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CO_2 Storage Capacity Evaluation in Deep Saline Aquifers for an Industrial Pilot Selection. Methodology and Results of the France Nord Project.

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Abstract

France Nord project is a Joint Industry Project that has grouped 4 public research institutes (BRGM, IFPEN, INERIS and Eifer) and 7 industrial partners (Total, GDF SUEZ, Storengy, EDF, Air Liquide, Lafarge and Vallourec) from 2008 to 2012. The first step of the France Nord project was to identify in the deep saline aquifers of the Paris Basin a geological site providing a storage capacity of at least 200 Mt of CO_2 during 40 years of injection. This level of capacity is considered as appropriate for a project of industrial size. In parallel, a review of the CO_2 emitters in Northern France was performed and potential CO_2 transportation solutions were reviewed. The second step was to implement a CCS pilot in a CO_2 storage target identified previously. An R&D program has also been implemented, reviewing key elements of the CCS chain.
Five potential CO_2 storage targets were analyzed in detail, following a regional geological assessment, a geological modeling and dynamical flow simulations. However, on the basis of available data, it was not possible during the project to identify a CO_2 storage site with the target capacity of 200 Mt of CO_2. As a consequence, the demonstration pilot was not implemented.
These results are discussed and compared to past CO_2 storage assessments of the Paris Basin that provided much higher estimations of the saline aquifer CO_2 storage capacity of the basin.

Keywords: CO_2; Paris Basin; geological storage; storage capacity; saline aquifer

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1. Introduction

The Paris Basin is the largest on-shore French sedimentary basin. It has been identified as a major basin to store CO_2 in saline aquifers. Since the 90's, the CO_2 storage capacity in saline aquifers was estimated through a succession of European projects: first evaluation was performed during the Joule project in 1996 [1]; a second evaluation was performed during the Gestco project in 2003 ([2] and [3]), which was updated during the EU Geocapacity in 2009 ([4], [5]). The estimations of the saline aquifer CO_2 storage capacity ranged from 800 Mt up to 27 Gt of CO_2 (a factor of 30 between lowest and highest estimations).

The France Nord project is a Joint Industry Project that has grouped 4 public research institutes (BRGM, IFPEN, INERIS and Eifer) and 7 industrial partners (Total, GDF SUEZ, Storengy, EDF, Air Liquide, Lafarge and Vallourec) from 2008 to 2012. The project included aspects related to CO_2 capture, CO_2 transportation and CO_2 storage in saline aquifers of Paris basin. The current paper is reviewing the main findings concerning the CO_2 storage evaluations.

The first step of the CO_2 storage part of the "France Nord" project was to qualify and select a site for CO_2 storage in saline aquifer in the Paris basin on the basis of available data. This site had to store the industrial emissions concentrated in the northern part of France. Its capacity had thus to be at least 200 Mt of CO_2 in order to store up to 5 Mt of CO_2 per year during 40 years.

The second step was to implement a CCS demonstration pilot of 100 kt of CO_2, in a target identified during the previous step.

This paper presents the methodology used for the first step (site selection and capacity evaluation) of the project and the main results of this site assessment.

Due to the impossibility to identify a CO_2 storage target with a capacity larger than 200 Mt of CO_2, the demonstration pilot was not implemented.

2. Aquifer selection

The aquifers investigated are located in the sedimentary formation of the Paris Basin. These reservoir formations were assessed from geological data and synthesis available at BRGM -the French Geological Survey ([6], [7]), published studies ([8], [9], [10]) and additional data provided for the project by the partners (TOTAL, GDF SUEZ and IFPEN)

Target formations were selected using the following criteria:

- the reservoir must have geographical, geological and petrophysical properties for storing large volumes of CO_2 safely;
- the reservoir has to be deeper than 1000 meters to minimize the volume of the storage;
- the aquifer has to be undrinkable and unsuitable for agricultural use due to its salinity (salinity > 10 g/l);
- it should not have any risk of interaction with potential third surface or subsurface activity.

