Dossier

This paper is a part of the hereunder thematic dossier
published in OGST Journal, Vol. 70, No. 4, pp. 523-784
and available online here
Cet article fait partie du dossier thématique ci-dessous
publié dans la revue OGST, Vol. 70, n°4, pp. 523-784
et téléchargeable ici

DOSSIER Edited by/Sous la direction de : **F. Delprat-Jannaud**

Characterization of European CO_2 Storage — European Project SiteChar
Caractérisation de sites européens de stockage de CO_2 — Projet européen SiteChar

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Oil & Gas Science and Technology – Rev. IFP Energies nouvelles, Vol. 70 (2015), No. 4, pp. 753-766
© J.-F. Gruson et al., published by IFP Energies nouvelles, 2015
DOI: 10.2516/ogst/2014057

Open Access

Dossier

Characterization of European CO_2 Storage – European Project SiteChar
Caractérisation de sites européens de stockage de CO_2 – Projet européen SiteChar

Techno-Economic Assessment of Four CO_2 Storage Sites

J.-F. Gruson[1], S. Serbutoviez[1], F. Delprat-Jannaud[1], M. Akhurst[2], C. Nielsen[3], F. Dalhoff[4], P. Bergmo[5], C. Bos[6], V. Volpi[7] and S. Iacobellis[8]

[1] IFP Energies nouvelles, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex
[2] British Geological Survey, Nottingham NG12 5GG, UK
[3] GEUS, Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen K, Denmark
[4] Vattenfall AB, SE-169 92 Stockholm, Sweden
[5] SINTEF Petroleum AS, PO Box 4763 Sluppen, 7465 Trondheim, Norway
[6] TNO Utrecht, Dept. Petroleum Geosciences, Princetonlaan 6, 3584 CB Utrecht, The Netherlands
[7] Istituto Nazionale di Oceanografia e di, Geofisica Sperimentale – OGS, Borgo Grotta Gigante 42/c, 34010 Sgonico (TS), Italy
[8] ENEL - Engineering and Research, Research Technical Area, Litoranea Salentina Brindisi – Casalabate, Loc. Cerano, 72020 Tuturano, Italy
e-mail: jean-francois.gruson@ifpen.fr

* Corresponding author

Abstract *— Carbon Capture and Storage (CCS) should be a key technology in order to achieve a decline in the CO_2 emissions intensity of the power sector and other intensive industry, but this potential deployment could be restricted by cost issues as the International Energy Agency (IEA) in their last projections (World Energy Outlook 2013) has considered only around 1% of global fossil fuel-fired power plants could be equipped with CCS by 2035.*

The SiteChar project funded by 7th Framework Programme of European Commission gives the opportunity to evaluate the most influential parameters of techno-economic evaluations of four feasible European projects for CO_2 geological storage located onshore and offshore and related to aquifer storage or oil and gas reservoirs, at different stages of characterization.

Four potential CO_2 storage sites have been assessed in terms of storage costs per tonne of CO_2 permanently stored (equivalent cost based). They are located offshore UK, onshore Denmark, offshore Norway and offshore Italy. The four SiteChar techno-economic evaluations confirm it is not possible to derive any meaningful average cost for a CO_2 storage site. The results demonstrate that the structure of costs for a project is heterogeneous and the storage cost is consequently site dependent. The strategy of the site development is fundamental, the technical choices such as the timing, rate and duration of injection are also important. The way monitoring is managed, using observation wells and logging has a strong impact on the estimated monitoring costs. Options to lower monitoring costs, such as permanent surveys, exist and should be further investigated.

Table 1 below summarizes the cost range in Euro per tonne (Discount Rate (DR) at 8%) for the different sites, which illustrates the various orders of magnitude due to the specificities of each site. These figures have how to be considered with care. In particular the Italian and Norwegian sites present very specific features that explain the high estimated costs. For the Italian site, the short duration of CO_2 injection associated with a low injection rate makes the CO_2 project comparable to a demo project. The Norwegian site is an offshore site located in a virgin area with high infrastructure costs and a combination of injection duration and injection rate that makes the derived costs very sensitive to the discount rate.

TABLE 1

Summary of the cost range in Euro per tonne (discount rate at 8%)

€/t CO_2	Equivalent storage cost at 8% DR	Injectivity (Mt CO_2/year)	Injection duration (year)
	Base cas	Base cas	Base cas
UK	11.4	5	20
Denmark	3.2	1.5	40
Norway	26.6	1	40
Italy	29	1	10

The results for both UK and Danish sites confirm therefore the value range calculated by the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP).

*The main uncertainties in the costs are linked both to the choice of economic parameters (*e.g. *injected quantities, contingencies) and to the technical choice of operations. This has been studied by sensitivity analyses: for example, if an injection rate is halved and the injection duration is doubled, the Equivalent Storage Cost (ESC) increases by 23% (UK case at 8% DR). Introducing a water production well and water treatment facilities also increases the ESC by 23%, at least on an onshore site. Techno-economic assessments were basically carried out using an 8% discount rate. For projects of long lifetime such a rate severely discounts the late cash flow, especially after 40 years, so that a discount rate of around 4% more in logic of public investment. Compared to other studies, it has to be noted that the scope of the SiteChar analysis does not consider compression and pumping cost, nor transportation cost. This simplifies the techno-economic evaluation but it may not adequately reflect the specific conditions of the individual developments and, hence, distort the comparison between different cases.*

Lastly, techno-economic evaluation poses questions to policy makers about the real lifetime of a CO_2 *storage project: what should be the abandon phase and the associated cost and what is the real value of the liability transfer after 20 years of storage? This issue is still an open question, which has been addressed in SiteChar assuming the same approach as ZEP (2011).*

To counterbalance these CO_2 *storage costs, policy makers have to set up incentives, either through ETS (Emission Trading System) credits, tax credits or public funding. To improve the commerciality of CCS, Enhanced Oil Recovery (EOR) should be taken into account in the regulation of CCS, as it is one of the rare sources for revenue from a commodity with a real market value.* CO_2 *storage in a saline aquifer close to oil and gas fields could also be considered as a source for* CO_2 *EOR.*

Résumé — **Évaluation technico-économique de quatre sites de stockage de CO_2** — La Capture et Stockage de Carbone (CSC) devrait être une technologie clé pour atteindre une baisse de l'intensité des émissions de CO_2 du secteur de l'énergie et de l'industrie, mais ce déploiement potentiel pourrait être limité par les questions de coût. Ainsi l'Agence Internationale de l'Énergie (AIE) dans ses dernières projections (*World Energy Outlook* 2013) a considéré que seulement environ 1 % des centrales à combustibles fossiles de la planète pourrait être équipé de la technologie CSC en 2035.

Le projet SiteChar financé par le 7^e programme-cadre de la Commission européenne donne l'occasion d'évaluer les paramètres les plus influents des évaluations technico-économiques de quatre projets européens pour du stockage géologique du CO_2, onshore et offshore d'une part, aquifère saline ou réservoirs de pétrole et de gaz, avec leurs différentes étapes de caractérisation d'autre part.

