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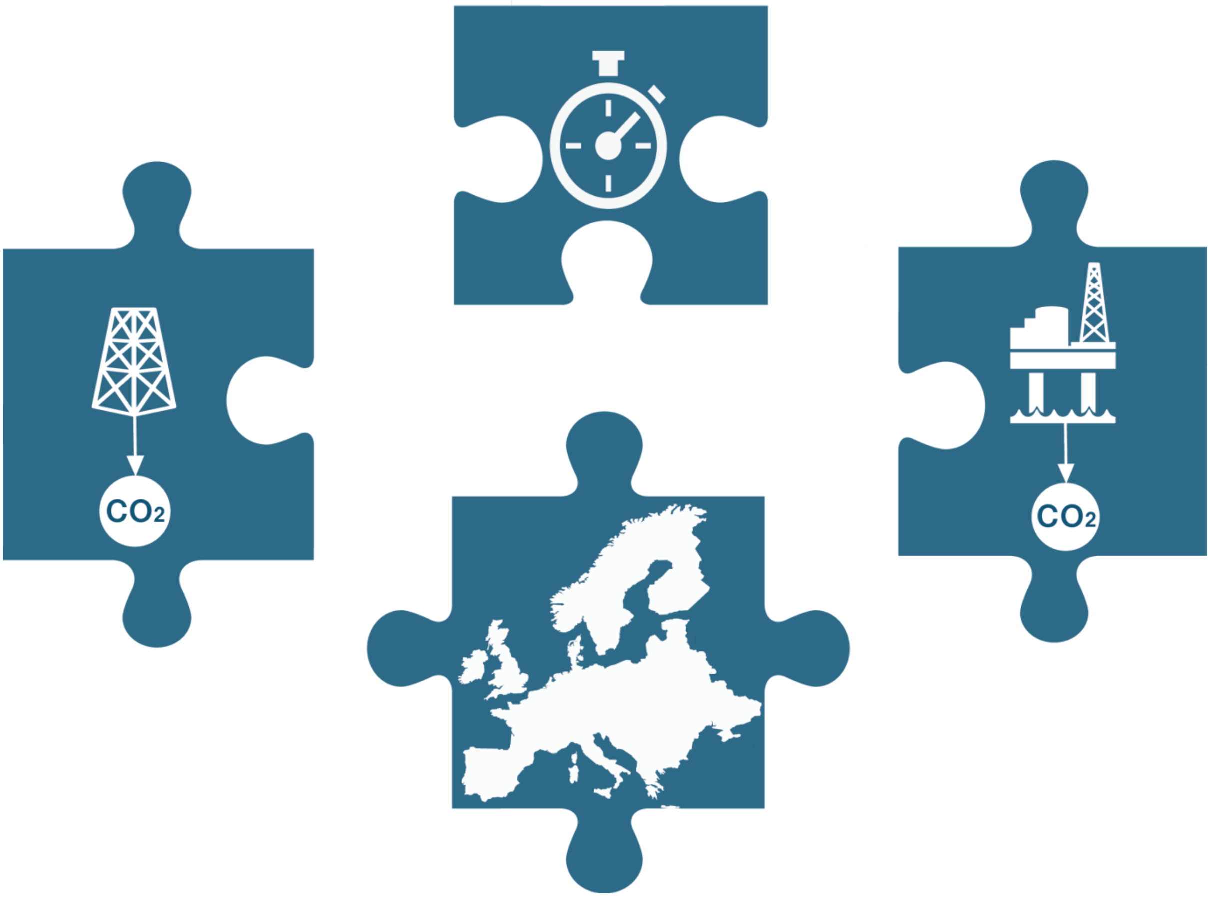
Scaling the CO_2 storage industry: A study and a tool

A study of the CO_2 storage industry in Europe to 2050 – and a tool to measure its feasibility, the requirements and the bottlenecks.



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This publication has been prepared by Bellona Europa to fuel the debate in Europe on the necessity of Carbon Capture and Storage (CCS) in reducing CO2 emissions from energy and industry cost-effectively. In particular, it examines the required CO2 storage capacity in Europe to 2050 that would be necessary to enable the deployment of CCS.

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BELLONA ENVIRONMENTAL CCS TEAM

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EXECUTIVE SUMMARY

Carbon capture and storage (CCS) is a critical technology in reducing CO_2 emissions from energy and industry. The Intergovernmental Panel on Climate Change (IPCC) estimates that the cost of the necessary emissions reductions would more than double without CCS. A failure to deploy CCS would thus be a failure to avoid a warming world.

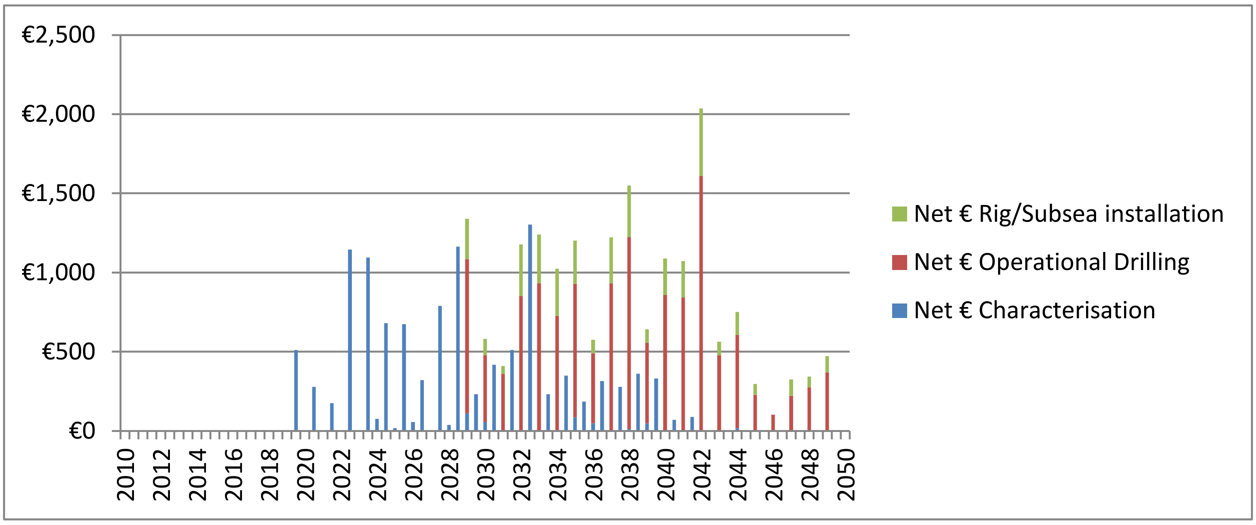
The availability of CO_2 storage is the linchpin of CCS deployment. A lack of storage capacity could render CO_2 capture futile, and in the worst case could discourage investments in CCS projects. A CO_2 storage industry that can match the scale of the oil and gas sector will therefore be necessary to enable the necessary scale of CCS deployment.

This report takes a look at the practicalities of developing CO_2 storage in Europe and answers three key questions:

1. What is the rate at which CO_2 storage needs to be developed for CCS to be deployed and climate goals met?
2. Is the nascent CO_2 storage industry capable of scaling up quickly?
3. What are the requirements of a CO_2 storage industry?

Bellona has built a simple yet robust model to answer these questions and give insight into the broad lines of the future scale of CO_2 storage activities. It examines storage scenarios for onshore and offshore storage in saline aquifers, depleted oil and gas fields, and for enhanced oil recovery (EOR). The model uses storage data and the anticipated CO_2 captured each year to measure the necessary CO_2 storage capacity to be deployed throughout Europe. It does so "just in time" and for "just enough" CO_2 storage to meet set targets.

The study finds that **annual investments in the range of €500 million need to begin by 2020, and increase rapidly into the 2020s, if we are to deliver the storage capacity required by the CCS projects operating in the 2030s** and beyond (see figure). The first large scale investments in commercial storage should take place in 2019. This finding shows that what some consider early deployment is in fact timely deployment if we are to reach EU Energy Roadmap 2050 goals. There is therefore a clear and urgent need to have a functioning investment environment for both CCS and CO_2 storage operators starting within the next five years. A robust policy framework must therefore be assured as soon as possible.



Annual investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). Reference scenario

The study also finds that the scale of the CO_2 storage industry will be large. Both in terms of material and human resources, **storage operations will be on par with the current oil and gas industry**. This could lead to a 'competition' for resources between 'carbon emitters' and 'carbon sequesters', which may delay growth of the storage industry. But it also affords Europe an opportunity to develop a huge new industrial sector that tackles climate change and provides thousands of jobs.

Regarding requirements of a storage industry, injectivity – the rate at which a well can inject CO_2 into a suitable storage site - is found to be as critical as storage capacity. **Lower injectivity could result in a doubling of the cost and scale of CO_2 storage deployment.** The role injection capacity plays in realising CCS is often underestimated. More effort is therefore needed to quantify the injectivity of prospective CO_2 storage sites.

The importance of injectivity is made even clearer by the finding that **most storage will likely take place offshore**. This reflects political and planning constraints that exist in Europe, but also the potential: Europe is fortunate in having a huge offshore CO_2 storage resource. Costs are generally higher offshore than onshore as greater demands are placed on characterisation and drilling. As reduced injectivity increases the required injection wells, an offshore scenario will have an even greater effect on CO_2 storage cost. Appropriate funding mechanisms for full-scale CCS as well as concrete investments in storage site development must therefore be a matter of policy priority.

CONTENTS

THE QUESTIONS

The rate of CCS deployment can be severely restricted by the availability (or lack) of CO_2 storage capacity. But a CO_2 storage industry at the scale of today's oil and gas sector, could catapult the necessary CCS deployment needed from both power generators and industrial producers. How much CO_2 storage capacity will be needed, what rate of injectivity (the capacity and ability of a well to receive injection) will be required and how much human, material, logistical and capital effort will be required to achieve this?

This study models, under diverse scenarios, the characterisation and deployment of CO_2 storage in Europe to 2050. It aims to answer the following questions:

- How large will the CO_2 storage business need to be?
- How many wells will be drilled and when?
- How much seismic will be shot and when?
- What injectivity/wellcount will be required to satisfy demand?
- When must characterisation begin and when will it peak?
- What are the bottlenecks to providing storage?
- Is European CO_2 storage development on target?
- What will the scale of activities be when compared to the present oil and gas activities?
- Will CO_2 storage be scalable and what are its requirements?
- What contribution will Enhanced Oil Recovery (EOR) make?

THE METHOD

Building a simple but robust model

Bellona has constructed an Excel-based model to investigate the practical deployment mechanics of CO_2 storage in Europe. The model aims to avoid being overly prescriptive or complex. It is impossible to predict the future, let alone model what activities will take place towards 2050. But the model is constructed to give insight into the broad lines of the future, the scale of CO_2 storage activities and identify the sensitivities of each of the CO_2 storage industries components. The key performance indicators may be identified under a range of scenarios for an EU-wide CO_2 capture rate, the type of storage capacity to be deployed and the geological characteristics of the storage site.

This model examines the large-scale feasibility of CO_2 storage deployment in Europe. Taking a bottom-up quantitative approach, it aims to provide a tangible and concrete picture of the steps and scale of transformation necessary to realise storage in European conditions. The model provides insight into what efforts are needed in the storage sector -what technologies and policies are most critical - and will aim to identify the critical variables. As an example, it is already becoming clear that on a practical level the rate of sustained injection rates is more important than the gross storage volumes provided.

Key variables for the function of the model

- The rate and cumulative CO_2 captured in the EU to 2050
- The types of CO_2 storage sites developed
  - Aquifer (onshore/offshore)
  - Depleted hydrocarbon (onshore/offshore)
  - Hydrocarbon and EOR (onshore/offshore)
- The storage capacity provided
- The injectivity of storage complexes
- The injectivity of wells
- The inputs required to develop the necessary CO_2 storage/injection capacity
  - Time taken to characterisation
  - 2D & 3D seismic necessary
  - CO_2 needed for injection testing
  - Drilling for both characterisation and injection wells
  - Civil works and other infrastructure

Goals for the model

- Simple
- Transparent
- Easily modifiable
- Extensive sensitivity analysis options

METHODOLOGY AND ASSUMPTIONS

A desk-based assessment has been undertaken in order to balance expert opinion on the multitude of points that must be considered to assess the overall feasibility of CO_2 storage development. This is also the case for the assessment of the potential of CO_2 EOR to facilitate CO_2 storage development. This study presents a meta-analysis of a handful of the most reliable sources in the research literature and in doing so examines the central questions posed.

Working assumptions

1. A business case for CCS exists – i.e. that there is a strong and sustained financial incentive to deploy the technology;
2. All non-technical challenges, such as public acceptance and financing, can be overcome.

The report takes a candid look at:

1. The total cumulative amount of CO_2 that will need to be stored;
2. The location and availability of CO_2 storage capacity in Europe;
3. The location, availability and suitability of CO_2 EOR candidate fields in the North Sea Basin (NSB);
4. The scale of activities necessary to develop this storage, including characterisation and drilling;
5. The scale of activities necessary to develop CO_2 EOR projects, including characterisation and drilling;
6. The transportation infrastructure needed to move CO_2 from its source to theoretical storage complexes and identified potential CO_2 EOR sites;
7. A realistic timeline for the development of all necessary infrastructures in the value chain, factoring in any timing interdependencies that may exist;
8. Storage site monitoring and maintenance requirements until closure;
9. The total investment cost associated with the above.

Cumulative CO_2 storage volumes

In terms of CO_2 storage volumes, this report assumes that the overarching goal is to limit global temperature rises to 2°C at the lowest cost. With this as a guiding principle, roadmap studies provide a useful indication of the scale of CCS deployment that can be expected in the future – and hence the needed cumulative CO_2 storage volumes.

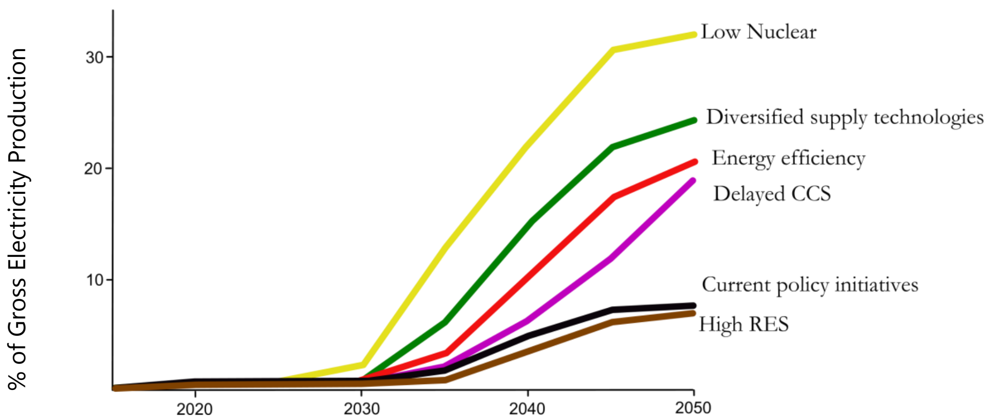


Figure 1 EU Energy Roadmap 2050 - Scenarios of contribution of CCS to decarbonisation

This report takes a closer look at two scenarios from the EU's 2050 Energy Roadmap (Figure 1) as the basis of its calculations:

1. The 'low nuclear' scenario shows that CCS will need to account for 32% of gross power generation in the EU by 2050 - a total of 248 GWe of installed capacity (79 GWe on solid fuels and 169 GWe on gas).
2. On the other hand, the 'RES' scenario shows that CCS will need to account for 7% of gross power generation in the EU by 2050 - a total of 53 GWe of installed capacity (18 GWe on solid fuels and 34 GWe on gas).

Together, the scenarios of the 2050 Roadmap result in the cumulative CO_2 storage volumes by 2050 shown in the table below (Table 1), where the figures for the three selected scenarios (Reference, RES and Low nuclear) are highlighted. The total captured CO_2 toward 2050 of these three scenarios is plotted to 2050 on a curve (Figure 2). Assumptions here include the rate of deployment of CCS and start date of CO_2 capture. In Figure 2 a simple linear extrapolation from 2025 of the EU Energy Roadmap 2050 data has been used to estimate CO_2 storage per year to 2050. The data can be plotted to other curves, for example showing that delayed CCS development will lead too much of the storage requirements being deployed rapidly at the end of the period.