The criteria defined above allowed selecting 5 stratigraphic targets (displayed in red in Fig. 1):

- Buntsandstein sandstones
- Donnemarie sandstones (Keuper)
- Chaunoy sandstones (Keuper)
- Boissy Sandstones (Keuper)
- Dogger limestones (Oolithe Blanche and Dalle Nacrée formations)

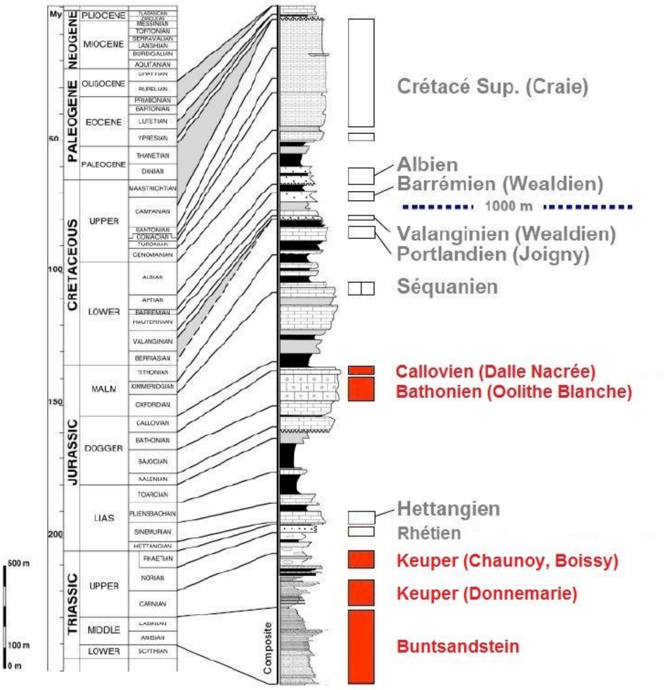

Fig. 1- Selection of the stratigraphic target suitable for CO_2 storage. Buntsandstein sandstones, Donnemarie, Chaunoy and Boissy sandstones (Keuper) and Dogger limestones. These targets are represented on the Paris Basin log (modified from Guillocheau et al., 2000 [8]).

In order to select one or more sites with at least 200Mt CO_2 storage capacity, these 5 stratigraphic targets were subject to 3 regional models (Buntsandstein, Keuper and Dogger).

An identical approach was applied on each model to identify potential sites and allow comparison.

The methodology can be summarized as follows:

- selection of a common structural scheme (selection of major faults) in the whole Paris Basin (Fig. 3);
- geometric modeling of reservoirs from available data (well logs, depth and thickness maps..) at basin scale;
- petrophysical filling at basin scale:
    - from properties maps (porosity, permeability) when available (Buntsandstein, Keuper);
    - from porosity measured on logs, establishment of porosity-permeability laws and propagation of petrophysical properties in the model (Dogger);
- selection of suitable injection sites considering the geological storage criteria (depth, salinity) and the properties of reservoir formation (thickness, porosity, permeability);
- definition of the boundary conditions of aquifers (stocked, outfalls) to compute the initial pressure and model the pressure variations during the injection period and after;
- refinement of the model in the suitable injection sites by a review of all available wells in order to simulate the injection of 200 Mt of CO_2 with vertical injectors perforated on the total height of the reservoir, 7 inches diameter and an overpressure authorized in the wells of maximum of 50% of the initial pressure;
- and finally, sites comparison, taking into account the geological uncertainties, the number of injectors necessary, their spacing, the extension of the pressurized zone and the potential interactions with other users in the study area.

During this phase of the project, five sites with a 200 Mt CO_2 potential storage capacity were identified:

- 2 sites in the Keuper aquifer, one site North of Paris and one site Southeast of the basin;
- 2 sites in the Dogger, both north of Paris;
- 1 site in Buntsandstein, at the far east of the Paris Basin (in the Lorraine region).

The three regional models have an East – West cumulative extension of 550 km and a North-South extension of 400 km, as illustrated on Fig. 2.