Les quatre sites de stockage potentiels de CO_2 ont été évalués en termes de coûts de stockage par tonne de CO_2 stockée de façon permanente (coût actualisé). Ils sont situés au large des côtes du Royaume-Uni, au Danemark (onshore), en Norvège et en Italie en zone offshore également. Les quatre évaluations technico-économiques réalisées dans le projet SiteChar confirment qu'il est impossible d'estimer un coût moyen représentatif d'un site de stockage de CO_2. Les résultats montrent que la structure des coûts des projets est hétérogène et que le coût de stockage va donc dépendre du site. La stratégie de développement du site est fondamentale, le calendrier, les choix techniques tels que le taux et la

TABLEAU 1

Résumé de la fourchette du coût en Euros par tonne (taux d'actualisation de 8 %)

€/t de CO_2	Coût actualisé avec un TA de 8 %	Taux d'injection Mt CO_2/an	Durée d'injection en années
	Cas de base	Cas de base	Cas de base
Royaume-Uni	11,4	5	20
Danemark	3,2	1,5	40
Norvège	26,6	1	40
Italie	29	1	10

durée de l'injection sont également importants. Les options choisies pour le monitoring, les puits d'observation et le suivi géophysique ont aussi un impact fort sur les coûts.

Le tableau 1 résume la fourchette du coût en Euros par tonne (avec un taux d'actualisation de 8 %) pour les différents sites, ce qui illustre les ordres de grandeur variés du fait de la nature de chaque site. Ces valeurs doivent être considérées avec précaution. En particulier, les sites italiens et norvégiens présentent des caractéristiques très spécifiques qui expliquent les coûts élevés. Pour le site italien, la courte durée de l'injection de CO_2 associée à un taux d'injection faible rend le projet de stockage de CO_2 comparable à un projet de démonstration. Le site norvégien est un site offshore situé dans une zone vierge avec des coûts élevés d'infrastructure et une combinaison de la durée d'injection et du taux d'injection qui rend les coûts obtenus très sensibles au taux d'actualisation retenu.

Les résultats pour les deux projets au Royaume-Uni et au Danemark confirment en revanche la gamme de valeurs calculées par le biais de la plate-forme ZEP (*European Technology Platform for Zéro Emission Fossil Fuel Power Plants*).

Les principales incertitudes des coûts sont liées à la fois au choix des paramètres économiques (la prise en compte des imprévus) et au choix technique des opérations (par exemple les quantités injectées). Cela a été étudié par des analyses de sensibilité: à titre d'exemple, si un taux d'injection est réduit de moitié et la durée d'injection est doublée, le coût actualisé de stockage est augmenté de 23 % (cas du Royaume-Uni avec un taux d'actualisation de 8 %). L'introduction d'un puits de soutirage de l'eau du réservoir et d'installations de traitement de l'eau augmente également le coût de stockage de 23 % sur un site onshore. Les évaluations technico-économiques ont été conduites en utilisant un taux d'actualisation de référence de 8 %. Pour les projets de longue durée ou à long terme un tel taux actualise fortement les flux de trésorerie tardifs de sorte qu'un taux d'environ 4 % apparait plus cohérent avec une logique d'investissement « public ». Comparée à d'autres études, il convient de noter que la portée de l'analyse SiteChar ne considère pas la compression et le coût de pompage, ni le coût de transport. Cela simplifie l'évaluation technico-économique, mais elle peut ne pas refléter adéquatement les conditions spécifiques des développements individuels et, par conséquent, fausser la comparaison entre différents cas.

Enfin, l'évaluation technico-économique pose des questions aux responsables politiques au sujet de la durée de vie réelle d'un projet de stockage de CO_2, sur ce que devrait être le coût associé au terme de l'exploitation (phase d'abandon) et sur la valeur réelle du transfert de responsabilité après 20 ans de stockage ? Cette question est encore une question ouverte, qui a été traitée dans le projet SiteChar avec la même approche que celui ZEP (2011).

Pour compenser ces coûts de stockage du CO_2, les décideurs doivent mettre en place des incitations, soit *via* le mécanisme des crédits ETS (*Emission Trading System*), crédits d'impôt ou des fonds publics. Pour améliorer la « rentabilité » de la CSC, la récupération assistée devrait être prise en compte dans la régulation de la CSC, car cette technique est l'une des rares sources indirecte de revenus possibles avec une valeur de marché réelle. Le stockage du CO_2 dans un aquifère salin à proximité de champs de pétrole et de gaz pourrait également être considéré comme de la récupération assistée potentielle.

INTRODUCTION

Similar to the appraisal phase of an oil or gas field before deciding whether or not to develop it, the selection of a site for CO_2 geological storage may require several site characterization campaigns (unless the site is a depleted gas or oil field with large amounts of information). Such site characterization costs might constitute a significant proportion of the total cost. The objective of the techno-economic analysis conducted in SiteChar is to provide an economic evaluation of the costs for site development, either onshore or offshore, so as to understand what the critical and most influential parameters are in the economic assessment rather than to focus on the costs themselves: three offshore sites in the UK sector of the North Sea off Scotland, South Adriatic and the Norwegian Sea and an onshore site in Denmark. The variability of sites and their characterization thus allows for an interesting range for comparison (Delprat-Jannaud *et al.*, 2013), which has to be put in perspectives due to the very different status of each project.

It has to be noted that for a research project it is difficult to achieve some degree of accuracy in the cost estimates. This holds even for an operator, because of the inherent uncertainty of the project, and because of the confidential nature of the data for consultants/operators.

This paper presents a comparative economic assessment of these four sites, including identification of principal costs. CO_2 storage costs for these four sites are analyzed, aiming to understand the elements that govern these estimates and thus to provide useful considerations on the costs of CO_2 storage relevant to policy makers.

The work has been divided into the following stages:

- *Definition of a methodology for collecting cost data.* This work has involved discussions with industry partners to define appropriate Capital expenditure (Capex) and Operating expenditure (Opex) cost categories. Definition of costs, including guidance on estimating costs where site-specific data were not available, have been produced;
- *Collection of cost data.* This task has been undertaken within the SiteChar activities dedicated to site characterization, according to the level of characterization reached for each site. Collected data include:
  - Capex estimates based on site-specific storage designs (as determined by results from site characterization) and including costs for detailed site investigations (*i.e.,* exploration well costs, injection test costs, site characterization and Front-End Engineering Design (FEED) costs);
  - Opex estimates including injection costs, Measurement Monitoring and Verification (MMV) costs.