Table 1: Cumulative CCS storage needs (billion tonnes of CO_2) for power generation and industrial processes up to 2050. No details are provided on the ramp-up of storage in these scenarios. (2050 Energy Roadmap)

	Power generation (Gt)	Process related (Gt)	Total captured CO_2 (Gt)
Reference	7.95	0.00	7.95
CPI	3.00	0.00	3.00
Energy efficiency	4.08	1.52	5.59
Diversified supply tec	6.80	2.18	8.98
RES	1.77	1.72	3.50
Delayed CCS	4.06	0.62	4.68
Low nuclear	10.45	2.35	12.80

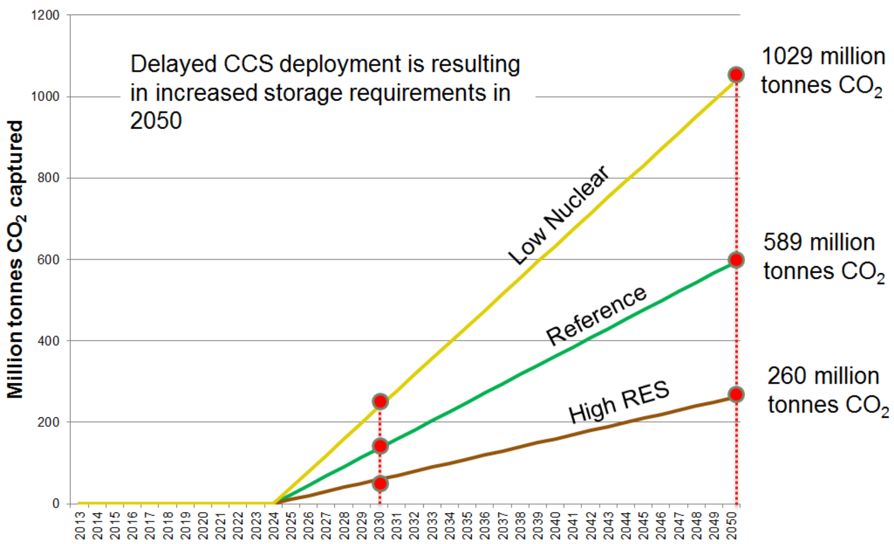


Figure 2 Linear extrapolation of EU Energy Roadmap 2050 CO_2 captured with start date at 2025, and hence CO_2 stored

Other CO_2 capture forecast to 2050 may also be used in this model. A forthcoming report from the European Technology Platform for Zero Emission Fossil Fuel Power Plants ('Zero Emissions Platform' - ZEP) in cooperation with the Norwegian University of Science and Technology (NTNU) will provide detailed and alternative CO_2 capture estimates to 2050.

Type and availability of CO_2 storage capacity

The evaluation of discovered and undiscovered storage resources is restricted to the six categories that are most relevant in Europe:

1. Onshore EOR
2. Offshore EOR
3. Onshore depleted oils and gas reservoirs
4. Offshore depleted oils and gas reservoirs
5. Onshore deep saline formations
6. Offshore deep saline formations

- A numerical distribution is set for the preference of deployment of potential storage categories.

These simplified CO_2 storage categories may be modified in a number ways, enabling extensive sensitivity analysis and the identification of key performance indicators (KPIs). In the case of traditional storage characterisation and development (categories 3 – 6), the primary variables include the anticipated storage capacities and injectivity.

- Numerical distribution of CO_2 storage capacity of developed storage sites
- Numerical distribution of CO_2 injection capacity of developed storage sites
- Numerical distribution of CO_2 injectivity per well of developed storage sites

Both onshore and offshore EOR projects (categories 1 – 2) are dependent on variables associated with original oil in place for EU reservoirs, oil recovery projections and the efficiency of incremental oil recovery due to CO_2 flooding.

- Numerical distribution of the original oil in place (OOIP) at developed EOR sites
- Mean anticipated incremental oil recovery as a percentage of OOIP
- Numerical distribution of the incremental oil production efficiency with CO_2 flooding at developed EOR sites
- Numerical distribution of CO_2 injectivity per well of developed storage sites
- Mean years of operation for a CO_2 EOR flood

Methodology for deployment of storage sites

The model automatically deploys necessary CO_2 storage capacity throughout Europe using the "just-in-time" approach. CO_2 storage and injection capacity is characterised and deployed with perfect foresight to meet the CO_2 capture rate for every year to 2050. In this way the annual anticipated CO_2 capture rate in Europe is the driver for CO_2 storage development.

Unique individual CO_2 storage sites are deployed to meet the requirements of CO_2 injection. The category of the storage site is informed from the numerical distribution set for the preference of deployment of potential storage categories. For example, the development of onshore CO_2 storage may be set to zero, and as a result no onshore storage sites will be developed. Each site's storage capacity, injectivity, the numbers of injection wells and where applicable oil recovery rates, are all informed from the distribution of parameters set by the user as described above.

The storage categories are simplified representations of CO_2 storage development with characteristics given as mean averages expected for Europe. Due to this, the storage sites are non-locational and thus this model does not include the development and deployment of transport infrastructure. Output data form the model may be matched to real-world geological data, allowing an investigation of the feasibility of the results produced.

Storage type characteristics, development time and costs

To address the scale of exploration, licensing and drilling resources necessary to develop large-scale CO_2 storage – both in terms of time, effort and money – this report builds on the findings of research commissioned by the International Energy Agency's Greenhouse Gas R&D Programme (IEAGHG) and carried out by Geogreen (Royer-Adnot, et al., 2011).

The IEAGHG study built detailed iterative workflows for the development of CO_2 storage including the identification of tasks, timing, phasing and success rates for all required activities to bring sites to final investment decisions (Table 2, Table 3). These workflows assumed a stringent storage regulatory framework in line with the European Union's Directive on CO_2 Storage (the 'CCS Directive'), requiring a license for exploration activities and successful injection tests.

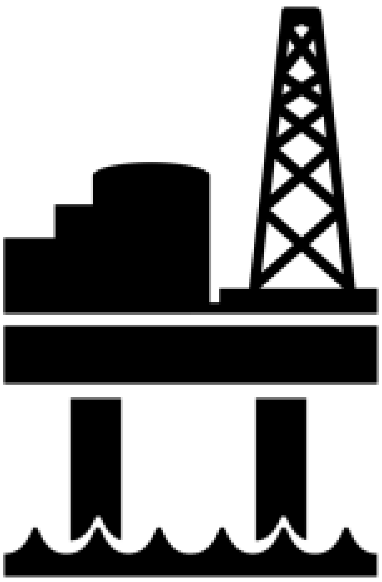
Table 2: Summary of modelling parameters and their effects (Royer-Adnot, et al., 2011)

Parameter	Effect
Deep saline formations vs. depleted oils and gas fields	Workflows, failure rates of various phases in the workflows, seismic data requirements, drilling or workover engineering costs
Onshore vs. offshore	Workflows, drilling and/or workover costs, failure rates
If offshore, water depth	Drilling costs due to the use of jack-up or semi-submersible rigs
Formation quality: highly suitable, suitable, or possible	Failure rates, seismic data acquisition costs
Well depth	Drilling time and, therefore, cost
Date	R&D cost components decrease over time
Place	Costs for adjusted regionally for qualified work, civil engineering and field work

Table 3: Cost and development time per step for onshore deep saline formation project in a highly explored area in a suitable formation with 2000 metre wells in OECD Europe in 2013 (Royer-Adnot, et al., 2011)

		Time (years)			Cost (€ million, 2010)[1]		
		10p	Mean	90p	10p	Mean	90p
Phase 0 Screening	*Studies and R&D*	0.5	0.75	1	0.5	0.75	1
Phase 1 Desk Based Assessment	*Studies and R&D*	0.5	0.75	1	1.25	2.5	5
Licensing Exploration Permit	*Administrative engineering, license application and award*	0.5	1.25	2	0.2	0.3	0.7
Phase 2 Site confirmation and characterization	*Studies and engineering*	0.5	1	1.5	3	5	8
	2D seismic acquisition	0.42	0.43	0.6	-	1.6	-
	3D seismic acquisition	0.42	0.43	0.6	-	7.2	-
	3D retreatment	0.05	0.2	0.3	-	-	-
	Mob/demob	0.02	0.08	0.15	0.75	1	1.25
	First well	0.03	0.06	0.11	-	4.82	-
	Second well (if any)	0.03	0.05	0.11	-	4.61	-
Licensing injection test permit	*Administrative engineering, license application and award*	0	1	1.5	0.2	0.3	0.7
Phase 2 injection test	*Injection test duration + data analysis*	0.5	1.25	2	-	60	-

Probability distributions for times, costs and failure rates were allocated to each step in the workflows, varying according to the parameters laid out in the table above (Table 2). Combined together, these figures yield straightforward, but large, models from which the cost and completion times necessary to develop storage sites could be calculated (Figure 3).



[1] All costs are expressed in 2010 Euros. M€ stands for Million Euros (10^6 Euros) and bn€ stands for billion Euros (10^9 Euros).

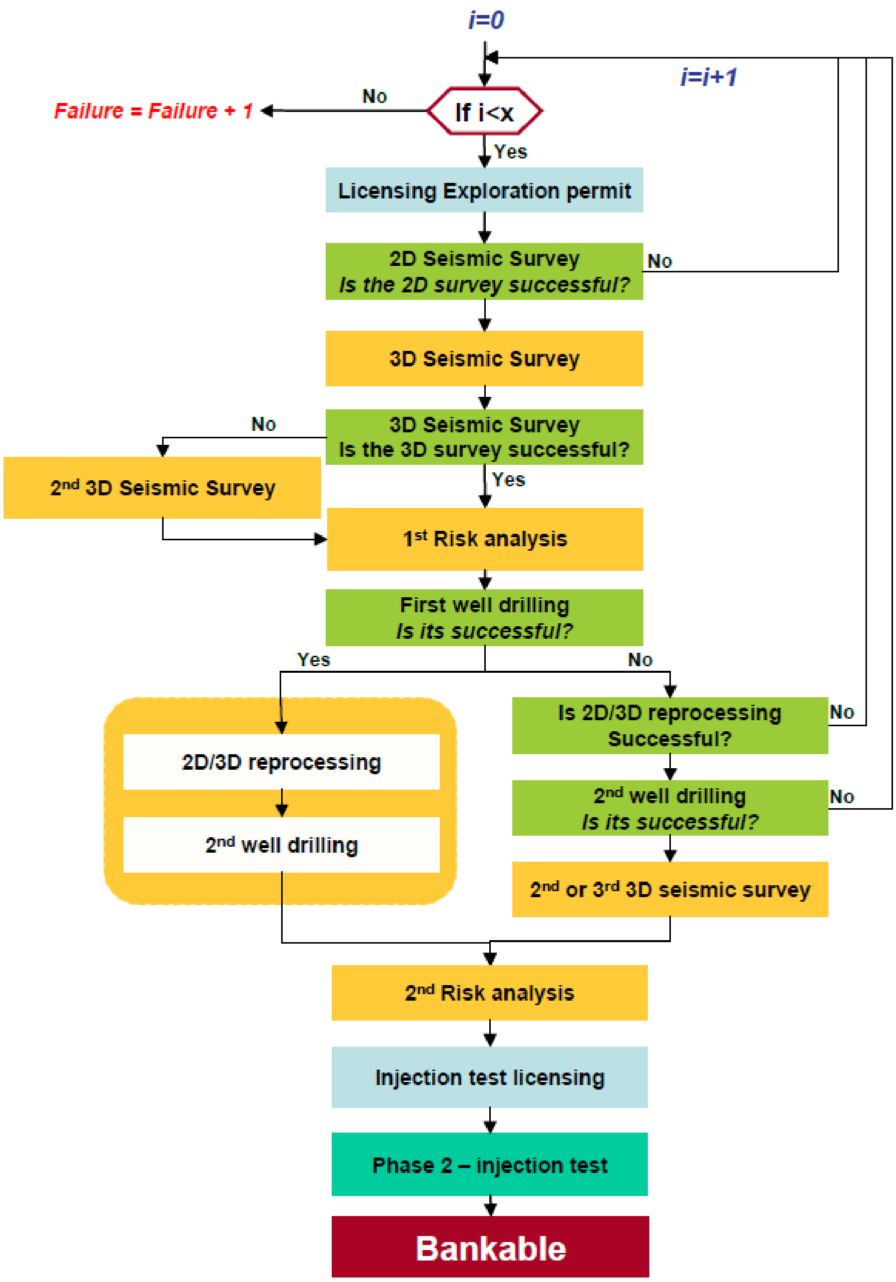


Figure 3: Generic workflow for an onshore Deep Saline Formation storage site (Royer-Adnot, et al., 2011)

Due to the extremely large number of permutations, the IEAGHG study employed a stochastic methodology, generating a population of storage sites with various characteristics according to the probability distributions in the tables above. The overall distributions of costs and timing – including mean values – were then derived from these populations. To illustrate, Figure 4 shows the cost distributions of deep saline formations in formations of varying suitability and depth. These distributions factor in the natural variation in other parameters (such as well depth and formation quality) as well as likelihoods of failure at each given stage.

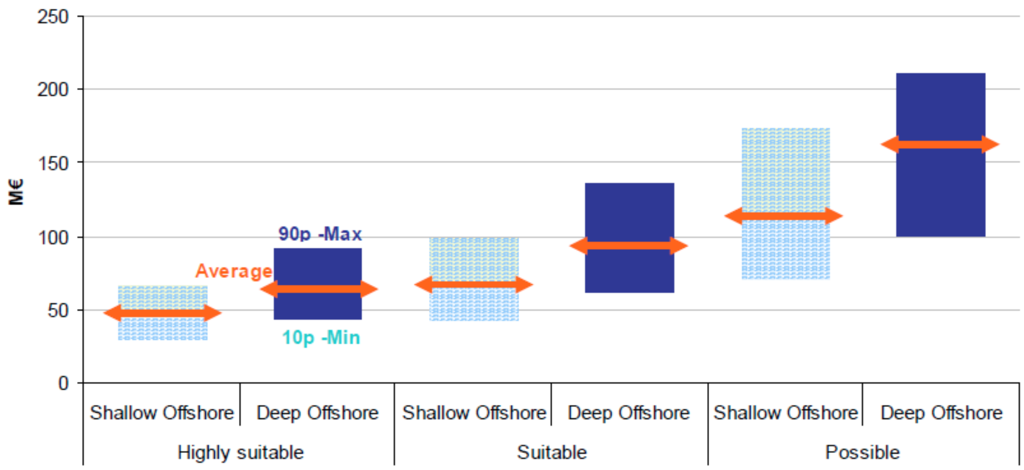


Figure 4: Offshore deep saline aquifer - comparison between shallow and deep offshore bankability development costs by different suitability of formation (Royer-Adnot, et al., 2011)

To simplify, the Bellona model uses mean time and cost figures for the six sites judged to be representative of the storage available in Europe: 1) An onshore deep saline formation; 2) An offshore deep saline formation; 3) An onshore depleted gas field; 4) An offshore depleted gas field; 5) An onshore depleted oil field; and 6) an offshore depleted oil field.

In line with geological understanding, each of these representative formations includes an assumed drilling depth of 2000 metres. It is to be assumed that the areas in which the formations are located are highly explored for oil and gas. This reduces drilling costs and contingencies, as well as the cost to acquire seismic data. It is also assumed that the formations are graded as 'suitable' for CO_2 storage – the median nominal classification for formation quality.[2] Offshore formations are assumed to be under more than 100 metres of water, requiring more expensive semi-submersible rigs for drilling and workover operations. And onshore formations are assumed to have no nearby CO_2 capture facilities available to affordably supply the volumes of CO_2 necessary for the injection test. Operations were deemed to take place before 2020, thereby increasing the R&D costs which decrease over time.

Mean development time and gross cost for storage types

Taking into account the above parameters, the following mean costs and development times (including losses for failed operations) were arrived at for each storage type. Because each of the workflows is the IEAGHG study corresponds with a so-called '100 Mt project' – a storage site that could receive between 1 and 3 million tonnes of CO_2 per year for 30 years[3] – the cost and timing figures below are scalable per tonne of CO_2 stored.

[2] 'Highly suitable' and 'possible' being the other two.

[3] The number of workflows necessary to develop a given amount of storage capacity is static: 100 projects of 100Mt require 100 workflows, and 50 projects of 200Mt also require 100 projects workflows.

Table 4: Mean 'bankability' costs and times for six representative 100Mt formations in Europe (including costs of failure)((does not include development costs including injection wells or rig))

	Mean development cost ($ million)	Mean development time (years)
Deep saline formation, onshore	35	8.5
Deep saline formation, offshore	93	9.5
Depleted gas field, onshore	23	5
Depleted gas field, offshore	38	5
Depleted oil field, onshore	43	10.5
Depleted oil field, offshore	51	7.5

The table shows that depleted gas fields offer the most affordable storage option, followed by onshore deep saline formations.[4] Offshore deep saline formations were the most costly, although it should be noted that costs in this category are very sensitive to water depth and formation quality.[5] Conservative conditions have been assumed for both water depth and formation quality.

When using averaged cost over a set of idealised storage types some provisos should be kept in mind. First, the figures above do not include the time and cost of actual development, including licensing, site construction, drilling, completion and commissioning. The timing gap between achieving bankable status and commencement of operations is typically anticipated to be between 3 to 5 years. Second, the decommissioning and monitoring of formations is not intended to be included in the model or study, but must be included in any life-cycle analysis of the costs of CO_2 storage.

Scale of activities to develop each storage type

More important than the capital requirements to develop CO_2 storage is the industrial scale and timing of the endeavour. Reviewing the scale and timing of activities needed to develop the necessary CO_2 storage capacity is the primary goal of this work.

The model estimates needs and timing of a selection of the industrial activities for each of the storage types. The model will estimate the need of such services on a scalable basis relative to the storage capacity and injectivity provided.