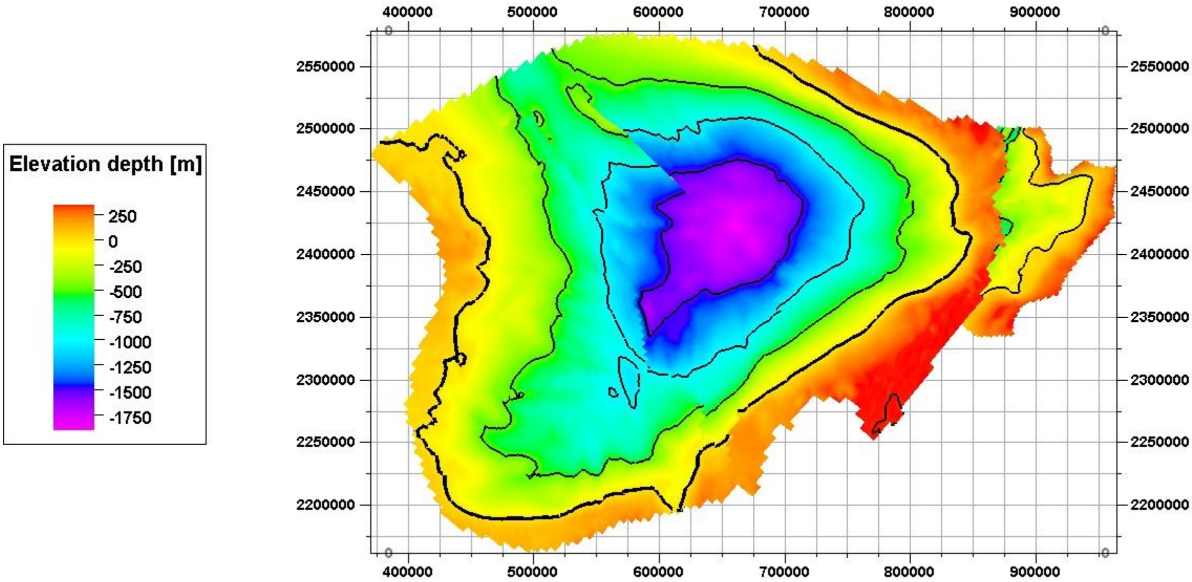

Fig. 2- Map view of the models, Easting and Northing is in meters. The color scale shows the depth of the models, with contours every 500 m.

Concerning the model of the Dogger formation, matrix porosity and permeability were computed from available log data (sonic, GR NPHI and RHOB on 160 wells), but, due to a complex diagenesis history, a dual porosity/permeability system occurs in the Dogger of the Paris Basin with presence of pathways of very high permeability. Actually, our knowledge of the Dogger does not allow any predictive localization of these drains. This means that we are not able to control the evolution of the CO_2 plume and its migration. Moreover, injection of 200 Mt of CO_2 in the permeable part of the Dogger results in an overpressure around 2 MPa that would impact the geothermal activity.

Because of these uncertainties on the Dogger geological properties and the possibility of an interaction with geothermal energy development within this level, this stratigraphic target was discarded.

Finally, only three sites (located in Keuper and Buntsandstein) were selected for further more detailed evaluation (Fig. 3).