  The orders of magnitude of cost data have been checked to limit the errors and discrepancies between sites are discussed.
- *Project global economic evaluation.* The project evaluation is based on discounted cost estimation only. No revenues from Enhanced Oil Recovery (EOR) processes or Emission Trading System (ETS) or tax systems are taken into account since these are out of scope of the SiteChar project. An ESC through discount rate assessments has been used:

$$\sum_{k=0}^{N} \frac{F_k}{(1+i)^k} \Big/ \sum_{k=0}^{N} \frac{Q_k}{(1+i)^k}$$

  The economic assessment of each storage site is done step-by-step from the reservoir characterization, to the site development, the site injection and the monitoring phase. The resulting costs are compared to the ZEP (2011) storage cost estimations. Similarities and differences between the storage sites are studied to explain the cost differences. Some storage costs from other publications are also presented, providing an overview of the wide range of costs concerning CO_2 storage;
- *Project sensitivity.* As the data collection quality might be questionable and very heterogeneous within the four sites, a real uncertainty study is not appropriate here. Instead, a sensitivity analysis to understand the main influential parameters for the estimated costs has been conducted on specific technical parameters of the site injection design, as well as on main economic parameters, such as the discount rates and the contingencies. Technical options for storage injection have also been addressed by changing the injection rate and the duration of injection, including or not including water production and water treatment.

1 SCOPE OF THE TECHNO-ECONOMIC ASSESSMENT

A comparative economic assessment of the four proposed CO_2 storage sites studied in the European Union's SiteChar project based on same hypothesis and same methodology for all sites and including identification of principal costs has been conducted.

The four considered sites are:

- *UK site.* The Outer Moray Firth site is a multi-store site comprising a hydrocarbon field within a regionally extensive saline aquifer sandstone offshore Scotland. The reservoir rocks of oil and gas fields are known in great detail but their capacity to store carbon dioxide is relatively small (mostly tens of million tonnes) compared to the potential capacity of saline aquifer sandstones (hundreds to thousands of million tonnes). A plausible CO_2 storage injection history has been developed over a 25-50 years term, compatible with likely current and future industrial sources. It is envisaged that the hydrocarbon field will provide near-term storage capacity, with the aquifer providing greater storage potential, later in the storage cycle. The techno-economic analysis considers as a reference case injection of 5 Mt CO_2/year for 20 years and production of water for pressure relief;

- *Danish site*. The Vedsted site is an onshore aquifer in Denmark. It is situated in the northern part of Denmark close to the Nordjyllandsvaerket power plant. The Vedsted structure was identified by *GEUS* as a possible candidate for geological storage of CO_2. It is an anticlinal closure within a fault block that includes several sandstone reservoirs of good quality at depths of 1 100-1 900 m below an excellent caprock. The capacity of the storage structure was estimated between 100 and 160 Mt of CO_2. The techno-economic analysis considers as reference case an injection rather small of 1.5 Mt CO_2/year for 40 years and no production of water;
- *Norwegian site.* The Trøndelag Platform site is an offshore aquifer located Mid-Norway in an area that contains gas with natural high CO_2 content that can be extracted and stored. The site is a virgin area well suited for CO_2 storage, with good reservoir, good caprock, low pressures and large volumes. The techno-economic analysis considers as reference case an injection of 1 Mt CO_2/year for 40 years and no production of water. Injection rate again is small against a coal power generation emissions (about 3 Mt for 500 Mw and 6 000 annually hours);
- *Italian site.* The South Adriatic site is an saline carbonate aquifer located in the South Adriatic Sea, close to the main Italian CO_2 emission power plant in Brindisi, where *Enel* started a pilot plant for CO_2 capture. The reservoir formation consists of mudstone and wackstone and is located at 1 000-2 000 m depth. It is overlaid by a few hundred metres of marls and clays. The techno-economic analysis considers as reference case an injection of 1 Mt CO_2/year for 10 years and no production of water. Injection rate and especially duration are quite low.

A bottom-up approach is applied compiling and adding up the various base costs.

Most expenses to be taken into account are site-specific. A depleted oil or natural gas field for instance requires less exploration than a saline aquifer for which only very few data are available. A detailed development plan for each site is thus essential for the techno-economic assessment, which was not always sufficiently developed at the current stage of the sites characterization. Collected data on the four sites are intended to encompass all Capex and Opex that will be mobilized over the life of the project.

The data collected are in million €, based on annual cash flow, and corrected to the reference year 2011. For Capex and Opex, the Upstream Capital Costs (UCCI) and the Upstream Operating Costs (UOCI) Indexes of IHS CERA are used. Note that the UCCI index of IHS CERA is the same in 2011 and in 2008. Consequently a 2011 capital cost is equivalent to a 2008 capital cost. Concerning Opex, the UOCI index of IHS CERA is only 1.5% higher in 2011 than in 2008, so the same assumption as for Capex has been done. No inflation during the lifetime of every project has been considered.

An equivalent cost formula has been chosen to compute the total storage cost. It gives the sum over the project time life of the discounted cash flows divided by the discounted quantities of CO_2 stored. It may be noted that, since no income is considered, applying a discount rate on the amount of CO_2 injected might be questionable. The ESC is the discounted storage cost divided by the discounted amount of CO_2 stored. This is this definition which has been chosen as reference case.

The SiteChar techno-economic assessment covers the exploration phase, the Front End Engineering and Design (FEED), the site development, the CO_2 injection phase and the long-term monitoring. The analysis is performed on the full lifetime of the storage site up to state/agency transfer of liability. SiteChar techno-economic assessments address only the storage part of the CCS project and thus exclude transport, capture costs, and heat and power costs at the power plant.

Special attention is put on how the costs entailed in each phase impact the total cost of storage according to the specificities of the sites and their development strategy. These costs are highly site specific. Computing an average cost for CO_2 storage is therefore not meaningful. Understanding what makes the differences between the costs estimated on the different sites will however provide interesting outcomes, the aim of this assessment being to understand the critical and most influential parameters in the economic assessment rather than to focus on the absolute value of the costs.

The various stages of the storage lifecycle are examined:

- the exploration phase. This phase requires the purchase or acquisition of seismic data and geological studies on the site. In some cases an exploration license is required. One exploratory well might need to be drilled; these wells may be re-used as development wells;
- the geological studies. This phase gathers all the characterization studies of the storage site (static and dynamic reservoir modeling, geochemical and geomechanical studies, well integrity and migration path study and the socio-geographic analysis, *cf.* SiteChar D1.4 (Neele *et al.*, 2013);
- the site development phase including the drilling of wells. The cost of the wells to be drilled is mainly determined by the onshore or offshore context and the depth of the reservoir. In some cases the investment amounts need to account for water production wells in order to mitigate

overpressure. It is important at this stage to distinguish the likely expected requirement for development from contingencies related to a worst case scenario. Water production wells for instance might lie in both offshore and onshore categories as will be illustrated on the UK and Danish sites;

- the CO_2 injection and eventually, the water production phase. It has been decided to omit the investment required for compression or pumping since these costs require an accurate comprehension of the reservoir and wellhead pressure, which is out of the scope of SiteChar;
- the seismic or non-seismic monitoring phase(s), including the frequency of the procedures. Two monitoring phases are envisaged, firstly before and during CO_2 injection and secondly, from the end of CO_2 injection until the transfer of liability, which requires less frequent measurements;
- the abandonment phase. This phase refers either to the complete closure or plugging of wells (injection and monitoring) or to a partial closure and shut-in of wells for future potential continued use. A default value for abandonment and post-closure costs corresponding to 15% of Capex is considered as fixed in the ZEP report on storage costs (2011).