- Time taken to characterise a storage site (years)
- 2D seismic (km/tonne CO_2 storage volume)
- 3D seismic (km/tonne CO_2 storage volume)
- CO_2 injection test (tonne CO_2 /tonne CO_2 storage volume)[6]
- Characterisation drilling (m/tonne CO_2 storage volume)
- Development drilling (m/tonne CO_2 storage volume)
- Civil engineering/Rig/subsea installation

[4] Depleted hydrocarbon fields (oil or gas) with water invasion may be good candidates as they have the potential to de-risk the storage in the connected aquifer as well as in the field.
[5] Assumes no proximal oil/gas de-risking.
[6] Requirement for CO_2 injection testing based on IEAGHG Gap analysis (Royer-Adnot, et al., 2011)

Numerous sources and input from experts have provided the basis for input data. Units for industrial activites will be given in both practical and monetary terms – allowing for an effective comparison of the future CO_2 storage industry with current oil and gas exploration and development activities (Table 5).

Table 5 Example input data for characterisation and development of offshore aquifer storage sites

Activity	Scale of activites	Cost of activites (€ 2010)
Time taken to characterise	9.5 years	-
2D seismic necessary	1500 km/100 Mt	€ 9m /100 Mt
3D seismic necessary	180 km^2/100 Mt	€ 7.2m /100 Mt
CO_2 injection test	20000 tonnes CO_2/100 Mt	€ 41.88m /100 Mt
Characterisation drilling depth	2000 meters	€ 20.14m for first well
Operational drilling depth	2000 meters	€ 17.58m for subsequent wells
Rig/Subsea installation	-	€ 40m /100 Mt
Agrigate cost of charicterisation	-	€ 93m /100 Mt

SCENARIOS

This section looks at operations for selection, storage capacity, injectivity and anticipated injectivity per well of CO_2 storage categories. Due the operation of the model and the randomised method employed for deployment of storage sites, specific storage sites may not be completely consistent for each rerun of an individual scenario. However, as the storage sites are non-locational this effect will not affect the outputs or the discussion to follow.

CO_2 capture rate

It is clear that the primary assumption when reviewing the potential development path of Europe's CO_2 storage activities is the rate and total quantity of CO_2 to be stored over the period. This study will review three potential CO_2 capture projections for the entire EU to 2050. The data has been plotted from the EU 2050 Energy Roadmap, with the rate of capture development matched to that predicted by the report (Figure 1, Table 1).

Low CO_2 capture rate (LOW-Capture)

The low prediction is the Low CO_2 capture rate (LOW-Capture). In this scenario a greater deployment of renewable energy sources reduces the CO_2 capture rate and forestalls deployment. CO_2 capture begins in 2035 at a rate of 28.6 Mtpa, rising to 171.6 Mtpa in 2040 and again to 346 Mtpa in 2050. The total CO_2 stored over the period is 3.5Gt. (Figure 5)

Reference CO_2 capture rate (REF-Capture)

The central prediction is the Reference CO_2 capture rate (REF-Capture). CO_2 capture and thus storage begin operations in 2030 at a rate of 36 Mtpa. It should be noted that this is approximately equivalent to 40 Sleipner CO_2 injection projects (Verdon, et al., 2013). By 2040 the capture rate has risen to 400 Mtpa, rising further to 630 Mtpa in 2050. The total CO_2 stored over the period is 7.95Gt. (Figure 5)

High CO_2 capture rate (HIGH-Capture)

The scenario where CCS plays the largest role in the decarbonisation of the EU is High CO_2 capture rate (HIGH-Capture). In this scenario the reduced deployment of nuclear energy results in an increased and earlier deployment of CCS technologies. CO_2 capture begins at a low rate of 5Mtpa in 2025, rising to 60 Mtpa in 2030. By 2040, 660 Mtpa are being captured per year, greater than the capture rate of the reference scenario in 2050. By 2050 the rate of CO_2 capture has increased to 960 Mtpa, with total of 12.8 Gt of CO_2 stored over the period (Figure 5).

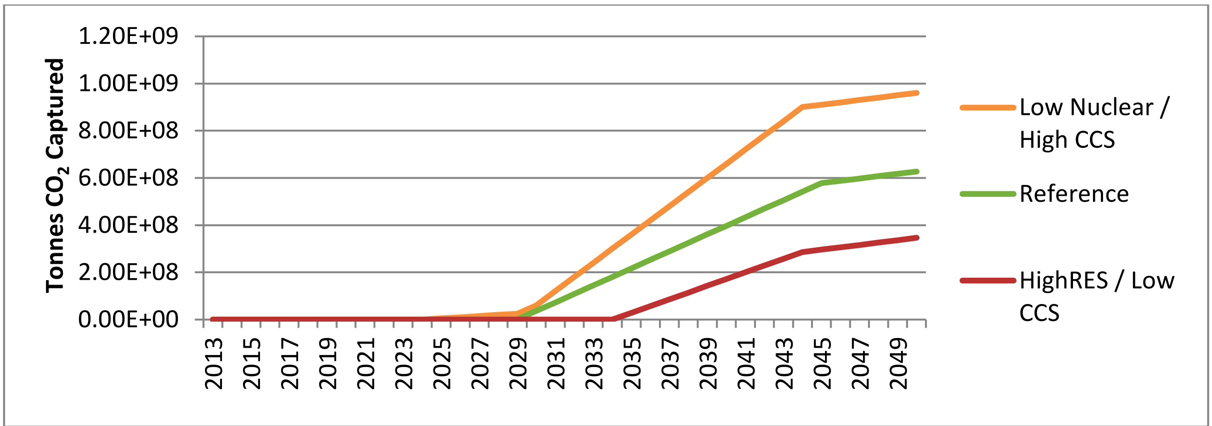


Figure 5 CO_2 Capture Rate based on EU Energy Roadmap 2050

CO_2 storage category deployment

The type of CO_2 storage that is favoured or permitted for development will have a large effect not only on the location of the storage but also on the scale of activities to characterise, develop and drill. In this way type of CO_2 storage deployment is likely to have major effects on the eventual size of the CO_2 storage industry and the investments needed to develop it.

The model allows for a distribution of expected CO_2 storage types, for example instances where little or no onshore CO_2 storage is permitted to 2050.[7] This study will review three simple scenarios for the type of CO_2 storage development that will be deployed to 2050.

Reference CO_2 storage category deployment (REF-Deploy)

The reference CO_2 storage category deployment (REF-deploy) assumes that both onshore and offshore aquifers account for the majority of CO_2 storage sites, providing 75% of the total. Depleted on- and offshore hydrocarbon sites provide the rest (25%) (Table 6). It is anticipated that aquifers will play a leading role in providing CO_2 storage capacity due to their potential large storage capacities, and wide geographical distribution across the EU. Individual aquifer storage sites are also anticipated to provide larger storage volumes, and thus be more suitable for receiving CO_2 from multiple sources over longer time periods (ZEP, 2010). Both offshore aquifer and hydrocarbon storage is expected to outnumber their

[7] Note: The distributions of CO_2 storage categories to be deployed reflect the number of storage sites and not the delivered CO_2 storage capacity or injectivity.

onshore equivalents. This not only shows that the offshore aquifer and depleted hydrocarbon storage resources are somewhat larger than the onshore storage resources in Europe, but it also reflects the political and planning constraints that may exist for onshore CO_2 storage development.

Low onshore CO_2 storage category deployment (LOS-Deploy)

The scenario low onshore CO_2 storage category deployment (LOS-deploy) aims to illustrate the potential of little onshore storage being permitted in EU member states to 2050. Such a scenario is required as major Member States such as Germany and Poland have already transposed the CO_2 Storage Directive in a way that disincentives onshore CO_2 storage (ZEP, 2010). In this scenario, the lion's share of storage sites are offshore (offshore aquifer 60%, offshore hydrocarbon 20%). Both onshore storage sites provide 10% respectively (Table 6).

EOR & CO_2 storage category deployment (EOR-Deploy)

This scenario will include the contribution of both onshore and offshore Enhanced Oil Recovery (EOR) to the provision of CO_2 storage and injection capacity in Europe (Table 6).

Table 6 Example of type distribution of CO_2 storage deployment Europe

Storage Type	REF-Deploy	LOS-Deploy	EOR-Deploy
Onshore EOR	0%	0%	20%
Offshore EOR	0%	0%	20%
Onshore hydrocarbon	10%	10%	10%
Offshore hydrocarbon	15%	20%	10%
Onshore aquifer	30%	10%	10%
Offshore aquifer	45%	60%	30%

Potential for regional CO_2 storage deployment analysis

The ability to set the type of CO_2 storage deployment enables regional CO_2 storage analysis. In this way, the anticipated deployment can be modified to reflect the CO_2 storage development in a particular regional, such as the North Sea basin. Clearly all storage development will be split between offshore aquifers, depleted hydrocarbon fields and EOR floods. The CO_2 capture rate and thus the CO_2 to be stored in the North Sea basin may be estimated from the countries bordering the North Sea.

Capacity of CO_2 storage sites

The expected storage capacity from each storage category will have implications for the operational life of each storage site and the total number of storage sites needed to permanently store CO_2 captured in Europe. CO_2 storage capacity for discrete storage types may be set over a range distribution, for example, with few very large capacity sites.

Studies such as the (EU GeoCapacity Project, 2009), (NPD, 2013), (SCCS, 2009), (Dooley, 2013) among others have all concluded that immense storage capacity exists in Europe. However, due to the relatively small number of commercial scale CO_2 storage pilots in operation there is uncertainty around the useable storage capacity that can be developed at individual sites (Hosa, et al., 2010). For example, storage capacity at the low end of predications may reflect a host of potential geological constraints as CO_2 storage is employed on a scale far larger than today. Potential effects to reduce usable storage capacity include low pore space use efficiency, poor CO_2 sweep efficiency, effective fracture pressure, pressure wave interference with other storage operators and smaller than currently anticipated trapping structures.

Two scenarios were run to reflect the low to reference assumption for CO_2 storage capacity at sites.

Reference storage capacity of storage sites (REF-CAP)

Adapting data from the (EU GeoCapacity Project, 2009), (IEA GHG, 2009), (SCCS, 2009), (ZEP, 2010), storage capacity for each storage category is given as a normal distribution. Depleted onshore hydrocarbon fields are given a median storage capacity of 50 Mt, while offshore hydrocarbon fields a median storage capacity of 125 Mt (Figure 6). Onshore aquifer storage sites are given a median storage capacity of 200 Mt, with offshore aquifer sites a median storage capacity of 300 Mt (Figure 7).[8]

Low storage capacity of storage sites (LOW-CAP)

The data used for the low storage capacity of storage sites (LOW-CAP) is the same as that of the REF-CAP but with expected capacity median reduced by 50%. In this scenario, onshore and offshore hydrocarbon fields have a median storage capacity of 25 Mt and 62 Mt respectively (Figure 6). Similarly on and offshore aquifers now have a median storage capacity of 100 Mt and 150 Mt respectively (Figure 7).

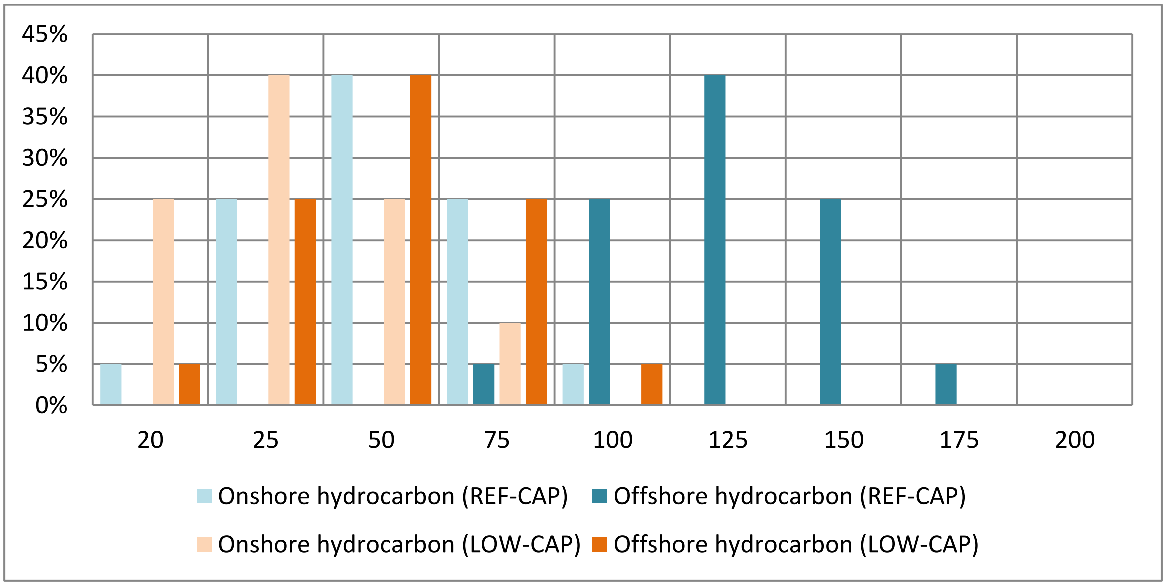


Figure 6 Onshore & Offshore storage capacity distribution for depleted hydrocarbon fields (Mt). Reference storage capacity of storage sites (REF-CAP) & Low storage capacity of storage sites (LOW-CAP)

[8] The largest capacity CO_2 storage project "Gorgon" off the west coast of Australia has an expected storage capacity of 129Mt (Hosa, et al., 2010).

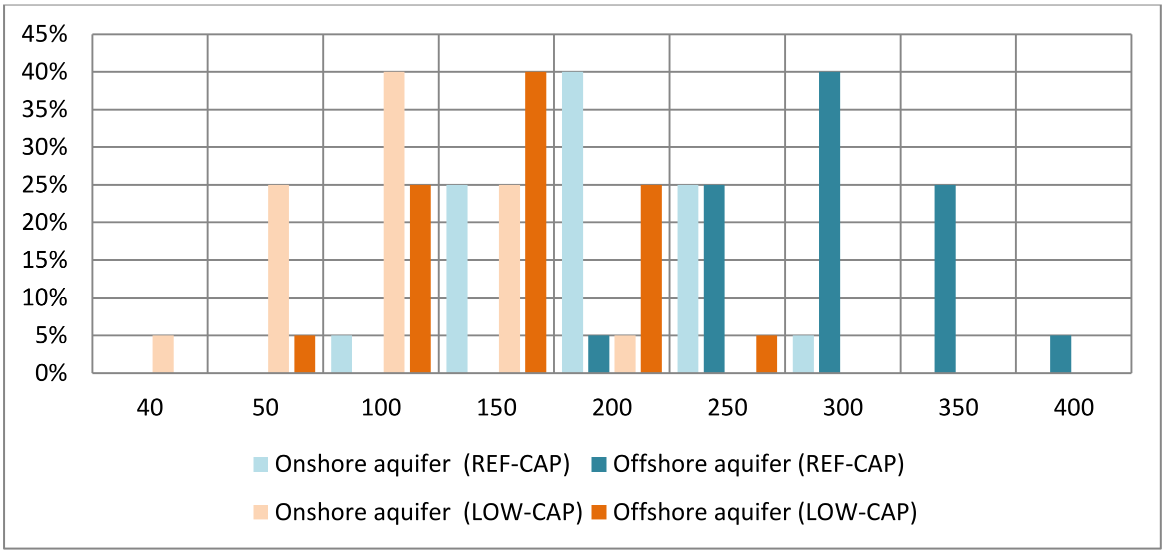


Figure 7 Onshore & Offshore storage capacity distribution for aquifer storage sites (Mt). Reference storage capacity of storage sites (REF-CAP) and low storage capacity of storage sites (LOW-CAP)

CO_2 injectivity of storage sites

The anticipated injectivity of storage sites is independent of storage capacity and will have direct effects on the number of storage sites needed to meet the annual injection requirements. Many real world realities will affect the potential injectivity of a storage site independent of the available storage capacity. These include the type and geometry of trap, pressure increases, and pressure wave interference with other storage operators among others.

It is possible to simplify the expected injectivity at a storage site by giving an expected operational life or "time to fill" for each of the storage sites as has been done by (ZEP, 2010). Inversely reviewing the operational life of storage sites produced by the model allows for a commercial feasibility analysis.[9]

Two scenarios were run for the low and reference injectivity of storage sites.

Reference injectivity of storage sites (REF-INJ)

For the reference injectivity of storage sites (REF-INJ) scenario onshore and offshore hydrocarbon fields have a median injection capacity per annum of 3 Mtpa and 4 Mtpa respectively (Figure 8). Similarly on- and offshore aquifers have a median injection capacity per annum of 6 Mtpa and 7 Mtpa respectively (Figure 9).

Low injectivity of storage sites (LOW-INJ)

As demonstrated by the Snøhvit project in the North of Norway (Grude, et al., 2013), lower than expected injectivity has the potential to be a reality for well-characterised storage sites. Indeed as discussed in (Bryant, 2013), injectivity of storage formations may in many cases be limited without water production.

[9] Storage sites that fill available storage capacity rapidly (e.g. <10 years) may not be suitable for the long term storage contract anticipated to be the norm between CO_2 producer and sink (ZEP, 2010).