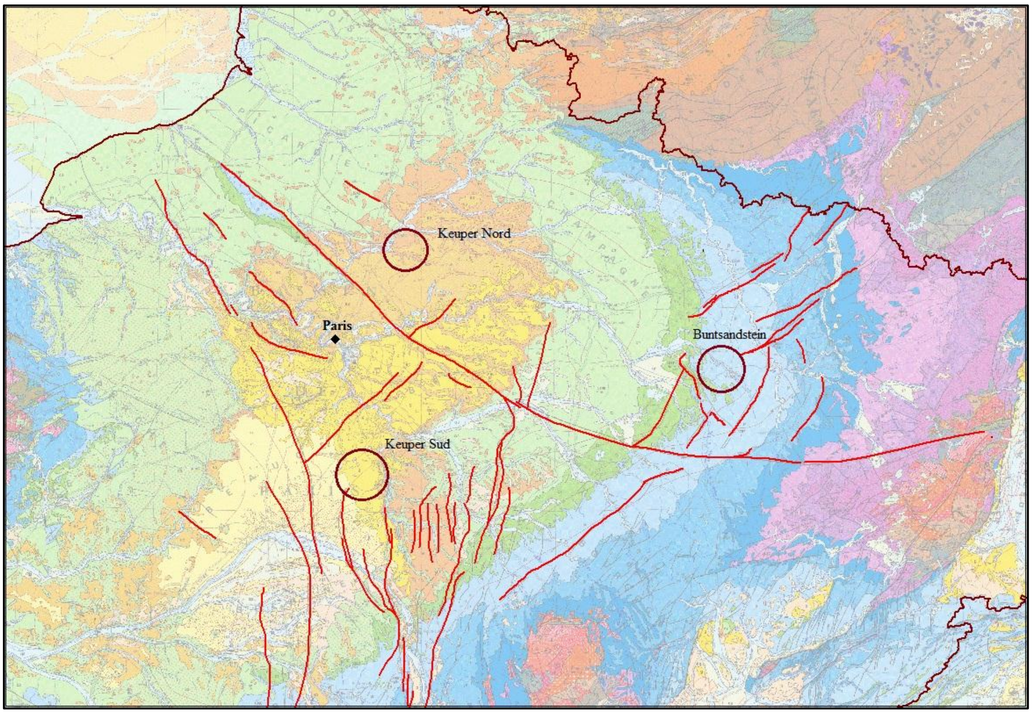

Fig. 3 – Study area in the northern part of France with the common structural pattern chosen for the project (red lines). The 3 sites selected at the end of the regional modeling are represented by circles.

- In the Keuper, the southern site (Keuper Sud) is considered as the most appropriate target despite some expected problems due to the number of faults in the area;
- The Northern site in Keuper formation (Keuper Nord) is structurally simpler but less efficient petrophysical properties (porosity and permeability) require a large number of injectors;
- Injection in the Buntsandstein presents a significant risk of conflict of use with the production of drinkable water from the same aquifer because CO_2 can migrate laterally from the deep salted part of the aquifer to the shallower fresh water production zone.

A more detailed modeling of these 3 sites resulted in more accurate assessments of the storage capacity by:

- refining geological and dynamic modeling, especially in the injection areas,
- testing several scenarii for commissioning of CO_2 injectors,
- investigating the behavior of the CO_2 with time.

3. Site modeling

The aim of this last step of site selection consisted in the elaboration of new fine models focused on the 3 most favorable sites defined earlier. The objective is to optimize the number of injection wells to reach 200Mt of injected CO_2 in the reservoir over 40 years. This second step of the project performed by Storengy team was conducted in two phases: a refinement of the geological and petrophysical modeling and the dynamic modeling.

In order to evaluate the sensitivity of the results regarding the parameters and the associated uncertainties, different models were computed.

Results for each site are described below.

3.1. Keuper Sud

Injection in the site “Keuper Sud” concerns the totality of the triasic formations. From base to top, it can be described as follows:

- Donnemarie formation : sandstones to conglomeratic sandstones with some silty layers
- Grès intermédiaires formation: shales and sandstones
- Chailly-Chaunoy formation: interbedded sandstones and shales.
- Chalain formation: continental deposits consisting of a shaly environment with some unconnected channels (sandstones).
- The top of the Trias consisting of the Rhetian marine deposits considered in the model as the caprock.

The geological model of "Keuper Sud" is based on the regional geological model produced by IFPEN in the previous stage. The fine model has to match the regional model in order to benefit from the boundary conditions. Properties of regional model (K, Phi, net thickness, salinity, T, P...) are used as input data; the structural schema has been completed with secondary faults pattern and complementary well data were added for a better definition of surfaces and petrophysical properties. Finally, the grid definition is 1000m x 1000m with 28 stratigraphic layers (to be compared with the regional model 3000m x 3000m x 8 layers, Fig. 4).

The model refinement led to a significant reduction of the net thickness compared with the regional model. This implies a lowering of the estimated storage capacity.

Two different petrophysical models were built:

- the first one includes porosity, from logs measurements, and permeability calculated using a Phi/K relationship.
- the second one includes a petrophysical facies modeling, based on a study done by Total [11]. Then, permeability and porosity were modeled for each facies, in order to have a more representative geographical distribution of the properties.