It has to be noted that the chronology (*i.e.,* start date and end date for each phase) is important to ensure that cash flows are properly positioned over time. Opex, if any, should be given in millions €/year or by default as a percentage (here 4%) of the corresponding Capex.

Economic parameters are also important. Several discount rates are tested: 8 and 12%, as most E&P companies will have a Weight Average Capital Cost (WACC) within this range and 0% as a way to evaluate the impact of a lower discount rate adequate for projects that are mainly financed by public funds in the long term, and have no revenue (*e.g.* no EOR and oil revenue). Of course the public-funding discount rate can differ from one country to another country. Contingencies are fixed to 20%, as in main industrial projects. For the four sites, the reference year for cost computation is 2011 and the Euro parity is 1 € = 1.39 USD in 2011 and 1 £ = 1.2 €.

Limitations of the techno-economic evaluations are the following:

- lifetimes of the projects are built adding a twenty-year period after the end of the injection;
- no oil revenues from EOR processes, subsidies, ETS or tax incentives are taken into account since revenues are out of scope of the SiteChar project;
- the techno-economic assessments address only the storage part of the CO_2 Capture and Storage projects and thus exclude transport, capture costs, as well as heat and power costs at the power plant.

Lastly, it has to be noted that some costs were difficult to estimate even for an operator, since no adequate analogue costs are easily available from existing cost databases. In this context, indicating the source of the cost data is important;

2 ECONOMIC ASSESSMENT OF THE UK SITE

The UK site lies offshore in the UK sector of the North Sea, approximately 75 km north-east of the St Fergus gas terminal on the Aberdeenshire coast of Scotland. It is a multi-store site that consists of a saline aquifer sandstone and a hydrocarbon field hosted within it. The project concept is for commercial-scale storage of CO_2 sourced from industrial plant along the eastern coast of Scotland and transported offshore *via* existing oil and gas pipelines from St Fergus to the storage site.

Table 2 summarizes site-specific details of the UK site.

The estimated total discounted cost is 602 M€. It corresponds to an equivalent cost of 11.4 €/t of CO_2 stored as shown in Figure 1.

Key elements of the assessment are the following:

- in terms of equivalent cost, the total cost of the UK storage is 11.4 €/t of CO_2 stored. It corresponds mainly to Capex (60%) related to the large development and water treatment costs;
- setting apart the exploration FEED cost, the UK storage site presents a low exploration cost, mainly due to the cheap access to the data (which are existing data). It is only 4% of the total storage cost;
- half of the storage cost is related to the site development, mainly Capex associated to the platform and the wells. Availability of existing wells does not lower the cost of the site development, since the cost for drilling a new well is considered as the same as the cost for converting a well (25 M€);

TABLE 2

Site specific details of the UK site

Site type	Reservoir type	Project lifetime (year)	CO_2 stored (Mt)	Injection duration (year)	Injectivity (Mt CO_2/year)	Nb. CO_2 injection wells	Nb. water production wells
Offshore	Depleted oil & gas field	40	100	20	5	5	1

- the offshore context of the site impacts the development phase as a new platform (with an estimated cost of 90 M€) is required to support 6 well slots;
- the CO_2 injection cost benefits from the absence of compression and pumping, as for the three other sites, but the water treatment requires a well conversion, also a yearly water treatment cost that amounts to 28% of the total storage cost;
- the monitoring cost is impacted by 27 runs of logging, it is the most important component of the monitoring cost and it is almost three times the cost of the seven 3D seismic surveys.

2.1 Economic Assessment of the Danish Site

The Vedsted site is an onshore saline aquifer in Denmark. It is situated in the northern part of Denmark close to the Nordjyllandsvaerket power plant. The capacity of the storage structure has been estimated between 100 and 160 Mt of CO_2 based on an analysis of existing data.

Vattenfall postponed the Danish project in September 2009 and completely abandoned the project in 2010 due to internal Vattenfall strategy.

Table 3 summarizes site-specific details of the Danish site.

The estimated total discounted cost is 29 M€. It corresponds to an equivalent cost of 3.2 €/t of CO_2 stored as shown in Figure 2.

In terms of equivalent cost computation, the total discounted storage cost, 40% being Capex and 60% Opex, is quite low: this can be explained by the zero injection cost and the effect of discounted cash flow on long term expenditures. The long lifetime of the project (70 years) leads indeed to a strong shortening of the late cash flows.

Key elements of the assessment are the following:

- the site exploration includes the drilling of an exploration well and seismic surveys. They are the main part (36%) of the storage cost;
- the site development includes a work-over to convert the exploration well. As the well injectivity is good only one injection well is necessary. The site development thus constitutes 21% of the total cost;

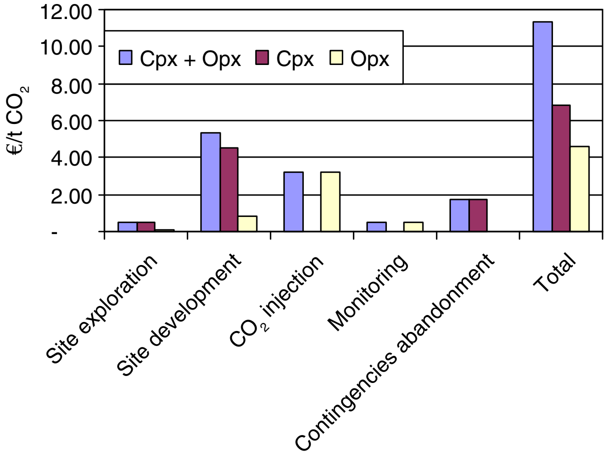

Figure 1

Capex and Opex by phase development at the UK offshore storage site. UK equivalent storage cost.

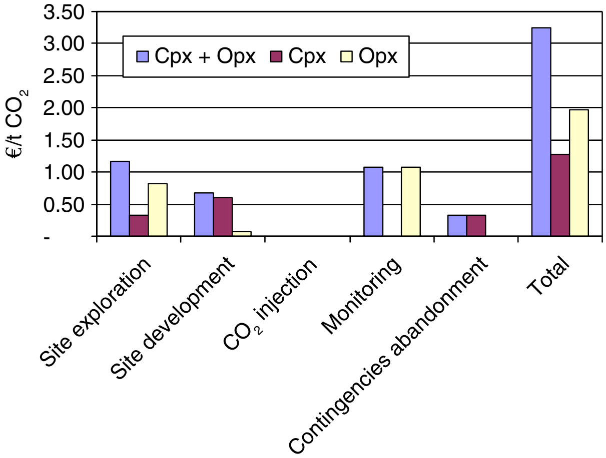

Figure 2

Capex and Opex by phase development at the Danish onshore storage site. Storage costs.