In this low injectivity of storage sites (LOW-INJ) scenario onshore and offshore hydrocarbon fields have a median injection capacity per annum 50% of REF-INJ, that of 1.5 Mtpa and 2 Mtpa respectively (Figure 8). Similarly on- and offshore aquifers now have a median injection capacity per annum of 3 Mtpa and 3.5 Mtpa respectively (Figure 9).

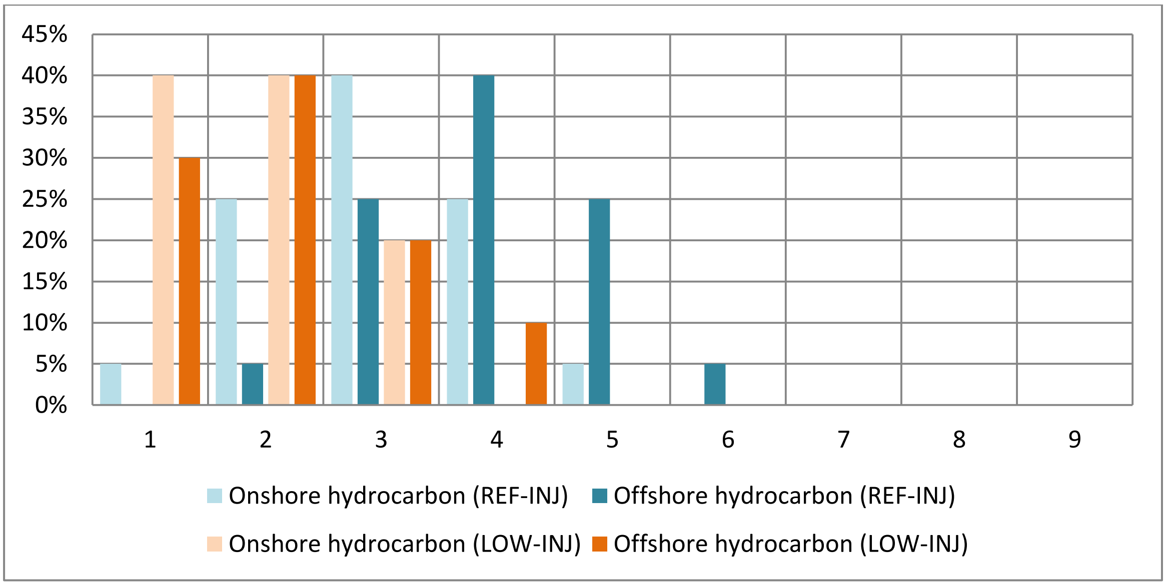


Figure 8 Onshore and offshore injection capacity distribution for depleted hydrocarbon fields (Mtpa). Reference injectivity of storage sites (REF-INJ) and low injectivity of storage sites (LOW-INJ)

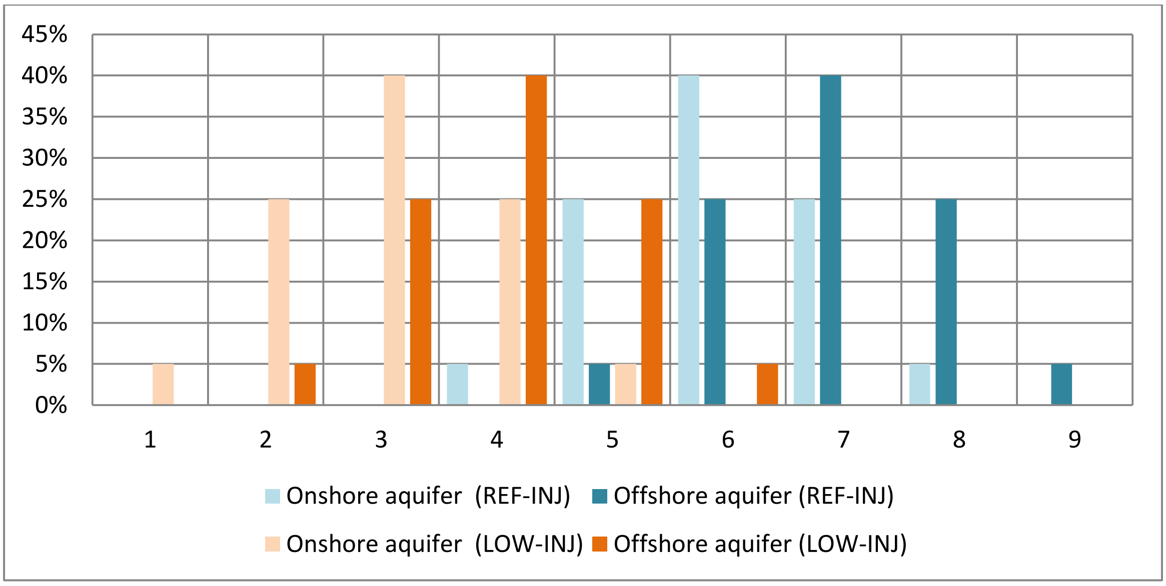


Figure 9 Onshore and offshore injection capacity distribution for aquifer storage sites (Mtpa). Reference injectivity of storage sites (REF-INJ) and low injectivity of storage sites (LOW-INJ)

CO_2 injectivity of wells at storage sites

The injectivity of development/operation wells at storage sites will have a direct effect on the number of wells needed to meet annual injectivity requirements. As (ZEP, 2010) highlights, drilling injection wells is expected to be the largest single expenditure in the delivery of CO_2 storage. As such, reduced average injectivity per well could greatly increase the number of wells necessary, with adverse results for the cost and scale of activities needed to develop the necessary CO_2 storage and injection capacity.

Two scenarios were ran for the low and reference injectivity per well per annum at storage sites.[10]

Reference injectivity per well (REF-I/W)

The reference injectivity per well (REF-I/W) is based on data from (Hosa, et al., 2010), (Azizi, et al., 2013), (Bryant, 2013) and (ZEP, 2010). All storage categories are treated as having the equivalent median injectivity per well of 0.6 Mtpa (Figure 10). It should be noted that (Hosa, et al., 2010) singles out Sleipner CO_2 storage with an injectivity of approximately 1 Mtpa as far greater than the average injectivity observed at other CO_2 storage projects to date. [11]

Low injectivity per well (LOW-I/W)

The low Injectivity per well (LOW-I/W) scenario uses a median injection per well of 50% of REF-I/W. All storage categories have the equivalent median injectivity per well of 0.3 Mtpa (Figure 10). This estimate is consistent with (ZEP, 2010) where 0.2 Mtpa was used as the lowest onshore injectivity.

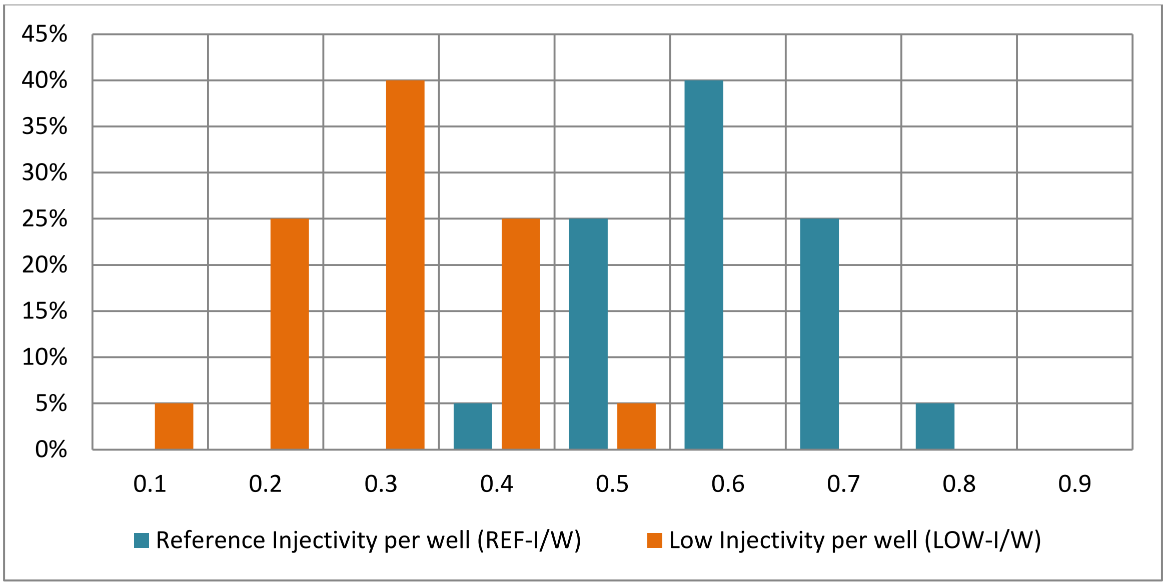


Figure 10 Distribution of expected CO_2 injectivity of wells at storage sites (Mtpa). Reference Injectivity per well (REF-I/W) and low Injectivity per well (LOW-I/W)

Operations of CO_2 EOR categories

Both the onshore and offshore EOR categories are treated differently than the CO_2 storage categories such as onshore aquifers. Here assumptions must be selected for the original oil in place (OOIP), the ultimate recovery rate (%) and the recovery rate (CO_2/bbl).[12] Other

[10] An addition of a third scenario for high injectivity/well or a water production scenario could be added in future.
[11] The Gorgon CO_2 storage site will inject 3.6 Mt/yr and is anticipated to use 8 injection wells at 0.45 Mtpa/well (Hosa, et al., 2010).
[12] CO_2/bbl = Net CO_2 utilisation factor in thousand cubic feet of CO_2 per barrel of oil recovered.

variables include the injectivity per well, the value of incremental oil (€) and the anticipated duration of the CO_2 flood (years).

One scenario is used for the EOR case. A distribution for OOIP is given for both onshore and offshore EOR schemes, with a median value of 150 million standard cubic metres (MSm^3) for the former and 300 MSm^3 (Figure 11). Ultimate recovery is set to 6% of OOIP and the recovery rate for both on- and offshore EOR projects have a median value of 4 thousand cubic feet (MCF) CO_2/bbl oil (Figure 12). The value of incremental oil recovery is set to €50 over the period and CO_2 import for EOR floods are expected to operate for 10 years. The injectivity per well at EOR projects is constant with the reference injectivity per well (REF-I/W).

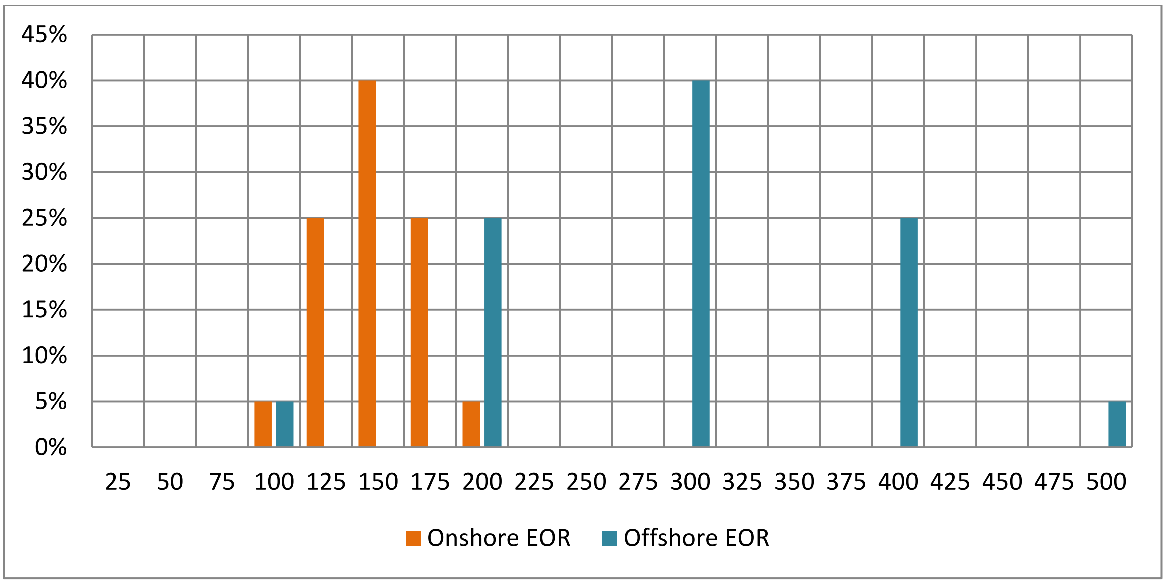


Figure 11 Distribution of expected original oil in place (OOIP)(MSm^3) for on- and offshore CO_2 EOR floods.

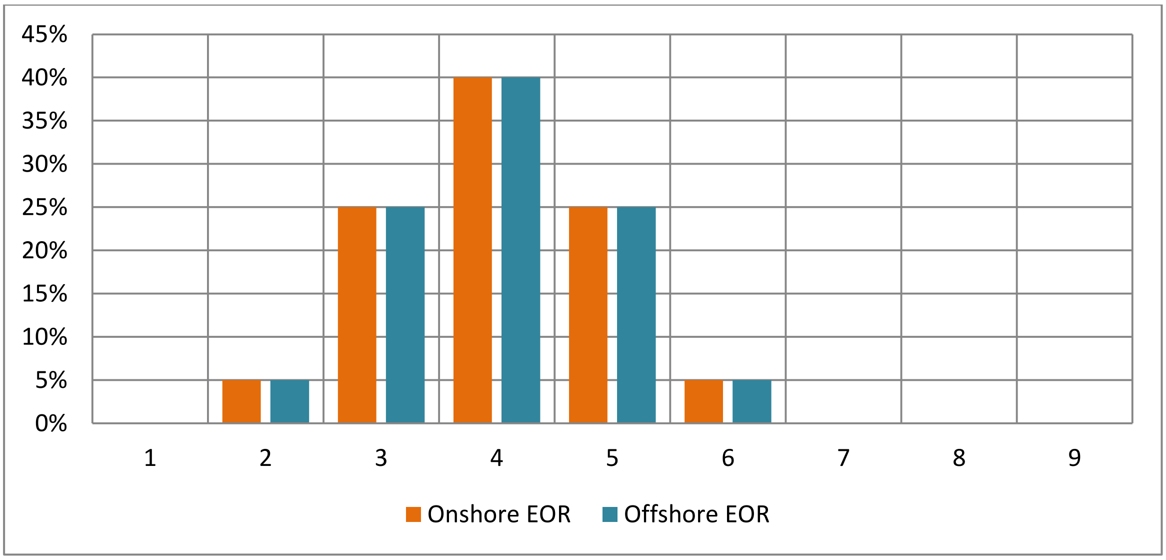


Figure 12 Distribution of expected recovery rate (MCF CO_2/bbl oil) for on- and offshore CO_2 EOR floods.

RESULTS AND DISCUSSION

Reference scenario

Below follows an in-depth description of results for the reference scenario. This scenario includes the REF-capture, REF-deploy, REF-CAP, REF-INJ and REF-I/W. Table 7 gives a breakdown of the categories of CO_2 storage deployment in Europe. **81 storage sites/complexes are developed to 2050 with 3 retiring by that year.** The storage complexes have average fill time of between 24 to 37 years. This is a little shorter than is currently envisioned for commercial CO_2 storage operations.

Figure 13 depicts the deployment of injectivity at storage sites to meet the EU wide CO_2 capture rate. Comparing this to Figure 14, where the filling of CO_2 storage capacity is depicted it is clear that injectivity is the major factor in the number of storage sites developed. Figure 15 depicts the contribution of each category to total CO_2 storage deployment. **Under reference assumptions offshore and onshore aquifers provide approximately 90% of the characterised CO_2 storage capacity.**

Figure 16 and Figure 17 depict when CO_2 storage appraisal and characterisation needs to begin in order to deliver sufficient CO_2 storage and injection capacity to meet the EU 2050 Energy Roadmap under reference conditions. **Strikingly the first large scale investments in commercial storage provision take place in 2019 (€500 million), increasing rapidly into the 2020s. This finding is critical as it shows that what some consider early deployment is in fact timely deployment if we are to reach EU Energy Roadmap 2050 goals.** Thus, failure to rapidly put in place a suitable investment framework for the CO_2 storage industry may critically hamper capture deployment. **In short, a functioning CO_2 storage market needs to exist by 2019 in order to meet the CO_2 injection and storage needs of the 2030s and 2040s.**

Figure 18 to Figure 21 give a brief overview of some of the practical considerations for the future CO_2 storage industry. **The number and rate of offshore wells to be drilled is comparable to the 2009-2013 appraisal and exploration activities of the UK oil and gas industry** (Oil & Gas UK, 2014).

Table 7 CO_2 storage deployment, retirement and average "fill time" in the Reference scenario.