The simulation computed on the first model is considered as an optimistic case because the reservoir is considered with homogeneous layers. The simulation indicates a potential injection of 140 Mt with 15 injection wells (Fig. 4). The Donnemarie sandstones represent a large part of the total storage potential as well as the Chalain formation; however there are very limited geological data on this formation, which implies a high uncertainty on its storage capacity estimation.

The second model based on facies analysis provides a pessimistic case study because the channelized layers are thus not homogeneous and some layers have disappeared during the upscaling process. This model gives a potential of 54 Mt for the same injection design as the first model simulation. The Donnemarie formation concentrates the majority of storage potential.

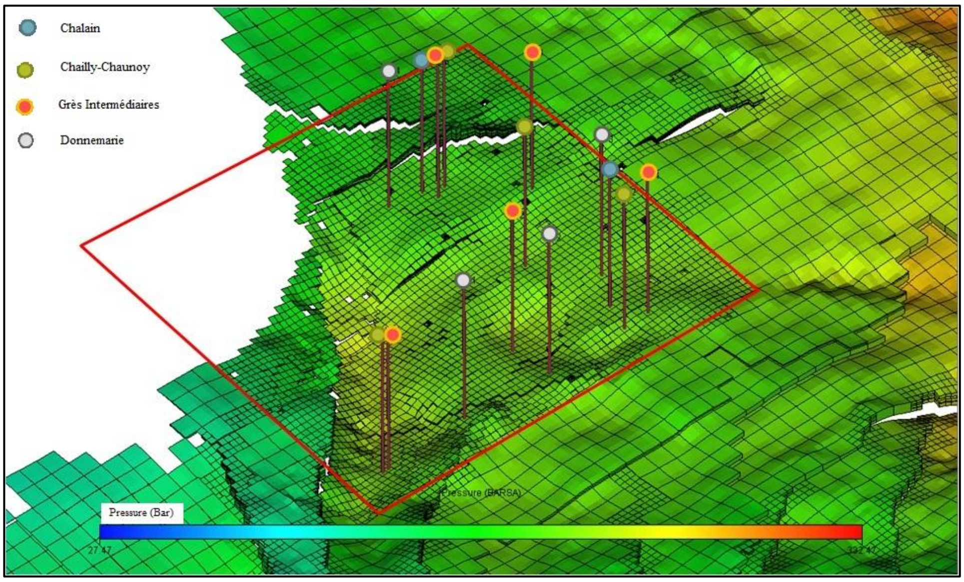

Fig. 4- “Keuper Sud” model with grid refinement around the injection zone and along the faults. The 15 wells necessary to inject from 54 to 140 Mt are represented with their stratigraphic target.

Note that modeling water production did not improve significantly the capacity due to the challenging connectivity of the sandstones.

3.2. Keuper Nord

The “Keuper Nord” zone is *a priori* of less interest than the “Keuper Sud” because:

- Chalain formation is almost absent,
- Grès intermédiaires formation are present on the half of the zone surface,
- Donnemarie sandstones are also almost absent,
- The only layer of interest in the zone is the Chailly-Chaunoy formation which shows good permeability (> 100mD).

The geological model of “Keuper Nord” was updated in the same way as “Keuper Sud”; the grid was fine-tuned (from 3000 m in the regional model to 300 m) and wells and logs analysis provided new petrophysical infill in the site area. As for the model “Keuper Sud”, this work induced a significant reduction of the global Net to Gross ratio with a new estimation of the NTG to 0.2. The evaluation of the storage capacity is 40 Mt with 20 wells and its assessment was not carried further.

3.3. Buntsandstein

On this zone, the geometry and petrophysics of the reservoir were completed with some additional well data provided by Total. The static model has been locally refined but the properties of the local model are sensibly identical to those of the regional model (Fig 5.).