TABLE 3

Site specific details of the Danish site

Site type	Reservoir type	Project lifetime (year)	CO_2 stored (Mt)	Injection duration (year)	Injectivity (Mt CO_2/year)	Nb. CO_2 injection wells	Nb. water production wells
Onshore	Deep saline aquifer	70	60	40	1.5	1	0

TABLE 4

Site-specific details of the Norwegian site

Site type	Reservoir type	Project time life (year)	CO_2 stored (Mt)	Injection duration (year)	Injectivity (Mt CO_2/year)	Nb. CO_2 injection wells	Nb. water production wells
Offshore	Deep saline aquifer	70	40	40	1	1	0

- as for the three other sites, no compression and pumping costs are taken into account. No water treatment and specific well production are considered at this stage, they will be addressed in the sensitivity analysis;
- the 60 years of monitoring (40 years of injection in addition to 20 years of post-injection) required before the transfer of liability to the public explain the high monitoring share (33%) in the storage cost.

2.2 Economic Assessment of the Norwegian Site

The Trøndelag Platform is located east of the Bremstein Fault Complex offshore Mid-Norway. The main target formation is the Garn Formation which has good properties for CO_2 storage.

One injection well is envisaged to inject 1 million tonnes of CO_2 per year into the target formation at a 1 850 m depth below the sea level. Sea depth at the injection site is around 200 to 300 m.

Injection period is assumed to be 40 years. CO_2 is injected into a structural anticline and it is anticipated to stay within the structure.

Table 4 summarizes site-specific details of the Norwegian site. It can be noted that the project setting is quite unusual: it is an offshore virgin area with a total lack of infrastructures. In addition the long project lifetime is very long, *i.e.,* 70 years including 40 years of injection.

The estimated total discounted cost is 160 M€. It corresponds to an equivalent cost of 26.6 €/t of CO_2 stored as shown in Figure 3.

Key elements of the assessment are the following:

- in terms of equivalent cost computation, the total storage cost (26.6 €/t of CO_2 stored) is mainly Capex (90%). Only 10% is Opex;
- the discounted site exploration cost (81 M€) is mainly driven by the exploration well and the FEED cost. The site exploration is the most important component of the storage cost; it represents half of the total;
- the discounted site development cost (30 M€) is mostly related to the construction of the sub-sea platform required by the lack of any existing infrastructure. The exploration well will be converted into an injection well. No production well is taken into account;
- the discounted injection cost is low (2 M€). It is mainly due to the well maintenance. The cost of the liability transfer that will occur in 2080 is strongly discounted and has thus minor impact on the injection cost. No compression, pumping or water management is considered;
- the discounted monitoring cost (7 M€) is totally Opex. It is mainly related to 3D seismic surveys that are planned every 5 years during 40 years. Temperature and pressure monitoring cost are considered negligible.

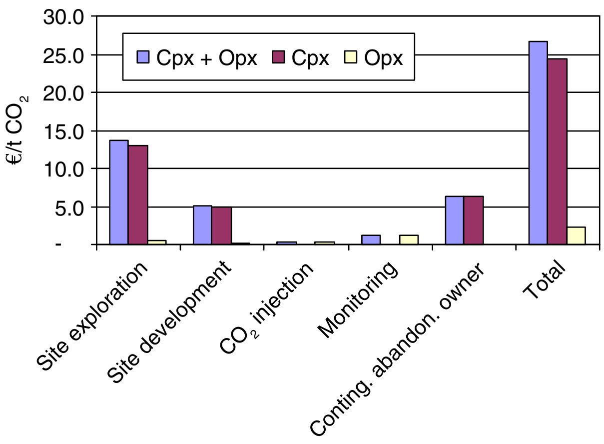

Figure 3

Discounted Capex and Opex by phase development at the Norwegian offshore storage site. Storage costs.

2.3 Economic Assessment of the Italian Site

The South Adriatic site consists of a structural trap in a carbonate saline aquifer, close to the main Italian CO_2 emission power plant in Brindisi where *Enel* started a pilot plant for CO_2 capture in April 2010. It is one of the biggest power plants in Italy, characterized by very high CO_2 emissions value (more than 15 Mt/year in 2004 – the highest emission rate in Italy).

Currently, there is no precise plan for CO_2 storage in this area. However, a techno-economic analysis has been conducted simulating a hypothetical scenario of CO_2 injection.

The storage complex of the Southern Adriatic site is a carbonate aquifer located in the foreland of the Apennines-Dinarides orogenic belts.

TABLE 5

Site-specific details of the Italian site

Site type	Reservoir type	Project timelife (year)	CO_2 stored (Mt)	Injection duration (year)	Injectivity (Mt CO_2/year)	Nb. CO_2 injection wells	Nb. water production wells
Offshore	Saline aquifer	40	10	10	1	1	0

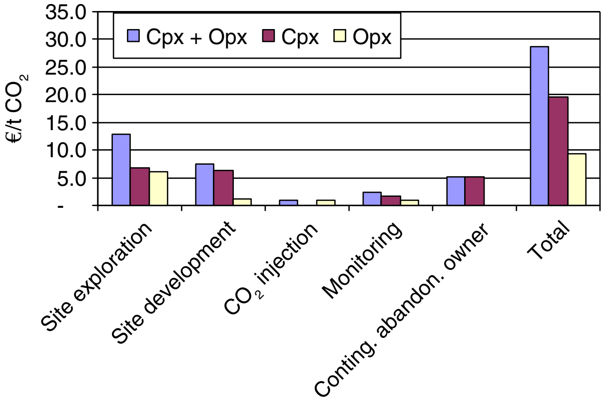

Figure 4

Discounted Capex and Opex by phase of development at the Italian storage site. Storage costs.

Table 5 summarizes site-specific details of the Italian site. It can be noted that the project setting is quite unusual: this is, as for the Norwegian site, an offshore virgin area, but here, the small scale of the project, the short duration of CO_2 injection associated with a low injection rate, increase dramatically the cost per tonne of CO_2 stored at a level comparable to a demo project.

The estimated total discounted cost is 97 M€. It corresponds to an equivalent cost of 28.8 €/t of CO_2 stored as shown in Figure 4. This high cost corresponds to a project which is more similar to a demonstration than to an industrial one.

Key elements of the assessment are the following:

- in terms of equivalent cost computation, the total cost of the storage is 28.8 €/t of CO_2 stored. 68% are Capex and 32% Opex;
- the site exploration cost represents half of the storage cost; it is the most important part of the storage cost. The 43 M€ costs related to the site exploration are expensive but realistic since this amount includes the drilling of a well;
- because of the need for the development of a platform, the site development is the second share of the total storage cost (26%), although the conversion of the exploration well into a CO_2 injection well. No work-over cost is included for the well conversion. Considering the large uncertainty of the well injectivity, a second injection well however might be necessary;
- as for the three other sites no compression or pumping is considered. No water production is envisaged. The only cost involved in the injection phase is thus the maintenance for wells and infrastructure (10 M€) that is spread on the 10 years of injection;
- monitoring represents 8% of the total storage cost. Most of the costs are Capex (68%) due to field development (platform and boreholes).