Storage Site	2050	2040	2030	Average fill time for storage type (years)
Onshore EOR	**0**	**0**	**0**	**n/a**
Offshore EOR	**0**	**0**	**0**	**n/a**
Onshore hydrocarbon	**4**	**2**	**1**	**24**
Offshore hydrocarbon	**11**	**9**	**2**	**34**
Onshore aquifer	**31**	**20**	**6**	**37**
Offshore aquifer	**35**	**23**	**3**	**27**
Sum	**81**	**54**	**12**	
	To 2050	To 2040	To 2030	Total
Storage Sites retired	**3**	**0**	**0**	**3**

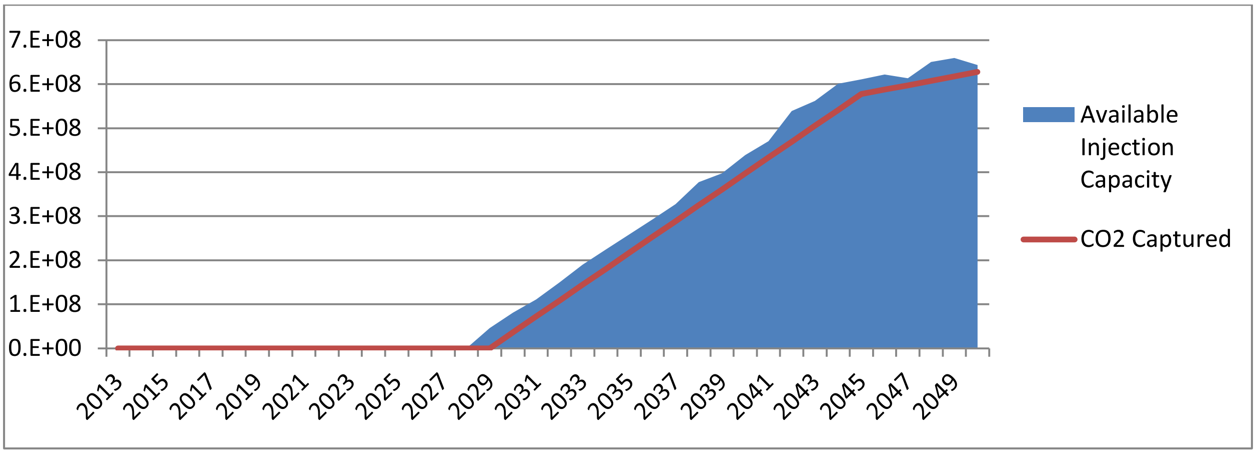


Figure 13 Injectivity available to CO_2 captured per annum (tonnes). Reference Scenario

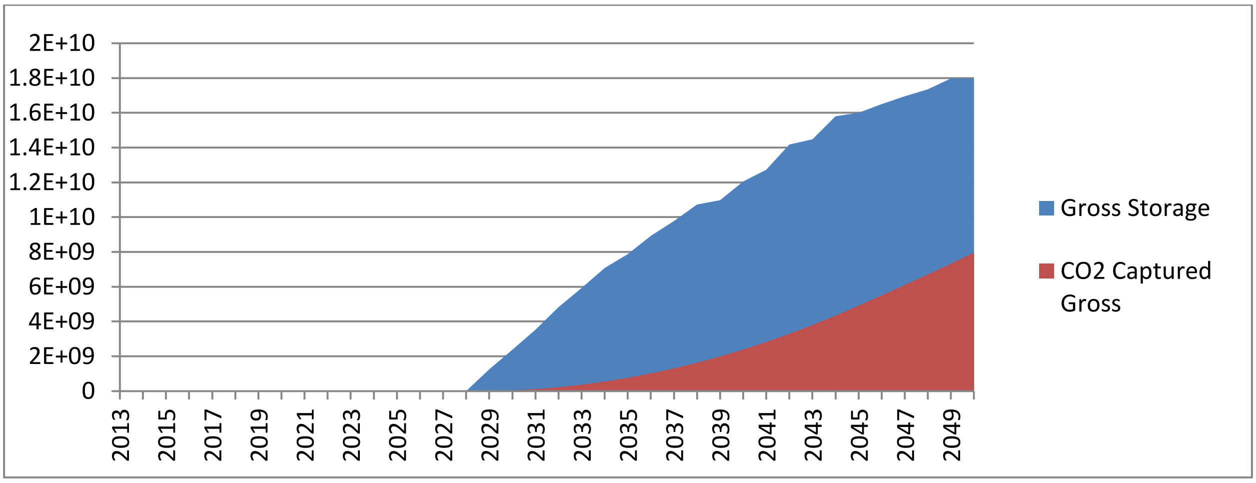


Figure 14 CO_2 storage deployment vs. CO_2 Stored (tonnes). Reference scenario

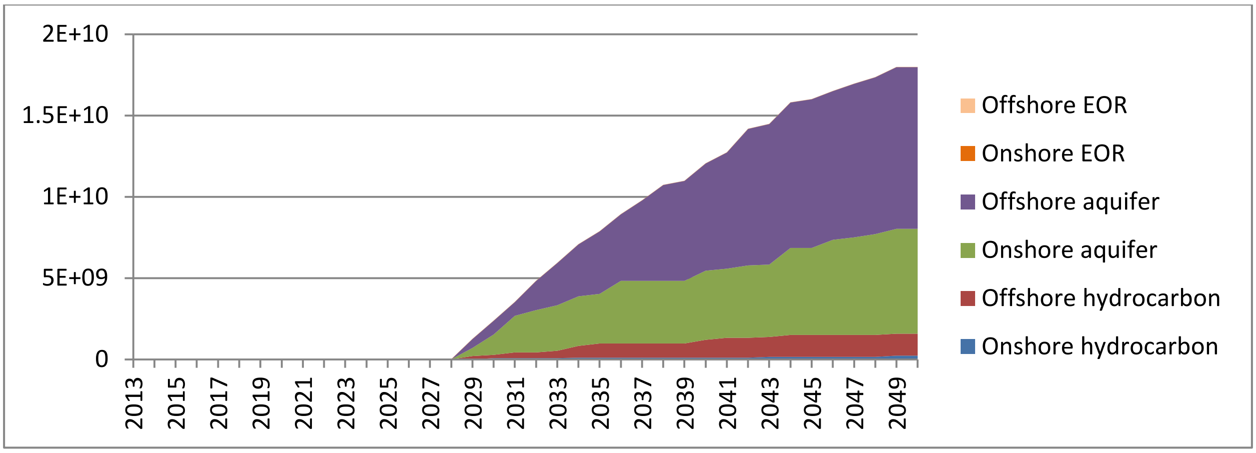


Figure 15 CO_2 Storage deployment categories (tonnes). Reference scenario

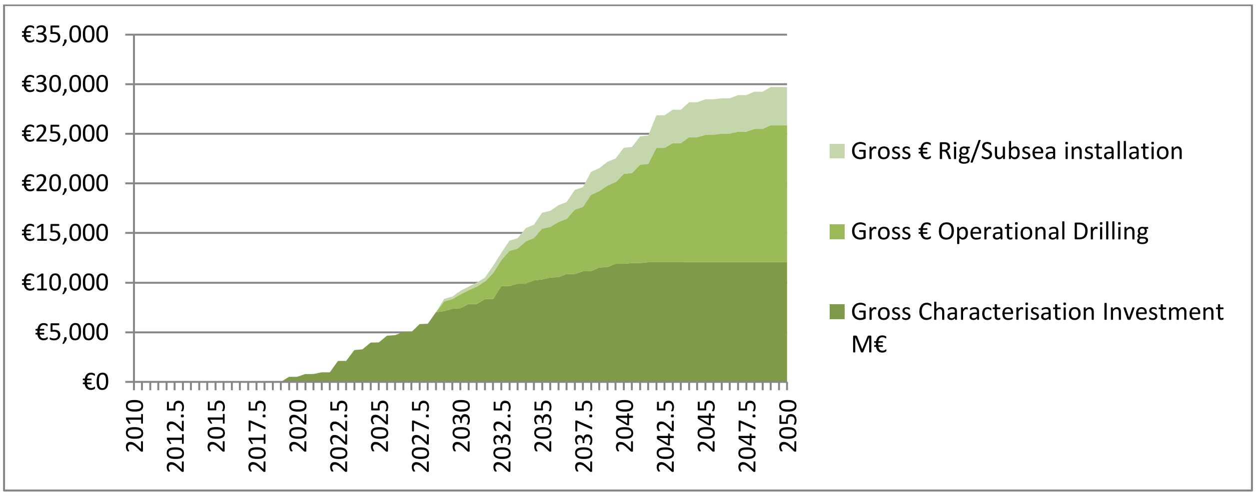


Figure 16 Gross investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). Reference scenario

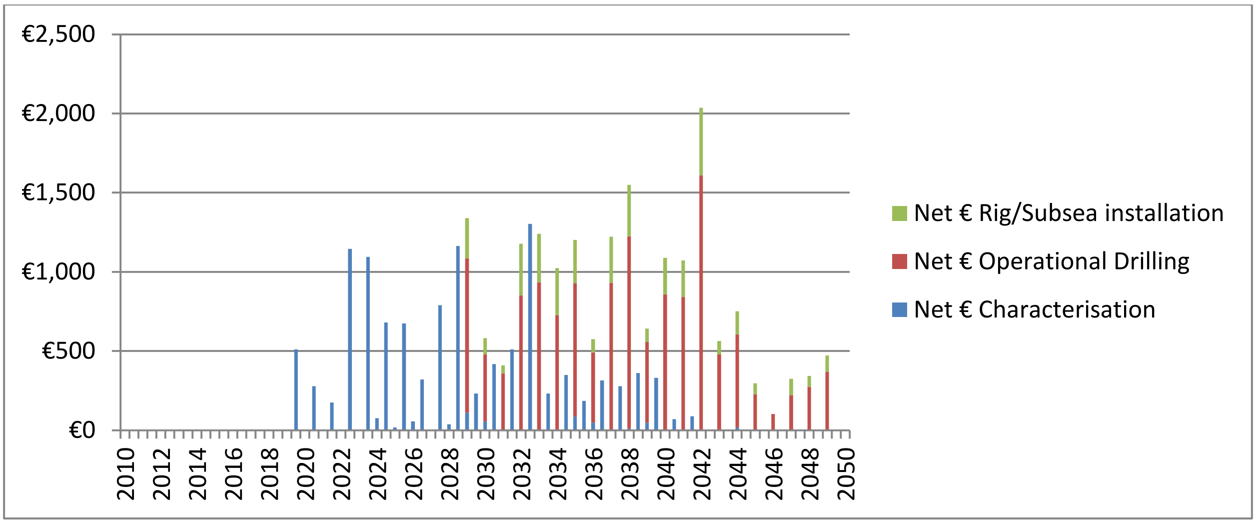


Figure 17 Annual investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). Reference scenario

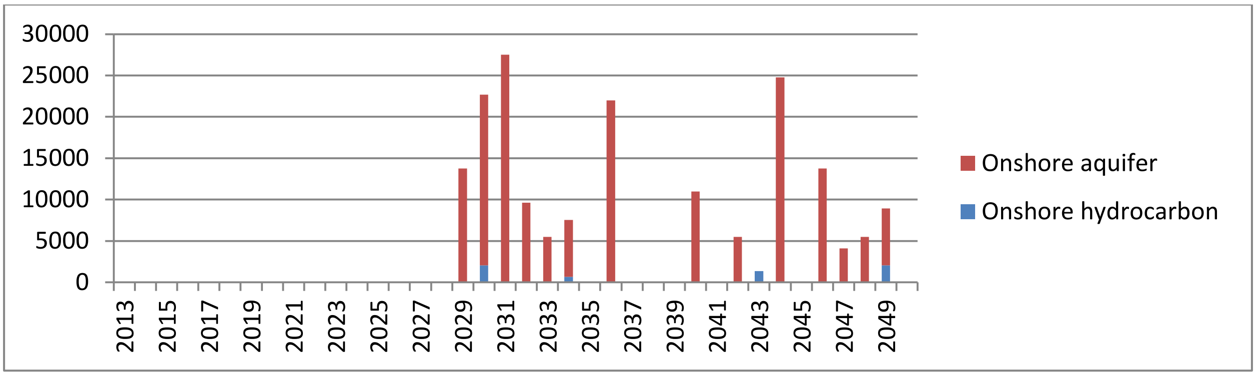


Figure 18 Truck journeys required for onshore storage characterisation (20 tonne truck journeys)

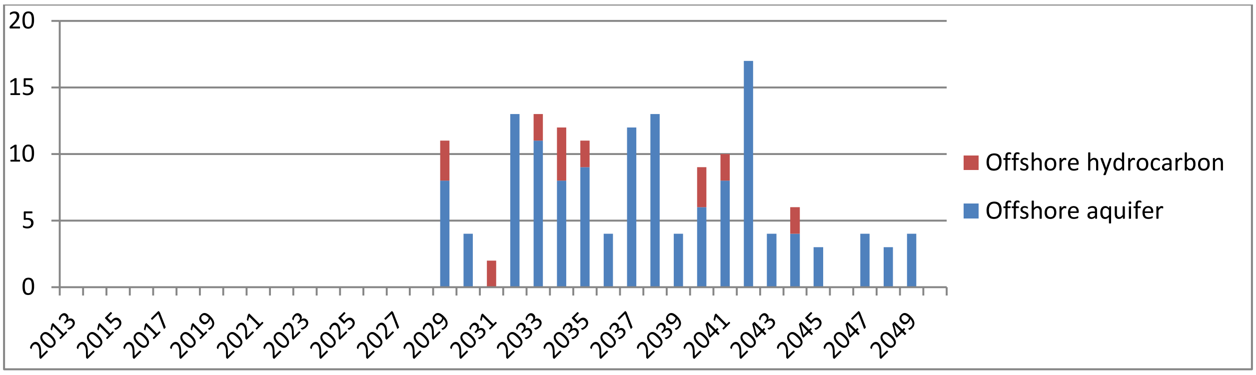


Figure 19 Ship journeys necessary to characterise offshore storage (15000 tonne ship Journeys). Reference scenario

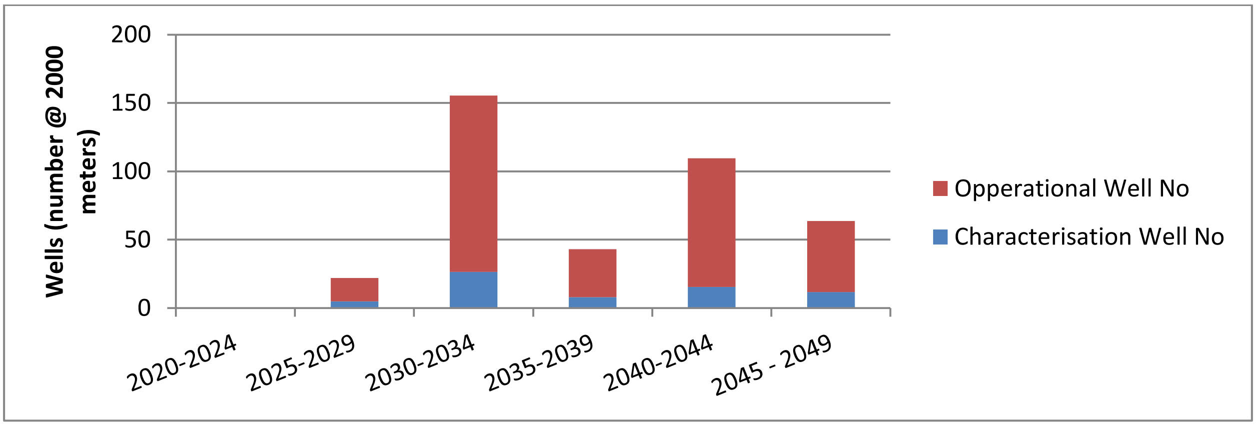


Figure 20 Wells drilled at onshore hydrocarbon and onshore aquifer. Reference Scenario

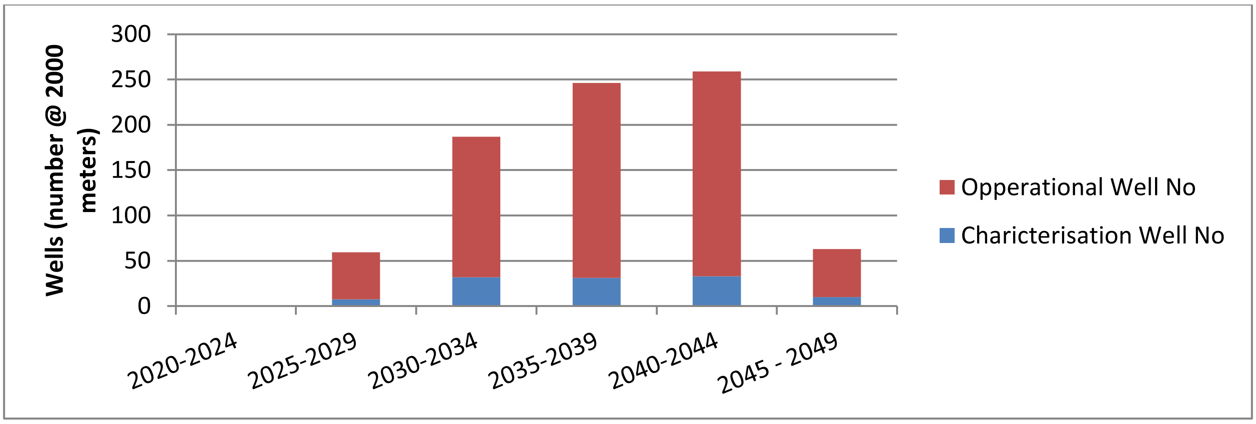


Figure 21 Wells drilled at offshore hydrocarbon and offshore aquifer. Reference Scenario

What effect does the capture rate have?

