressure is accepted (10 MPa), an efficiency of 1% is derived which leads to a capacity of 8.4 Gt CO_2.
Regarding *offshore aquifers of the German North Sea*, the GeoCapacity report can be taken as conservative assessment [2]. There, a best estimate of 2.9 Gt CO_2 is derived, by conducting a bottom-up analysis of 13 aquifer structures in the North Sea, contributing more than 100 Mt CO_2 storage capacity each. This site-specific analysis is the most correct way to determine capacities theoretically. Unfortunately, the used parameter values and the applied methodology is not published, i.e. no critical analysis can be conducted. Nevertheless is this approach preferable to a very general top-down approach and thus this capacity with a range from 1.9 to 4.5 Gt CO_2 is adopted.
Potential CO_2 storage in hydrocarbon fields is limited in Germany to *depleted gas fields* as oil fields have only negligible capacity. An analysis of cumulative gas recovery and reserves data from fields >10 Mt CO_2 delivered a volume of gas of 898 billion m^3 [data base from 13]. This volume is multiplied with the density of CO_2 of 600 kg/m^3 and with a gas expansion factor of 1/250 to receive a capacity of 2,155 Mt CO_2. As commented above, a sweep efficiency of 75% should be applied to derive an effective storage capacity in German gas fields. This reduces the capacity to 1,616 Mt CO_2. If instead the above mentioned limitation to fields >100 Mt is chosen, a capacity of 934 Mt CO_2 can be calculated including only 5 fields [14].
In *total*, German effective storage capacity amounts to 5 Gt CO_2 (with a range of 4 to 15 Gt). This is lower than most of the existing studies predict, ranging from 3 to 44 Gt CO_2 [15] (see Fig. 21). The main reason is that cautious efficiency factors for saline aquifers and gas fields are applied. Most recent calculations of BGR delivered a capacity of 9 to 15 Gt [16], which is in the range of the conservative assessment presented here and half in regard to BGR's former results of 2005 [6].

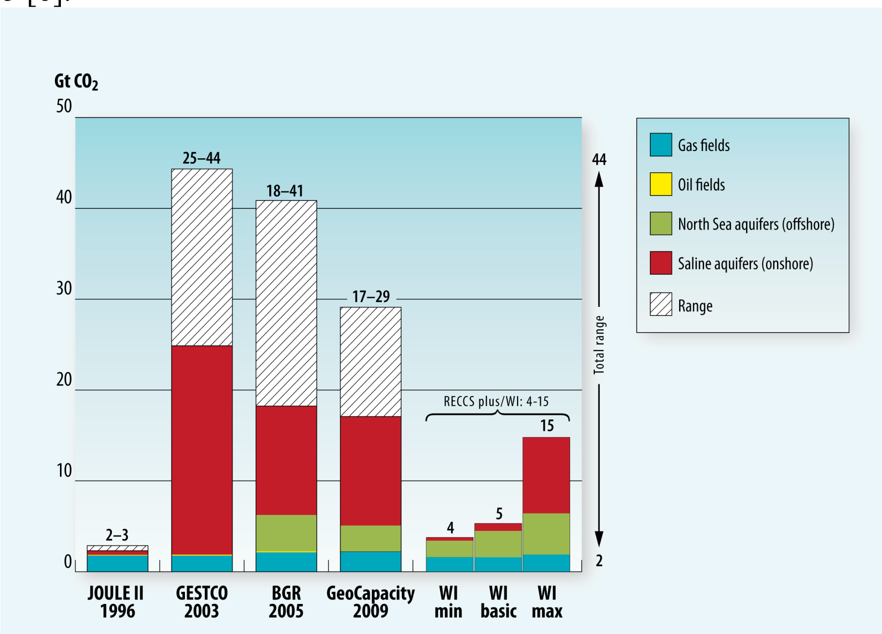

Fig. 1 Overview of different CO_2 storage estimates for Germany

3.2. Netherlands, France, Denmark, Norway, UK and Poland

The Netherlands

Recent publications derive a storage capacity for the Netherlands of 2 – 3.5 Gt CO_2 [17-19]. Capacity in *saline aquifers* is very limited with 0.3 to 0.75 Gt CO_2. If a minimum size of 50 Mt CO_2 per site is demanded, no storage could be conducted in these aquifers. Thus the Netherlands' CO_2 storage capacity is provided mostly by *gas fields* which will become depleted in the mid 21st century. The biggest gas field is the Groningen field, which could contribute in the depleted state up to 7 Gt CO_2 storage capacity. But this field is still under production until 2040 or 2050, which might be too late for CCS application [17]. Thus, the total conservative effective storage capacity is assumed to 3 Gt CO_2, as this figure lies in the range of most recent published estimates and excludes the Groningen gas field.