3 COMPARISONS WITH ZEP (EUROPEAN TECHNOLOGY PLATFORM FOR ZERO EMISSION FOSSIL FUEL POWER PLANTS) COSTS

In terms of storage costs, the technical and economic assessments conducted by ZEP (2011) serve as a reference (the Costs of CO_2 Storage, post-demonstration CCS in the EU – IEA GHG/ZEP – 2011). They are based on the 2010 work performed by *Mac Kinsey* consulting firm and contributions by IEAGHG.

The range of storage costs is quite wide: it varies from 1 to 20 €/t of CO_2 stored. This extreme variability is tied to the different types of possible reservoirs and the highly variable injectivity of wells. Uncertainty with regard to basic costs is a minor but yet contributing factor.

Figure 5 displays the median cost and the range of minimum and maximum costs in € per tonne of CO_2 stored, depending on the type of storage. Six classifications of storage are distinguished:

- Onshore (Ons) *vs* Offshore (Offs) sites,
- Depleted Oil or Gas Field reservoirs (DOGF) *vs* Saline Aquifers (SA),
- sites with Legacy wells (Leg) *vs* without Legacy wells (NoLeg).

In summary, the ZEP report points that:

- onshore storage is less expensive than offshore, since no platform is required and drilling is cheaper;
- storage in a depleted oil or gas field is less expensive than in a saline aquifer, since the oil or gas fields have already been explored and have existing wells that might be re-used;

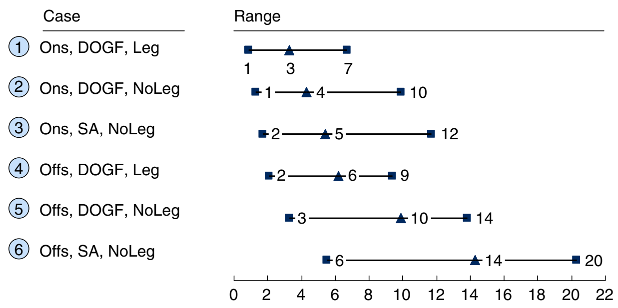

Figure 5

Storage cost ranges in €/t of CO_2 stored by storage type, with uncertainty ranges (ZEP, 2011). See text for abbreviations.

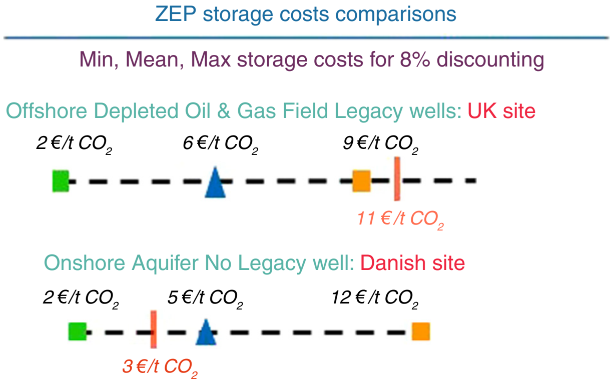

Figure 6

SiteChar UK and Danish sites estimated storage cost (red bars) compared to minimum (green squares), mean (blue triangles) and maximum (orange squares) ZEP estimations.

- the highest storage costs and the greatest variability in storage costs are associated to offshore saline aquifers, for which limited data is available.

Figure 6 compares the estimated SiteChar costs with the ZEP range of costs, excluding for the Italian and the Norwegian sites, rather comparable to a demo project due to short duration of the CO_2 injection and low injection rate.

For consistency, the most important common assumptions applied across the ZEP study on storage cost estimates are summarized below:

- project lifetime: assumed to be 40 years of injection for commercial projects and 25 years for demonstration projects, followed in both cases by 20 years of post-injection monitoring, before hand-over of liability to the competent authority;
- CO_2 stream: annual storage rate of 5 Mt (5 million metric tonnes). This corresponds to the CO_2 emissions of a typical coal-fired power plant equipped with CO_2 capture. Variation of this rate has not been modeled explicitly.

The UK is slightly above the upper limit of the ZEP estimation. Although this site is in a hydrocarbon area, it does not benefit from suitable infrastructure. It is served by a floating installation shared with another field, and a platform costing 90 M€ is necessary.

The onshore case (Denmark) is close to the mean value for onshore storage in saline aquifer without legacy well.

4 LESSONS LEARNT FROM THE SITECHAR ASSESSMENTS

Table 6 summarizes the ESC for a discount rate of 8% for the four SiteChar sites.

Comparison between the different sites estimations raises the following issues:

- storage capacity. It might be surprising to note that the site with the highest storage capacity is the UK depleted oil and gas field and saline aquifer although the injection strategy has yet to be optimized to maximize the storage capacity. This may be explained by the fact that quite a large amount of data is available whereas for the other sites the characterization has been conducted based on low-case capacity scenarios, for sake of prudence. This specific feature of the sites panel has to be taken into account when comparing in €/t of CO_2 stored the sites;
- site exploration. The exploration cost of the Danish onshore site is lower than those of the offshore sites, except for the UK site. Amongst the offshore sites, the UK site has the cheapest exploration cost since this site has already been explored in contrast to the Norwegian and Italian sites that are in virgin areas;
- site development. The development cost of the Danish onshore site is lower than those of the three offshore sites. It has no FEED costs and just a well work-over costing 8 M€. The development costs for the three offshore sites (between 5 to 7.5 €/t CO_2) mostly benefit from an existing exploration well which is converted to a CO_2 injection well, but these offshore sites require a platform or subsea development. In addition, wells are much more expensive offshore than onshore;
- CO_2 injection. Without any cost associated with compression and pumping, the total injection cost for all sites is very low: zero for the Danish site and 2 and 3 M€ for the Norwegian and Italian sites, respectively, that both take into account the injection well maintenance. Indeed, the injection period planned for the Danish site is 20 years, which corresponds to the lifetime of a well so that no well maintenance should be necessary.

TABLE 6

Summary of the estimated costs for the four SiteChar sites. Cost values presented in M€ and €/t of CO_2 stored.

Site	Type	Storage capacity (Mt CO_2)	Site exploration	Site development	CO_2 injection	Monitoring	Contingencies and abandonment	Total
UK	Offs, DOGF, Leg	100	28 M€	283 M€	170 M€	28 M€	93 M€	599 M€
			0.53 €/t	5.33 €/t	3.20 €/t	0.53 €/t	1.76 €/t	11.4 €/t
Denmark	Ons, SA, NoLeg	60	10 M€	6 M€	0 €	9.6 M€	3 M€	29 M€
			1.2 €/t	0.7 €/t	0 €/t	1.1 €/t	0.3 €/t	3.2 €/t
Norway	Offs, SA, NoLeg	40	81 M€	30 M€	2 M€	7 M€	38 M€	159 M€
			13.7 €/t	5.1 €/t	0.36 €/t	1.2 €/t	6.3 €/t	26.6 €/t
Italy	Offs, SA, NoLeg	10	43 M€	25 M€	3 M€	8 M€	17 M€	97 M€
			12.9 €/t	7.5 €/t	1 €/t	2.3 €/t	5.1 €/t	28.8 €/t

Onshore, Ons. Offshore, Offs. Depleted Oil or Gas Field reservoirs, DOGF. Saline Aquifers, SA. Sites with Legacy wells, Leg. Site without Legacy wells, NoLeg.