Figure 22 compares the injectivity necessary to meet HIGH-Capture & LOW-Capture Scenarios.[13] The total number of storage complexes deployed increases to 127 for the HIGH-Capture scenario, with just 47 needed in the LOW-Capture scenario (Table 8). **Due to the earlier deployment of CO_2 capture under HIGH-Capture, characterisation is also brought forward to 2014.** However, activities for characterisation remain relatively small during the 2010s with a total investment in characterisation of approximately €500 million. Similarly under LOW-Capture characterisation efforts do not begin until the mid-2020s.

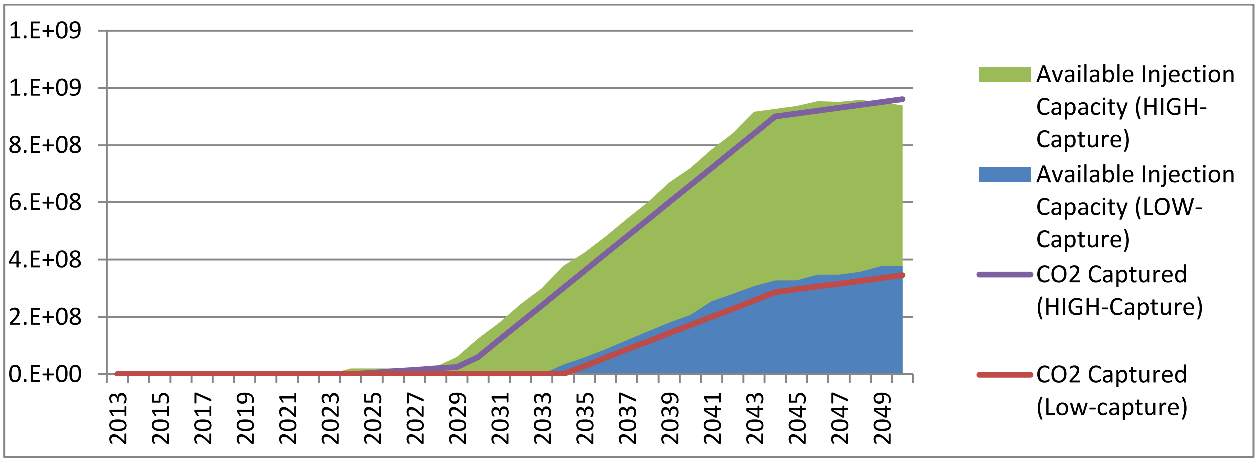


Figure 22 Injectivity available to CO_2 captured per annum. HIGH-Capture & LOW-Capture scenarios

Table 8 7 CO_2 storage deployments and retirement in the reference and HIGH-Capture Scenario.

Storage Site	2050	2040	2030
Onshore EOR	**0**	**0**	**0**
Offshore EOR	**0**	**0**	**0**
Onshore hydrocarbon	**12**	**5**	**1**
Offshore hydrocarbon	**21**	**11**	**3**
Onshore aquifer	**44**	**31**	**11**
Offshore aquifer	**50**	**38**	**4**
Sum	**127**	**85**	**19**
	To 2050	To 2040	To 2030
Storage Sites retired	**9**	**0**	**0**

How important is effective storage capacity?

Adjusting the reference scenario to exhibit lower CO_2 storage capacity (LOW-Cap) can help us investigate the effect this would have on CO_2 storage development.[14]

Unsurprisingly, **the reduced storage capacity also reduces the average fill time for all storage categories** (Figure 23). This in turn markedly increases the number of storage sites

[13] All other parameters remain reference
[14] All other parameters remain reference

necessary to accommodate CO_2 captured to 2050 from 81 to 107 (Table 9). The reduction in average fill time will have an adverse effect on the commercial operation of storage complexes. Additionally, the increased necessary deployment increases characterisation and development needs over the period. For example, **for the period 2040-2044 drilling activities will increase by proximately 20%.** There is a need for CO_2 storage estimates to be improved, as a future with lower than anticipated effective storage capacity at CO_2 storage sites would severely hamper the feasibility and commercial viability of storage operators.

Table 9 CO_2 storage deployments and retirement in the Reference scenario and LOW-Cap.

Storage Site	2050	2040	2030	Average fill time for storage type (years)
Onshore EOR	**0**	**0**	**0**	**n/a**
Offshore EOR	**0**	**0**	**0**	**n/a**
Onshore hydrocarbon	**11**	**2**	**1**	**13**
Offshore hydrocarbon	**18**	**9**	**2**	**15**
Onshore aquifer	**39**	**20**	**6**	**18**
Offshore aquifer	**39**	**24**	**3**	**15**
Sum	**107**	**55**	**12**	
	To 2050	To 2040	To 2030	Total
Storage Sites retired	**32**	**3**	**0**	**35**

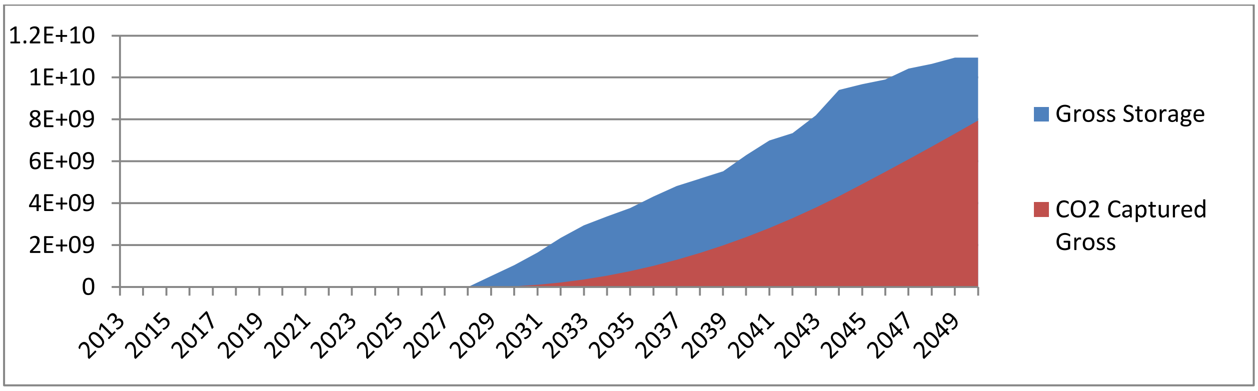


Figure 23 CO_2 storage deployment vs. CO_2 stored (tonnes) Reference scenario and LOW-Cap.

How important is injectivity per well?

A reduced injectivity of LOW-I/W does not have direct impact on the number of storage sites needed or the overall injectivity of these sites. It does, however, notably increase the number of injection wells necessary. **For both onshore and offshore drilling activities the number of wells increases by approximately 100% over the reference scenario** (Figure 24, Figure 25).

Under LOW-I/I scenario, over the period 2035-2039 drilling activates to develop offshore CO_2 storage become more comparable to the total drilling operation in the UK oil and gas industry (Figure 27). Indeed if the HIGH-Capture rate is used the number of wells required increases further, to an extent potentially exceeding current activities on the UK continental shelf. It should be noted that this holds under the assumption of REF-Deploy and that 40% of storage sites are onshore. Offshore drilling activity will increase substantially if onshore storage is reduced or unavailable.

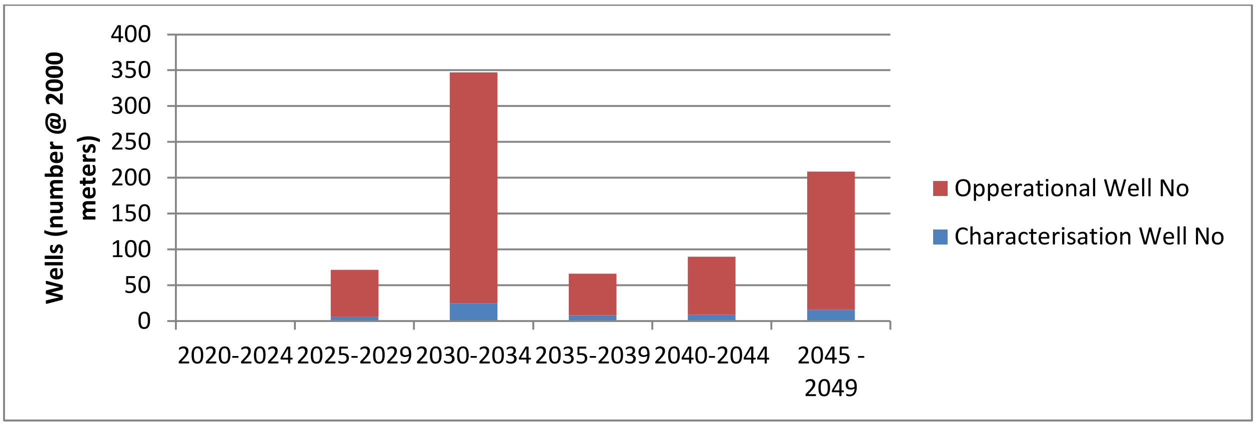


Figure 24 Wells drilled at onshore hydrocarbon and onshore aquifer. LOW-I/W

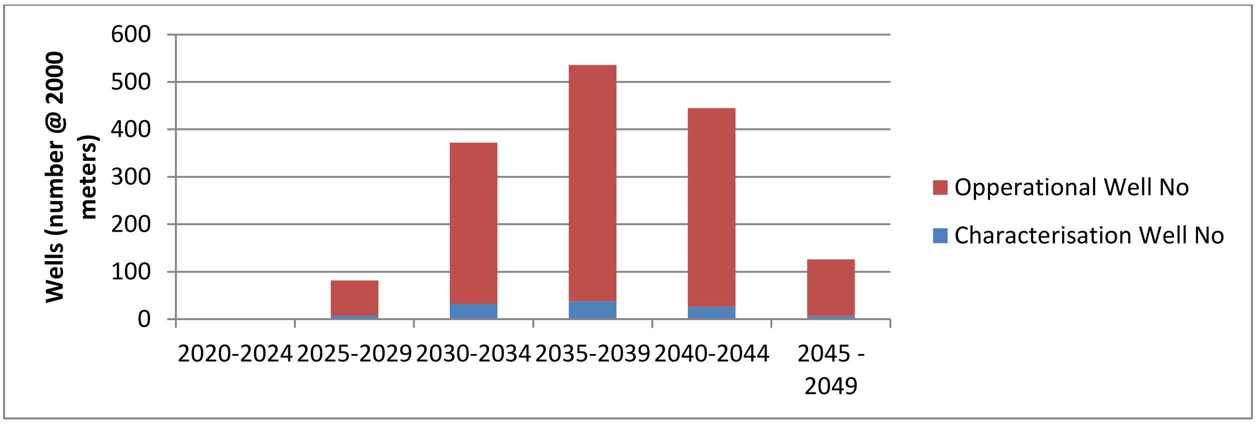


Figure 25 Wells drilled at offshore hydrocarbon and offshore aquifer. LOW-I/W

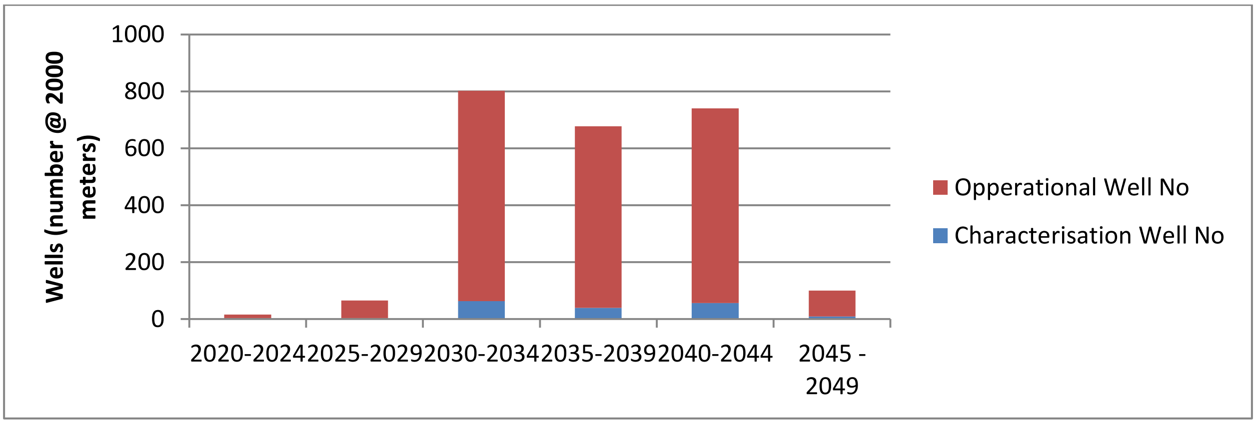


Figure 26 Wells drilled at offshore hydrocarbon and offshore aquifer. LOW-I/W and HIGH-Capture

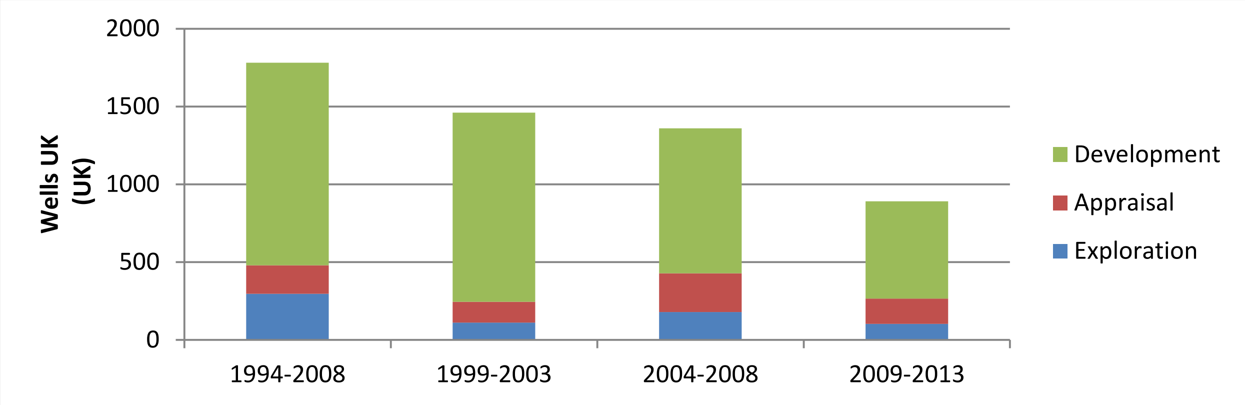


Figure 27 Development, appraisal and exploration wells completed offshore UK. (Oil & Gas UK, 2014)

How important is injectivity per storage site?

Applying reduced injectivity for storage sites (LOW-INJ) and low injectivity per wells (LOW-I/W) result in an approximate doubling of the number of required storage sites to meet CO_2 capture rates (Table 10). Injectivity of storage sites is the strongest driver after the CO_2 capture rate for the number of storage sites required. Figure 28 depicts the low storage capacity utilisation due to the low injectivity. Applied with a HIGH-Capture the number of storage complexes needed increases to 300.

Indeed, the increase in sites necessary has implications for the amount of sites that must be characterised, seismic shot, and injection tested, as well as for the development wells to be drilled.[15] In this way, LOW-INJ is a strong driver for cost increases over reference scenario. Gross characterisation investments double over that of the reference scenario (Figure 29). However, the lower injection rates increase the average fill time for all categories, thus prolonging the time that each storage site provides injection capacity.

In short, it is clear that sustained injectivity of storage sites is critically important, potentially more so than volumetric storage capacity where much effort has focused to date.

[15] Water production to increase both CO_2 storage density and increase injectivity has not been reviewed in this report.

Table 10 CO_2 storage deployments and retirement in the Reference scenario & LOW-INJ & LOW-I/W.

Storage Site	2050	2040	2030	Average fill time for storage type (years)
Onshore EOR	**0**	**0**	**0**	**n/a**
Offshore EOR	**0**	**0**	**0**	**n/a**
Onshore hydrocarbon	**15**	**12**	**1**	**38**
Offshore hydrocarbon	**30**	**25**	**4**	**77**
Onshore aquifer	**63**	**47**	**12**	**78**
Offshore aquifer	**86**	**52**	**6**	**78**
Sum	**194**	**136**	**23**	
	To 2050	To 2040	To 2030	Total
Storage Sites retired	**3**	**0**	**0**	**3**

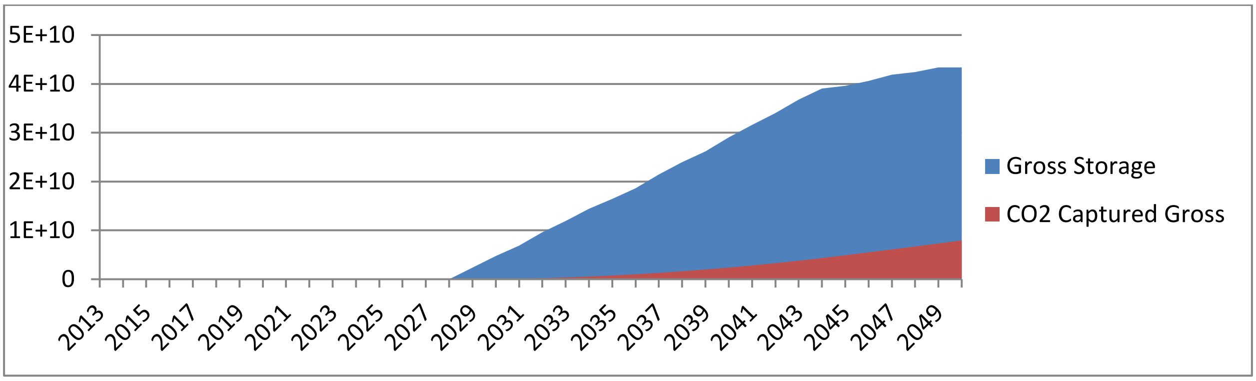


Figure 28 CO_2 storage deployment vs. CO_2 stored (tonnes) Reference scenario & LOW-INJ and LOW-I/W.