France

There are several deep sediment basins in France and the estimated potential storage capacity varies widely. In *saline aquifers* it ranges from 0.7 to 26 Gt CO_2 [15]. If more conservative assumptions are considered, i.e. storage is restricted to traps and efficiency factors are included to derive an effective capacity, the lower value of this range seems more realistic. Additionally, *depleted oil and gas fields* provide space for 770 Mt of CO_2. according to [2]. Therefore, a total conservative effective storage capacity in France of 1 Gt CO_2 is assumed.

Denmark

The storage capacity in Denmark is mainly based on *deep saline aquifers*. GeoCapacity gives a capacity of 2.5 Gt CO_2 in these formations [19]. *Oil and gas fields* provide only minor capacities with 0.2 Gt. Analysing the capacity in saline aquifers regarding conservative assumptions, the Thisted structure should be discussed cautiously. It comprises about 70% of the storage capacity in aquifers. GESTCO included an overview of geochemical properties of its different structures [3]. This specific formation has a very low degree of permeability (< 2 mD), which would complicate injection pretty much. As it is not known whether this disqualifies the formation as suitable for injection, the Thisted structure is excluded from the conservative estimate. This leads to an effective potential for CO_2 storage in saline aquifers of 700 Mt. Adding the gas and oil fields, this amounts to approximately 1 Gt effective storage capacity for Denmark.

Norway

Norway and its *Utsira Formation* are considered by many as the biggest potential sink for CO_2 in Europe for the next decades to centuries. Utsira has excellent permeability and porosity values, enabling CO_2 to be stored there. To create space, salt water has to be produced and deposited into the ocean. The nascent space would be equivalent to a CO_2 storage capacity of 40 Gt [20]. A complete exchange of the formation water by CO_2 would lead to very optimistic theoretical capacity of 600 Gt CO_2. If conservative assumptions are applied based on [3,4], the effective capacity of Utsira would be only around 1 Gt CO_2. Sleipner, the most famous CCS project worldwide, has been injecting 1 Mt CO_2 per year into Utsira since 1996.

Beside Utsira, offshore Norway offer other possibilities to store CO_2 whereas the crystalline Norwegian mainland does not allow any CO_2 injection. These offshore structures are saline aquifers and depleted oil and gas fields. The estimation for *saline aquifers* amounts to very high theoretical numbers of up to 476 Gt but if storage is limited to traps and an adequate efficiency factor is applied, this capacity is reduced to a minimum (10 Gt CO_2) [4].

The capacity in *depleted oil and gas fields* varies on a smaller but also notable scale. GeoCapacity calculate the capacity to 3 Gt whereas GESTCO determines that slightly over 10 Gt could be stored in fields with a capacity greater than 100 Mt of CO_2. This is the amount provided also by JOULE II [3,4,2]. In total, the conservative effective storage capacity in Norway is assumed to 21 Gt CO_2.

United Kingdom of Great Britain and Northern Ireland (UK)

Like for Norway, the CO_2 storage capacity of the UK is also solely based on offshore formations. *Deep saline aquifers* provide most of the storage capacity. It varies between 7 and 15 Gt CO_2 effective capacity [3,19,21,22]. *Depleted oil and gas fields* provide additionally around 7.5 Gt CO_2 storage capacity, where only fields providing more than 50 Mt capacity each are selected [4,19]. As a conservative result, the GeoCapacity approach seems reasonable with an assumed effective capacity of 15 Gt CO_2.

Poland

Poland is investing a lot of money in the CCS technology and is willing to promote its implementation – though there has not been extensive research on the storage capacity. The only available assessment considered a potential of 1.76 Gt of CO_2 in *aquifers* and 0.76 Gt of CO_2 in *hydrocarbon fields* [19]. In addition, 415 Mt of CO_2 storage space in *coal fields* is estimated. In total, this would amount to a conservative effective storage capacity of 3 Gt CO_2.