The injection period planned on the Norwegian site (40 years) is higher so that some well maintenance will be necessary. The suggested well maintenance on the Italian site might be surprising since the planned injection period is only 10 years. In fact, the duration of the injection is in accordance with the duration of a pilot project and was agreed with the industrial partner of the project, however a longer injection duration would be recommended for a more conservative estimate. The injection period for the UK site is 20 years so that no well maintenance has been planned. However, water production and treatment is here taken into account to mitigate overpressure. This explains the relative high cost of the CO_2 injection phase on the UK site;

- monitoring. The monitoring cost of the offshore UK site is three times higher (28 M€) than for the over sites. This UK monitoring site has actually a detailed monitoring program, as required for the dry-run storage permit application that includes many monitoring geophysical logging runs. Except the Italian site, the other sites present a more simple monitoring plan costing between 7 and 10 M€. Relative to the amount of CO_2 stored the range of cost can double, from 1 €/t CO_2 for the Danish and Norwegian sites to 2.3 €/t of CO_2 for the Italian site;
- contingencies and abandonment. These costs reflect the importance of Capex in the total storage cost. The UK site that considers a 90 M€ offshore platform and 6 wells has the biggest contingencies and abandonment cost, while the onshore site in Denmark has the lowest one, which could be questioned;
- total. SiteChar assessments lead to a wide spread of cost from 3 to 30 €/t CO_2 stored, reflecting a very site-dependent cost. Highest costs are linked to offshore sites and low amount of CO_2 stored (due to low injection rate or short duration of the storage) but it must be noticed that a huge uncertainty is also attached to these costs due to the bottom-up approach used and early stage of these project and the scope of the analysis.

5 UNCERTAINTIES AND SENSITIVITY ANALYSIS

To calculate a storage cost, the costs of basic operations on the storage site are added together in a ‘bottom-up’ method. This approach raises the question of whether all basic costs have been taken into account as pointed out above; this might result in an uncertainty of +/−30% to 50% in the final result. As well known, the parameters that influence the total cost of storage include:

- *the site storage capacity.* Just as the reserves in oil or gas fields can be classified as proven or possible, there is a great deal of uncertainty tied to the total capacity of a storage site. The reservoir capacity is estimated using reservoir models and flow pressure simulations. For depleted oil and gas and reservoir, there are quite a lot of data to constrain the storage capacity, but for deep saline aquifer, the storage capacity will have to be refined as new data become available. In particular, the uncertainty on the storage capacity of the Norwegian and Italian sites is quite high at this stage of the characterization;
- *the injection rate or well injectivity.* A single rate is generally used for the entire site. In reality, the rate varies from one well to another based on petrophysical properties and permeability; it might also vary over time due to the formation of hydrates, for example. This issue has not been tackled in the SiteChar sites characterization;

- well completion. In addition to drilling costs, the cost of completing a well is considered highly variable (+/−50%) by the ZEP (2011). This is illustrated by the quite large range of values used in SiteChar;
- additional wells. ZEP (2011) estimation considers observation wells. However these wells, generally shallower than the reservoir and with a limited diameter, have a relatively low impact on costs, particularly when existing wells are re-used. A shallow borehole is for instance envisaged on the Italian site, but, as a default value, the cost associated with drilling was assumed equivalent to the cost for an injection well;
- water-producing wells. The number of such wells and the quantity of water they produce might generate high costs for water treatment and reinjection. Water production is required to mitigate overpressure in the UK site. This is also an option for the Danish site in the case overpressure management is required. This might in fact be the case for any CO_2 storage in an aquifer. The solution investigated in SiteChar is to produce water which can be discharged into the North Sea subject to regulatory restrictions related to the amount of oil in the produced water. As seen on the UK site, the water treatment is a significant part of the storage cost but it is not prohibitive. Such a solution for overpressure mitigation could be envisaged in any country which has a sea frontier. For other countries, CO_2 storage in depleted hydrocarbon fields might be the only cost-effective solution as hydrocarbons are more compressible than water and pressure relief by water production may not be needed;
- well life cycle. Wells have a limited life span which is generally estimated at around 20 years. Additional investments are then required for work-over and drilling operations. This issue has not been tackled in SiteChar;
- storage monitoring. Regulations require a monitoring plan for the delivery of a storage permit. This phase might be very complex: it might vary over time with different phases such as the injection period and the long-term post-injection period. It might require many runs of data acquisition and processing ranging from seismic data (2D, 3D, well seismic surveys, etc.) to geochemical data. Another option is to use permanent survey installations that allow cost reduction and better data quality due to enhanced measures repeatability. The SiteChar project presents quite a large variety of monitoring plans including 2D and 3D seismic surveys, 3D VSP acquisition as well as permanent survey installations and logging. Each monitoring program is site dependent and requires site-specific methods and time intervals for 3D seismic acquisition.
- the discount rate. It has a significant impact on the total net discounted value of a project, since storage is a long-term endeavor (40-100 years until the transfer of responsibility). *The cost of withdrawing from the site and contingencies.* In the ZEP (2011) study, these factors are assumed at 15% and 20% of Capex, respectively, which is common in technical economic assessments for contingencies;
- the transfer of responsibility for the site to the government. It is quoted as a cost per tonne of CO_2 stored. Due to a lack of information, national regulations, or knowledge, this rate is a hypothetical value set at around 1 €/t of CO_2 stored.

6 SENSITIVITY ANALYSIS

A sensitivity analysis is conducted on both generic and site-specific parameters of the SiteChar sites so as to infer the crucial elements that govern the storage costs.

The reference economic parameters are identical for all sites:

- discount rate equal to 8%,
- contingencies equal to 20% of Capex,
- abandonment cost equal to 15% of Capex,
- owner expenses equal to 0.

The reference technical parameters are summarised in Table 7 for each site.

The results of some of the various sensitivity tests which have been conducted are presented in the following Tables 8 to 10 (sensibility analysis for the four sites, reference parameters are in yellow):

Table 8 shows the sensitivity to the discount rate of the ESC, *i.e.* discounted storage cost divided by the discounted amount of CO_2 stored, at different discount rates (0%, 8% and 12%) for the four sites. Overall, the cost per tonne of CO_2 stored increases with the discount rate, but the increase is smaller from 8% to 12% than from 0% to 8%. The change associated to the change of the discount rate is highly dependent on the characteristics of each individual site.

Table 9 shows the sensitivity of the ESC with contingencies (20% and 40%) and the % change with each increase in contingencies at each of the four sites. Overall, the ESC increases with the contingencies values. The % change is again highly dependent on the characteristics of each individual site but can be considered as not a key issue.