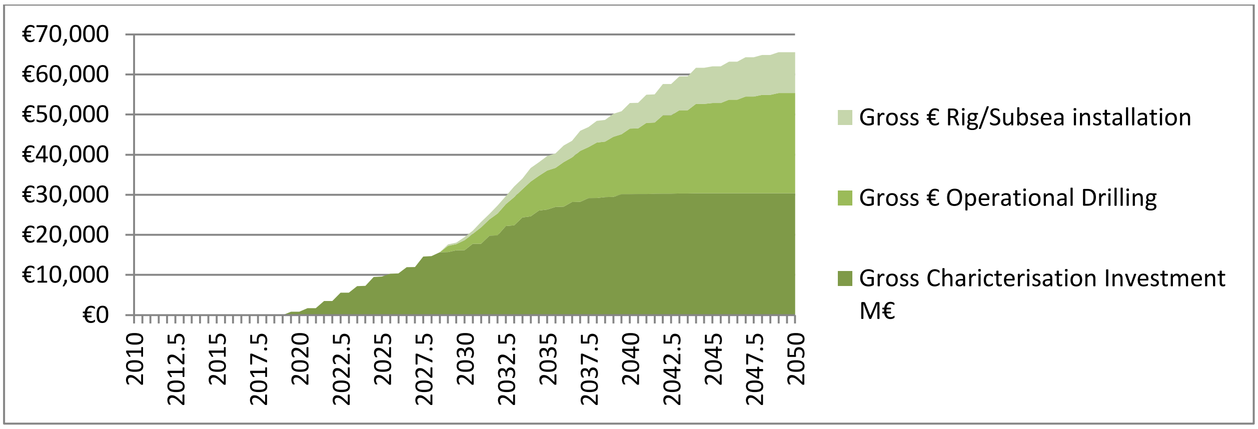


Figure 29 Gross investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). LOW-INJ & LOW-I/W

What if storage must take place offshore?

As described above, there is potential that the lion's share of CO_2 will be stored offshore to 2050. In Europe we are fortunate in having very large potential offshore CO_2 storage resources. The following scenario will review what effect low onshore storage (LOS-Deploy) will have on the scale of activities necessary to enable sufficient CO_2 injection and storage (Figure 30).

The increased fraction of offshore storage capacity increases the cost of deployment as characterisation and drilling offshore is generally more expensive. This in turn makes LOS-Deploy more sensitive to changes in parameters surrounding injectivity and capacity. That is to say that **reduced injectivity will have an even greater effect on CO_2 storage cost when more storage is deployed offshore.**

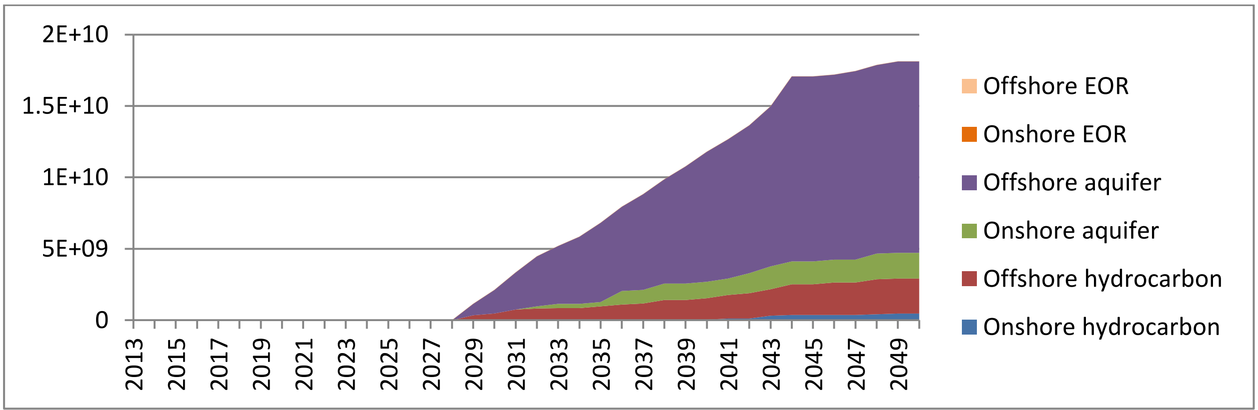


Figure 30 CO_2 Storage deployment categories (tonnes). Reference & LOS-Deploy

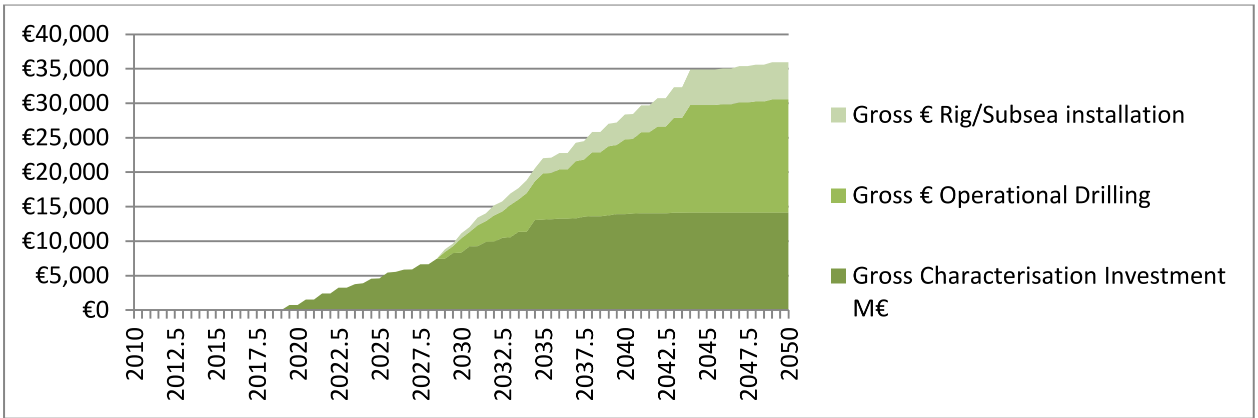


Figure 31 Gross investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). Reference and LOS-Deploy

HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ and LOW-I/W

The following is a review of the effects of simultaneously lower than expected storage capacity, injectivity per site and injectivity per well on predominantly offshore CO_2 storage operations. This scenario combines HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ and LOW-I/W.

The CO_2 injection rate in 2040, 660 Mtpa rising to 960 Mtpa in 2050 with total of 12.8 Gt of CO_2 stored over the period (Figure 32). The scenario has the highest number of deployed storage sites/complexes at 331. The cost is subsequently the highest of any scenario run, at approximately €90 billion for characterisation, drilling and rig installation (Figure 33). Average fill time is from 23 to 40 years, which fits the expected commercial timeline for CO_2 capture projects. The fill time results from a lower than expected storage capacity and lower injection rate per site. In the absence of water production from the storage site, lower injection rates also results in a greater number of sites needed and thus elevated cost estimates. The costs are increased further by the low injectivity per well, which results in more wells being drilled to satisfy injection requirements. Indeed, as the bulk of storage is provided offshore the number of wells and their cost is higher than any scenario (Figure 35). The anticipated drilling programme will be in excess of current activities in the UK oil and gas sector.

As with previous HIGH-Capture scenarios CO_2 site characterisation must begin during this decade, with characterisation investments reaching €1 billion per annum in 2020, subsequently elevating to approximately €1.9 billion in 2025 (Figure 34). As an example of the scale of characterisation over much of the five year period 120,000 km of 2D seismic and approximately 19,000 km^2 of 3D seismic will be shot (Figure 37). This is equivalent to the largest multi-client 3D survey ever shot by any company offshore Norway (Oil & Gas Journal, 2014).

It is clear that even with all parameters set to the least desirable, the required CO_2 storage and injection capacity can be delivered on time and at an eminently achievable scale.

Table 11 CO_2 storage deployments and retirement in the HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

Storage Site	2050	2040	2030	Average fill time for storage type (years)
Onshore EOR	**0**	**0**	**0**	**n/a**
Offshore EOR	**0**	**0**	**0**	**n/a**
Onshore hydrocarbon	**36**	**23**	**1**	**23**
Offshore hydrocarbon	**74**	**52**	**9**	**33**
Onshore aquifer	**35**	**24**	**5**	**34**
Offshore aquifer	**186**	**124**	**22**	**40**
Sum	**331**	**223**	**37**	
	To 2050	To 2040	To 2030	Total
Storage Sites retired	**36**	**3**	**0**	**39**

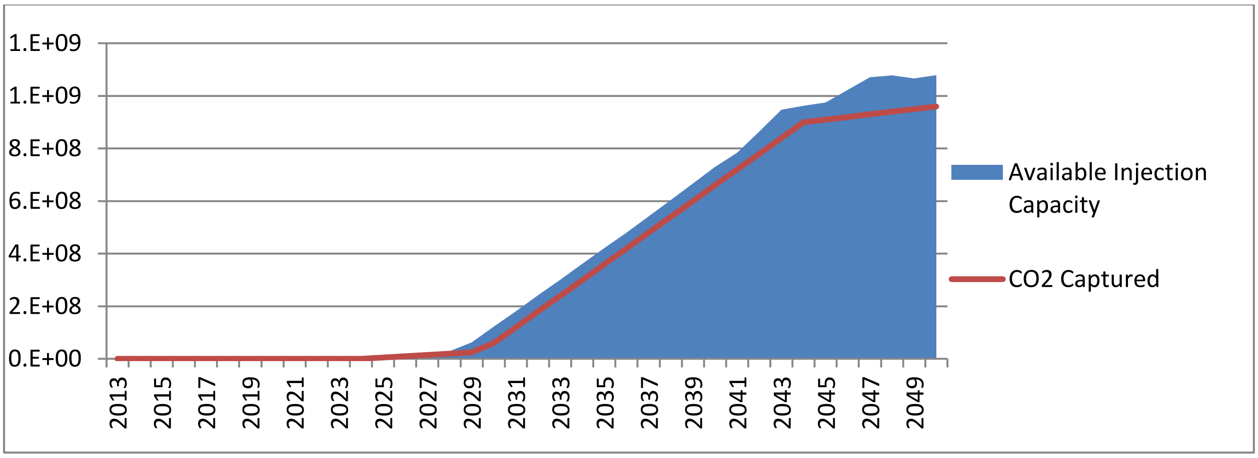


Figure 32 Injectivity available to CO_2 captured per annum. HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

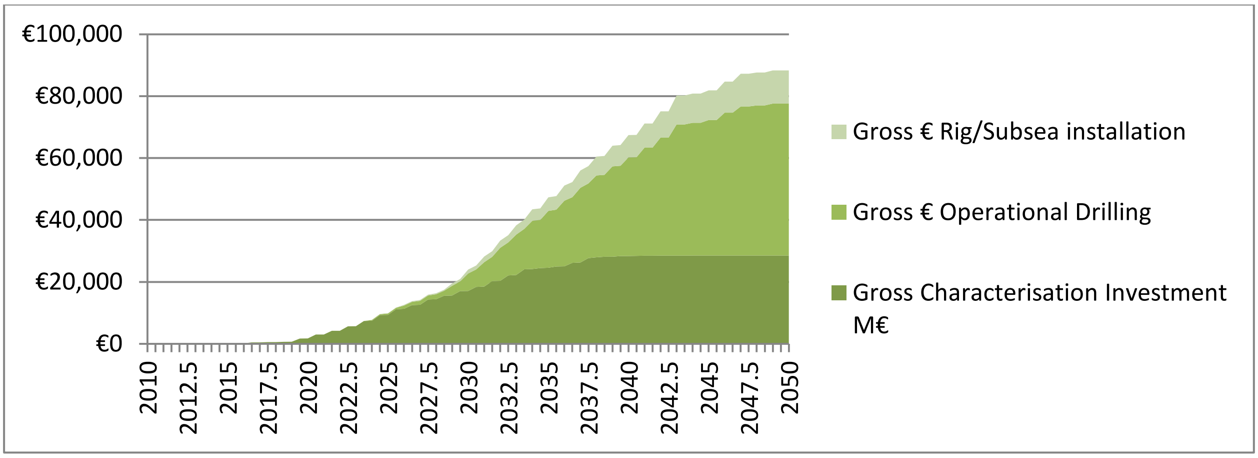


Figure 33 Gross investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

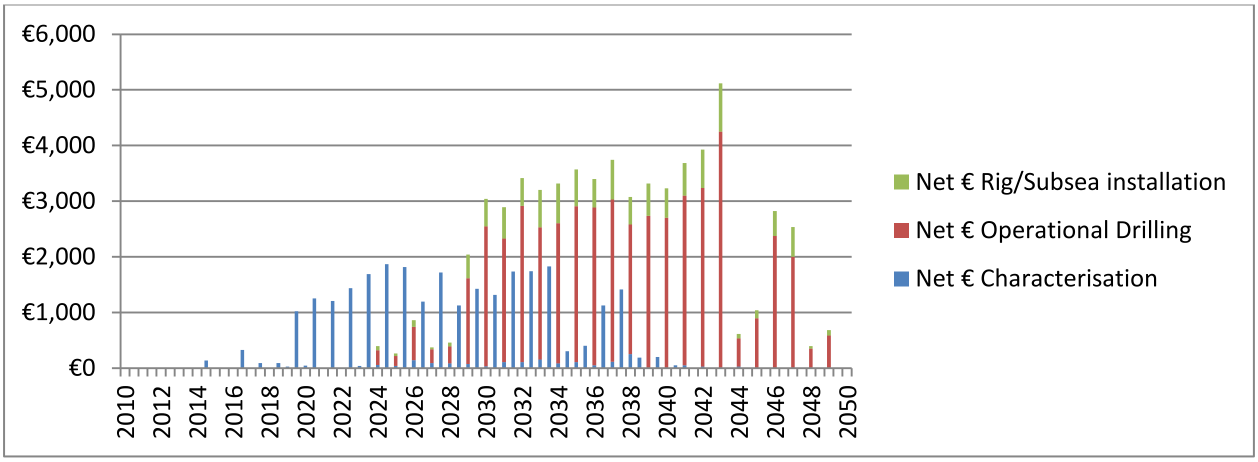


Figure 34 Annual investment (€ million) to characterise storage sites (on year characterisation begins) and development (on year storage is delivered). HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

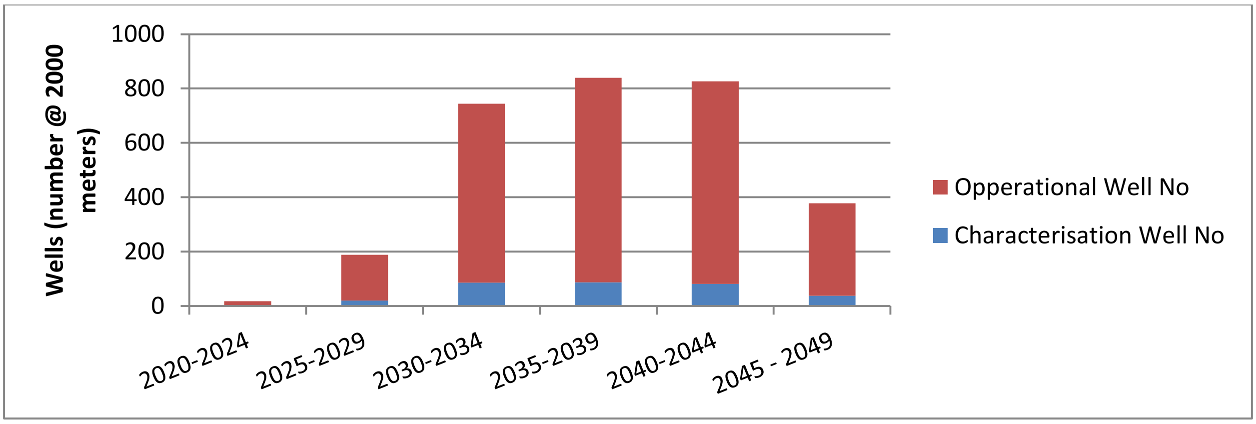


Figure 35 Wells drilled at offshore hydrocarbon and offshore aquifer. HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