Two areas were assessed for injection, located respectively east and west of the Marne Fault (Fig. 3 and 5). The potential of the eastern zone has been reassessed to 133 Mt with 4 injectors but the risk of gas migration to the production zone of drinkable water was confirmed. It was thus decided to simulate the behavior of the reservoir further to the west in an area which does not present such risk owing to the Marne fault; however, petrophysical properties, thickness of the reservoir and lateral extension are significantly lower and injection simulations show a potential of only 87.5 Mt with 23 wells with the necessity to produce brine in order to keep a reasonable pressure in the reservoir. The produced brine has to be reinjected east of the fault to form a hydraulic barrier and prevent the migration of the CO_2 (Fig. 5.).

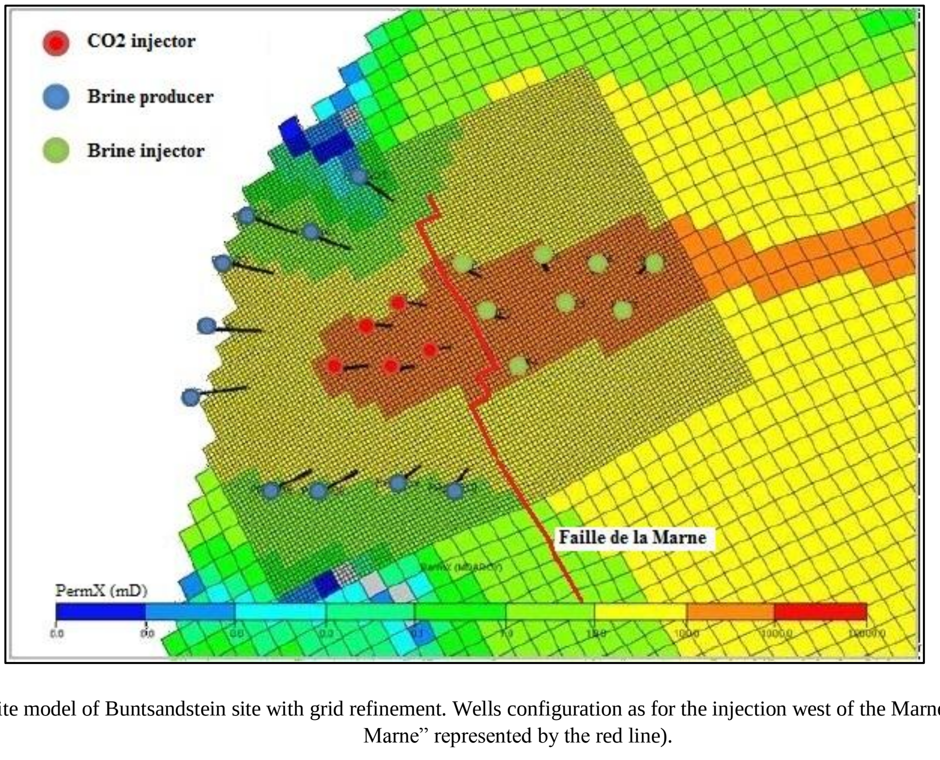

Fig. 5- Site model of Buntsandstein site with grid refinement. Wells configuration as for the injection west of the Marne Fault (“Faille de la Marne” represented by the red line).

3.4. Summary of the storage capacity identified in the France Nord project

The objective of the storage capacity identification task in the France Nord project was, using the same methodology on several site, to optimize the number of wells required to inject 200Mt of CO_2 over 40 years (5Mt/year). Some alternative cases were performed in order to evaluate the uncertainties of our results.

Table 1. Summary of the storage capacity identified in the France Nord project

Site	Potential of injection	Number of wells	Comments
Keuper Nord	40 Mt	20 wells	
Keuper Sud	140 Mt	15 wells	Without facies modeling (optimistic case)
Keuper Sud	54 Mt	15 wells	With facies modeling (pessimistic case)
Buntsandstein	157 Mt	21 wells	Injection east of the Faille de la Marne. Risk of CO_2 migration towards the drinkable part of the aquifer was considered as too important.
Buntsandstein	87 Mt	23 wells	Injection west of the Faille de la Marne Aquifer properties significantly degraded compared to the previous case

All these result are largely under the objectives of the France Nord project. It was thus decided not to go further through the second step of the project which was to implement a CCS demonstration pilot of 100 kt of CO_2, in one of the 3 targets identified previously.