4. Discussion

The derived conservative storage capacities are summed up in Fig. 2. It shows, that the most promising formations are situated offshore in the North Sea of Norway and the UK. These two countries provide 36 of the total 49 Gt CO_2 conservative storage capacity of North-West Europe.

Additional to the compilation of storage capacities of the selected countries, the CO_2 emissions in 40 years are outlined. A total of 1.2 Gt CO_2 is emitted per year [2] which would amount to 47.6 Gt after 40 years. It is this period, the potential lifetime of a coal-fired power plant, which is compared to the conservative storage capacities of these countries (49 Gt). The remainder is 1.4 Gt which indicates that even under conservative storage capacity assumptions the entire 40-years-long CO_2 emissions of North-West Europe might be stored underground. From the considered countries, only the offshore North Sea areas of Norway and the UK provide sufficient potential to import CO_2. Especially for the biggest emitter Germany with possibly limited storage capacity to sequester the desired amount of CO_2, the North Sea space of Norway and the UK could be used within a pipeline infrastructure for CO_2 storage.

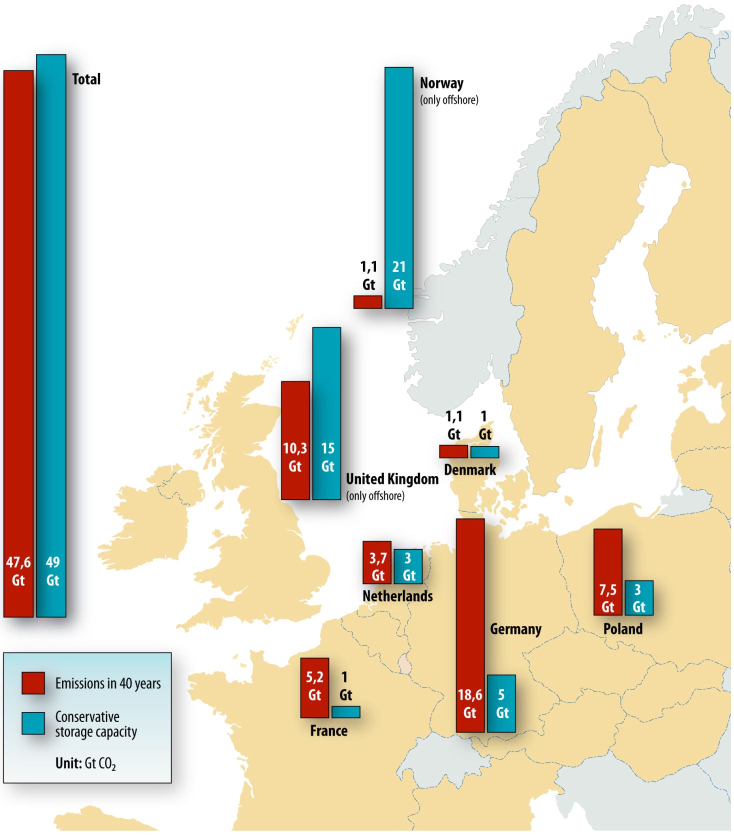

Fig. 2 Overview of conservative capacity estimates of CO_2 storage in Germany's neighbouring countries compared with 40 years emissions from large point sources

This simplified comparison, however, disregards several difficulties:

- 17% higher emissions to be captured and stored if considering *increased demand* for energy caused by capturing (+30%) and a CO_2 capture rate of only 90%
- Geographic source-sink matching
- Limited injection rates at specific sites
- Environmental impacts through production of salt water
- Soft factors (societal acceptance)

Taking these issues and difficulties into account, it is quite uncertain, whether the storage potential will be sufficient for the storage of all CO_2 emissions being captured in the future. However, it appears the North Sea would have sufficient capacity to at least store some of the northern European emissions.

5. Conclusion

Summarising, it was shown that CO_2 storage capacity for Europe, and especially for Germany, might be highly overestimated and that the assumption that adequate storage space exists is still uncertain. Only site-by-site investigations would solve this lack of knowledge. At the same time, a consistent method for the calculation of CO_2 storage capacity is needed in order to make comparisons throughout Europe. Nevertheless, a conservative estimate for CO_2 storage potential is necessary for policy makers and industry stakeholders to enhance the discussion and deliver a range for CO_2 sequestration, even if it can be done only very roughly at present. Such an estimate presented here shows that, in the best case, the storage potential in Europe will be sufficient for the storage of all CO_2 emissions, even if not there where the emissions are captured.

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