Table 10 shows the sensitivity of the ESC for site specific options and the % change with each increase in rate at each of the four sites.

Although the options tested are quite different between the sites, the weight of injection rate appears clearly as a common key parameter. However, for the Norwegian site as assessments on the investment required to increase of the injection rate have not been done, it has been impossible to evaluate the likely decrease of the storage cost for this site.

TABLE 7

Data summary of the reference technical parameters for each site>

	UK	Denmark	Norway	Italy
ZEP type of site	Offs, DOGF, Leg	Ons, SA, NoLeg	Offs, SA, NoLeg	Offs, SA, NoLeg
Project time life (years)	40	70	40	70
Mt of CO_2 stored	100	60	40	10
Injection duration	20	40	40	10
Injectivity per well (Mt CO_2/year)	1	1.5	1	1
Number of injection wells	5	1	1	1
Number of production wells	1	0	0	0
Equivalent cost 8% discounting (€/t of CO_2 stored)	11.4	3.2	26.6	28.8

TABLE 8

Sensitivity of the ESC to the discount rate>

ESC €/t CO_2	0%	8%	12%	Delta 0% to 8%	Delta 8% to 12%
UK	7.4	11.4	13	35	14
Denmark	1.7	3.2	5.1	47	59
Norway	6.8	26.6	50.8	74	91
Italy	14	29	42	52	45

TABLE 9

Sensitivity of the ESC to the contingencies>

ESC €/t CO_2	Contingencies 20% Capex	Contingencies 40% Capex	Delta %	Capex %
UK	11.4	12	5	62
Denmark	3.2	3.4	6	40
Norway	26.6	30.2	40	90
Italy	29	32	10	60

TABLE 10

Sensitivity of the ESC to some specific options:
UK: injection rate divided by 2, injection duration multiplied by 2, 3 injection well instead of 5, water production divided by 2;
Denmark: water production with one water production well;
Norway: injection rate divided by 2;
Italy: injection duration multiplied by 2>

ESC €/t CO_2	Base case	Option	Delta %
UK	11.4	14	23
Denmark	3.2	4	25
Norway	26.6	53	99
Italy	29	20	-31

CONCLUSIONS/DISCUSSIONS

Economic assessments of the four SiteChar sites confirm the main common characteristics on storage costs:

- location and type of field (available knowledge and re-usable infrastructure), reservoir capacity and quality are the main determinants for costs:
  - per unit volume injected, onshore storage is cheaper than offshore. This is clearly illustrated on the studies conducted in SiteChar. The Danish site is by far the cheapest storage option, each phase of the project being cheaper than those of the offshore sites;
  - storage in depleted oil and gas field is cheaper than storage in deep saline aquifers. Among the offshore sites, the UK site has a relatively low exploration cost. However the exploration cost of the Danish site is even lower. This is due to the fact that the Danish site is an onshore aquifer and has in addition already been investigated;
  - larger reservoirs have a lower unit-cost than smaller ones. This is clearly observed on the UK and Danish sites: the total discounted cost is by far the highest, but the equivalent cost is low due to the large storage capacity. It is also clear from the estimation of the Italian site that, even if the total discounted cost is relatively low, a limited storage capacity makes the equivalent cost high;
- high pre-FID (Final Investment Decision) costs for deep saline aquifers reflect the higher need for exploration compared to depleted oil and gas reservoirs and the risk of spending money on exploring aquifers that are ultimately not suitable. A risk-reward mechanism must therefore be put in place for companies to explore the significant deep saline aquifers potential in Europe. Clearly, it appears that the site exploration phase for the UK oil and gas depleted reservoir site is only 4% of the total cost whereas, for the other sites that are all saline

aquifers, it is 36% for the Danish site and around 50% for the two other sites;

- well costs are approximately 40-70% of total storage costs and the resulting large cost ranges (up to a factor 10) are driven more by (geo)physical variations than by the uncertainty of cost estimates. The cost of wells is actually a major factor of the costs of each storage site estimated in SiteChar. In addition, even if there are existing wells, the cost for converting a well is far from negligible, as noted on the UK site;
- there is a need to develop exploration methods that will increase the probability of success and/or lower the costs of selecting suitable storage sites.

The four SiteChar techno-economic evaluations confirm it is not possible to derive any meaningful average cost for a CO_2 storage site. The results demonstrate that the structure of costs for a CO_2 storage project is very heterogeneous and the storage cost is consequently very site dependent. The strategy of the site development is fundamental, the technical choices such as the timing, rate and duration of injection are also important. The way monitoring is managed, using observation wells and logging has a strong impact on the estimated monitoring costs. Options to lower monitoring costs, such as permanent surveys, exist and should be further investigated.

The difference in estimated costs for each of the sites is due to the site's location (onshore/offshore), the amount of CO_2 stored, the injectivity of the wells, the number of CO_2 injection and water production wells, and the possible necessity for water production and treatment. Moreover, at each site, the seismic monitoring plan includes many types of survey, used in distinct ways and with various frequencies.

Main uncertainties in the costs are not linked to the data themselves but rather to the choice of economic parameters (discount rate, contingencies) and to the technical choice of operations. They have been addressed by a sensitivity analysis. It has been shown that a halved an injection rate and a doubled injection duration increases the storage cost by 23%. Including a water production well and water treatment increases the storage cost by 23%.

Techno-economic assessments were carried on using an 8% discount rate. For projects of long lifetime such a rate hardly discounts the late cash flow, especially after 40 years, so that a discount rate of around 4% could be advisable. Compared to other studies, it has to be noted that the scope of the SiteChar analysis does not consider compression and pumping cost, nor transportation cost. This simplifies the techno-economic evaluation but it also restricts the use of the results which have to be compared with the same perimeter of analysis.

Lastly, techno-economic evaluation poses questions to policy makers about the real lifetime of a CO_2 storage project: what should be the abandon phase and the associated cost and what is the real value of the liability transfer after 20 years of storage? This issue is still an open question, which has been solved in SiteChar using the same approach as ZEP (2011).

To counterbalance the CO_2 storage cost, policy makers have to set up incentives, either through the ETS, tax credits or public funding. Enhanced Oil Recovery must be taken into account in the regulation of CCS, as it is one the rare possible opportunities for revenue. Even CO_2 storage in saline aquifer storage might be considered as a source for CO_2 EOR in close proximity to oil and gas fields.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 256705 (SiteChar project) as well as from *Enel*, *Gassnova*, *PGNiG*, *Statoil*, *Vattenfall*, *Véolia Environnement*, and the Scottish Government.

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Manuscript submitted in December 2013
Manuscript accepted in December 2014

Cite this article as: J.-F. Gruson, S. Serbutoviez, F. Delprat-Jannaud, M. Akhurst, C. Nielsen, F. Dalhoff, P. Bergmo, C. Bos, V. Volpi, and S. Iacobellis (2015). Techno-Economic Assessment of Four CO_2 Storage Sites, *Oil Gas Sci. Technol* **70**, 4, 753-766.