4. Comparison of the aquifer storage capacity with previous estimates

A first assessment of the saline aquifer CO_2 storage capacities was performed during the Joule II project (1996).

The capacity was evaluated at 810 Mt of CO_2, which is a relatively low number. This can be explained by various assumptions

- CO_2 can only be stored in structural traps,
- only 3% of the aquifer pore volume is considered to be in a structural trap (number derived from an Utsira evaluation),
- 6% of the water in these traps can be replaced by CO_2 as these traps are considered to be “open”, in pressure communication with the rest of the aquifer,
- The global storage efficiency is hence reduced, of 0.18%,
- Note also that in this study, the potential conflicts with potable water led to removing Buntsandstein from the review.

A second study assessment was performed during the GETSCO project (2003) where a range of capacity was established:

- a high case, assuming open aquifer on the full volume of water with a storage coefficient of 6%,

- a low case, analogue to the Joule approach where the storage coefficient accounts for structural traps with a value of 0.18% for Buntsandstein and Keuper and a value reduced to 0.01% in Dogger as most traps are considered filled with hydrocarbon reservoirs and are hence considered as unavailable for aquifer storage.

This second assessment leads to a range of capacity from 668 Mt up to 27 Gt of CO_2.

The GESTCO evaluation for the Paris Basin was updated during the EU Geocapacity report (2009), with two estimates:

- a high case, entitled storage capacity estimation for aquifers, identical to the GESTCO approach,
- a low case, entitled conservative capacity estimation for aquifers, where storage capacity is taken at 2% for open aquifers (instead of 6% previously) and 0.1% for closed aquifers (applying to Keuper only).

This third assessment leads to a range between 7.9 Gt to 27 Gt of CO_2 in saline aquifers of the Paris Basin.

Table 2 summarizes these assessments and compares them to France Nord results. For France Nord Keuper, both sites (Keuper Nord and Keuper Sud) are stacked.

The table clearly reflects that storage coefficients of 2% or 6% do not apply to the Paris Basin as overpressure constraints impede storing such volumes of CO_2, despite the modeling of open boundary conditions or water production.

Table 2. Summary of various CO_2 storage capacity assessments of Paris Basin saline aquifers for each estimate (column) the methodology is mentioned on the second line, and for each aquifer the storage efficiency E is reminded

	JOULE II (1996)	**Projets GESTCO (2003) et EU GEOCAPACITY (2009)**			**France Nord (2009-2011)**
	Traps	Traps	Total	Conservative	Flow models
Dogger	189 Mt (E=0.18%)	9 Mt (E=0.01%)	4320 Mt (E=6%)	1440 Mt (E=2%)	Potential Conflict with geothermal resources
Keuper	529 Mt (E=0.18%)	130 Mt (E=0.18%)	4331 Mt (E=6%)	72 Mt (E=0.1%)	90-180 Mt
Buntsandstein	Conflict with fresh water	529 Mt (E=0.18%)	17640 Mt (E=6%)	5880 Mt (E=2%)	~ 90 Mt
Other fm.	91 Mt	-	845 Mt	530 Mt	-
TOTAL	809 Mt	668 Mt	27136 Mt	7922 Mt	180-270 Mt

5. Conclusion

The assessment phase of the project has shown that it was not possible to identify a single site to store 200 Mt CO_2 over 40 years on the basis of available data. The best identified site is the “Keuper Sud” site. Its storage capacity ranges between 54 and 140 Mt, with the necessity to drill about 15 injection wells over a large area (about 3000 km^2).

This demonstrates that high storage coefficients of 2% or 6% as used during previous GESTCO and EU Capacity projects do not apply to the saline aquifers we have studied. The constraint of the acceptable overpressure is the main obstacle to a massive injection of CO_2 in saline aquifers regardless the boundary condition considered (open aquifer). The injection rates are directly driven by this overpressure phenomenon. Do not take into account this phenomenon leads to an overestimation of storage capacity as shown in comparison with previous capacity estimates.

As shown by Thibeau et al. [12], this result is not specific to the area we have considered, and applies to a very large variety of saline aquifers.

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