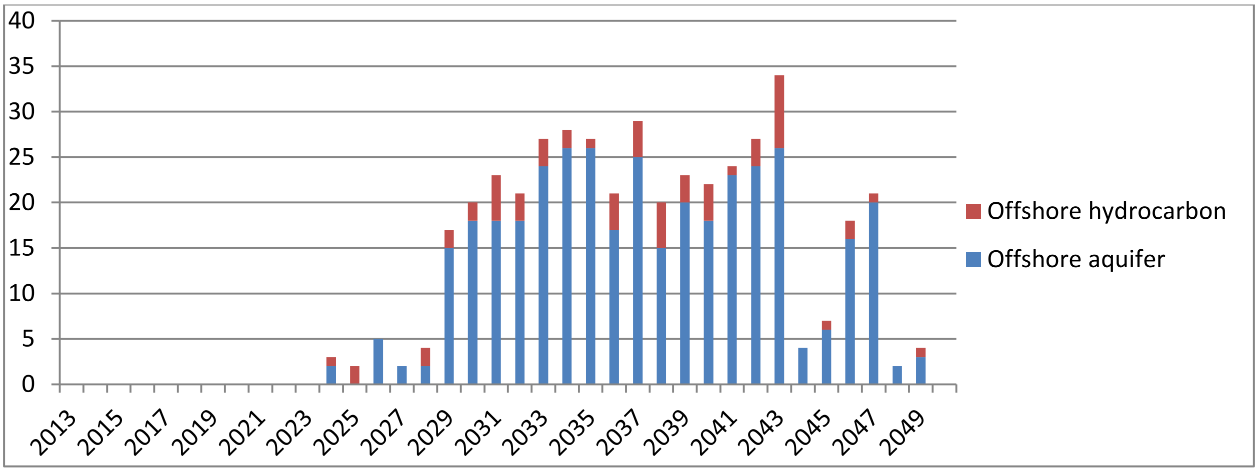


Figure 36 Ship journeys necessary to characterise offshore storage (15000 tonne ship journeys). HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

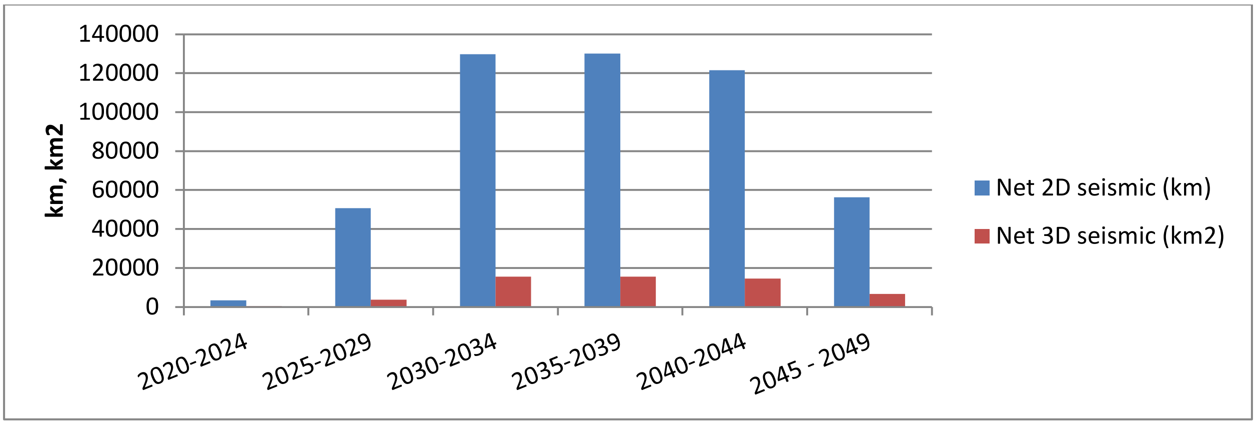


Figure 37 Offshore 2D and 3D seismic required for characterisation (km, km^2) HIGH-Capture, LOS-Deploy, LOW-CAP, LOW-INJ, LOW-I/W

Enhanced Oil Recovery (EOR) scenario

As discussed CO_2-EOR has the potential to realise the maximum potential of European energy resources while simultaneously building the infrastructure and expertise to enable the CO_2 storage industry. CO_2-EOR projects have been steadily increasing in the last decade, most in the U.S., facilitated by rising oil prices and favourable governmental incentives. However to date only one offshore CO_2 injection campaign has been undertaken at the Lula oil field in the offshore pre-salt Santos Basin, Brazil (cslforum, 2013) (Alvarado, et al., 2010). The 2011 European Value Chain for CO2 (ECCO) study clearly demonstrated the time critical dimension of CO_2-EOR application in Europe. The total number of CO_2-EOR applicable fields begins to decline post-2015, accelerating dramatically post-2020 due to the retirement and abandonment of existing infrastructure. In this way and as with CO_2 storage development the exploitation of CO_2-EOR in Europe is also time critical.

In this scenario onshore and offshore EOR projects make up approximately 40% of the total CO_2 storage sites deployed (Table 12). However, the contribution of EOR projects to the total storage capacity is relatively minor when compared to aquifers and depleted hydrocarbon fields (Figure 38). Figure 38 gives a detailed overview of the CO_2 stored at EOR projects over the period to 2050. Even in this scenario with a very large deployment of EOR, less than 6% of injection capacity will be provided by offshore EOR projects.

Whether such a deployment of EOR in Europe is practicable is debatable. Both Figure 40 and Figure 41 give estimates of the incremental oil production over the period. This incremental oil production may be crucial in catalysing early investment and development of CO_2 storage activates in Europe. However, whether sufficient oil fields would be available or suitable to undergo CO_2 floods as modelled in this scenario at this time is unclear. Table 13 gives details on the on the 29 offshore EOR projects deployed by the model. An analysis will be carried out in order to contrast the hypothetical CO_2 EOR fields and time of deployment to real world data. As has been made clear in studies such as (Løvseth, et al., 2012) the window of opportunity for the best offshore EOR candidates will have passed by 2030. In this scenario EOR projects are only feasible from the late 2020s as that is when sufficient CO_2 begins to be captured.

Table 12 CO_2 storage deployments and retirement in the Reference & EOR-Deploy

Storage Site	2050	2040	2030	Average fill time for storage type (years)
Onshore EOR	**26**	**16**	**3**	**10**
Offshore EOR	**29**	**23**	**4**	**10**
Onshore hydrocarbon	**9**	**6**	**2**	**21**
Offshore hydrocarbon	**12**	**5**	**2**	**37**
Onshore aquifer	**14**	**9**	**1**	**37**
Offshore aquifer	**38**	**25**	**3**	**27**
Sum	**128**	**84**	**15**	
	To 2050	To 2040	To 2030	Total
Storage Sites retired	**43**	**6**	**0**	**49**

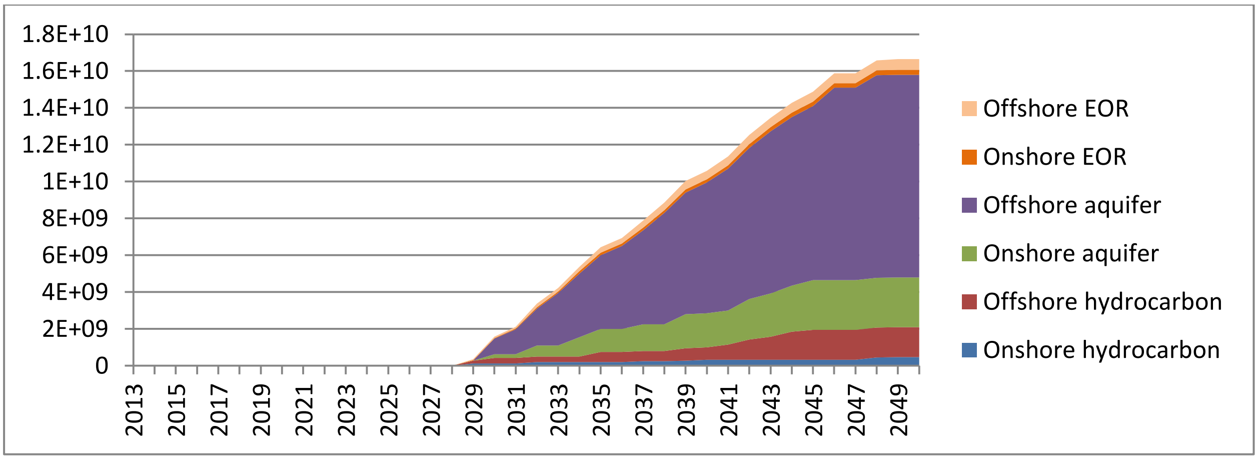


Figure 38 CO_2 Storage deployment categories (tonnes). Reference & EOR-Deploy

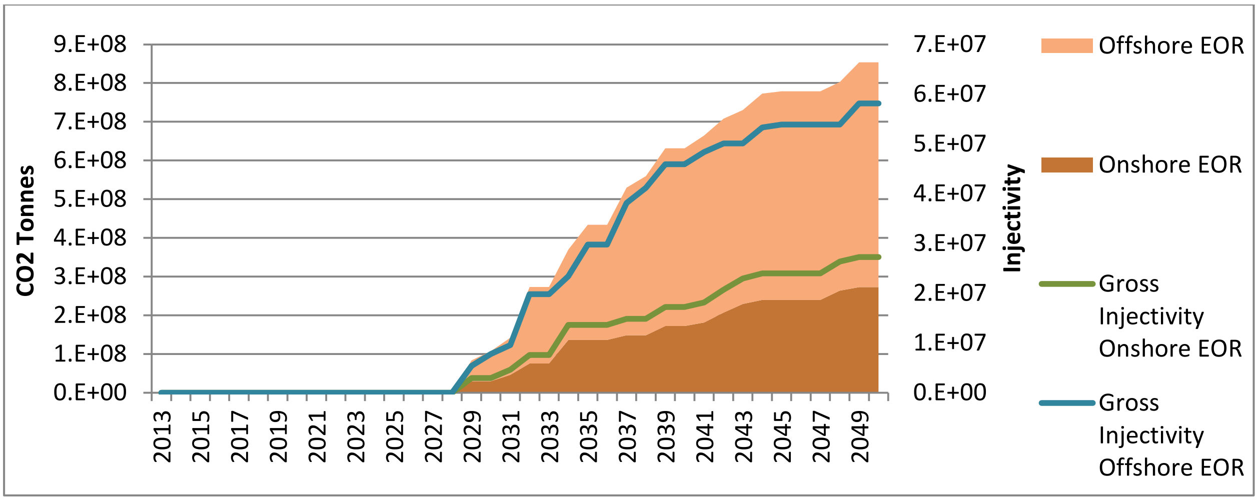


Figure 39 Onshore and offshore EOR deployment, CO_2 storage capacity delivered through EOR projects (tonnes). Reference and EOR-Deploy

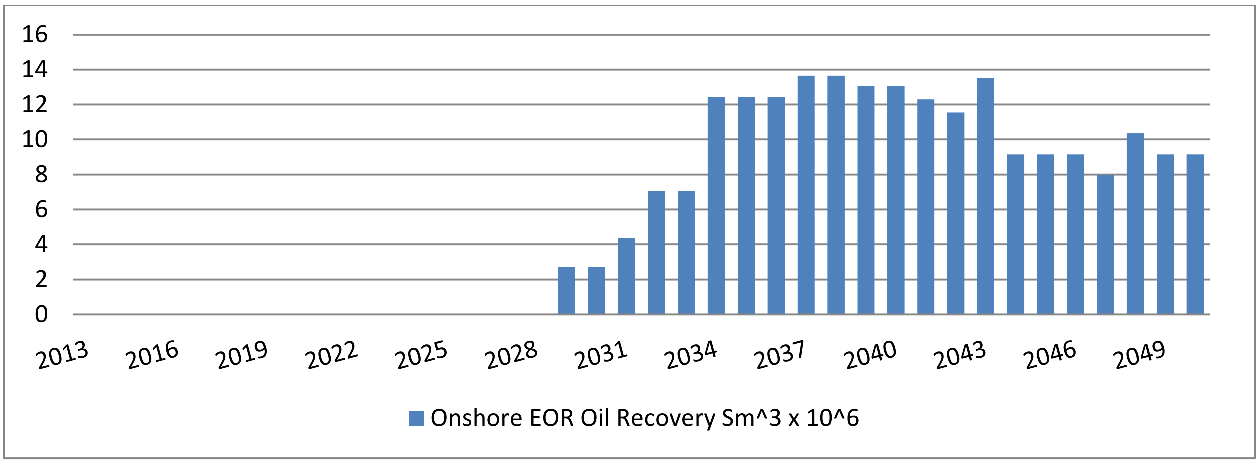


Figure 40 Onshore incremental oil produced per annum (sm^{3e6}). Reference & EOR-Deploy

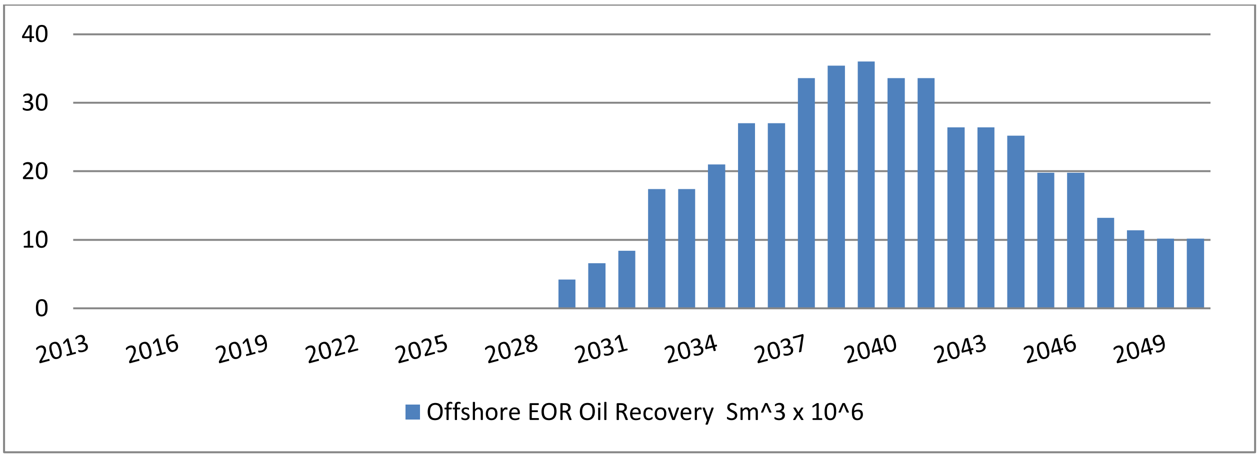


Figure 41 Offshore incremental oil produced per annum (sm^{3e6}). Reference & EOR-Deploy

Table 13 Offshore CO_2 EOR project produced to 2050. Reference & EOR-Deploy

EOR Project Start Date	CO_2 Injectivity Mtpa	SOOIP (MSm^3)	Ultimate Recovery @ 6% (MSm3)
2029	2,995,238	300	18
2029	599,048	100	6
2029	1,797,143	300	18
2030	2,396,190	400	24
2031	1,797,143	300	18
2032	3,194,921	400	24
2032	1,597,460	200	12
2032	2,995,238	500	30
2032	2,396,190	400	24
2034	2,396,190	400	24
2034	1,198,095	200	12
2035	2,396,190	400	24
2035	1,198,095	200	12
2035	1,597,460	200	12
2035	1,198,095	200	12
2037	2,995,238	300	18
2037	1,797,143	300	18
2037	2,396,190	300	18
2037	1,198,095	200	12
2038	2,995,238	300	18
2039	1,797,143	300	18
2039	1,198,095	200	12
2039	1,797,143	300	18
2041	2,396,190	300	18
2042	1,797,143	300	18
2044	3,194,921	400	24
2045	599,048	100	6
2049	1,797,143	300	18

CONCLUSIONS AND FUTURE WORK

Urgent need to invest in CO_2 storage industry

The lead times for the characterisation and development of CO_2 storage capacity both on- and offshore is measured in years. This study has found that there is a critical need to have a functioning investment environment for CO_2 storage operators from the end of this decade. This is the case under both reference scenarios and high capture rate scenarios.. Annual investments in the range of €500 million need to begin by 2020 in order to provide the injection and storage capacity needed for the 2030s. Even under a low capture scenario these investments are only delayed to the mid-2020s. It should be noted that such a delay would likely reduce the eventual CCS deployment in Europe – locking out a key low carbon technology.

CO_2 storage industry will be large

This study has given insights into the potential scale of CO_2 storage operation in Europe to 2050. Under all capture scenarios the activities to characterise and develop storage sites are proven to be of a feasible scale. The investments or activities of CO_2 storage do not dwarf the investments or activities of comparable industries, such as the oil and gas sector.

This however, is not to say that the investments and activities are insignificant. The scale of the CO_2 storage industry has the potential to be comparable to the scale of current oil and gas activities. The need for wells, seismic, injection testing and expert human resources will rival and may even surpass that of oil and gas operations in many European countries.

This raises the discussion of the rate of return for prospective CO_2 storage operators. This is specially the case when considering a potential competition with the oil and gas industry for limited drill rigs and human resources. It is clear that a robust business case for CO_2 storage, with long term security, must exist to attract human and financial capital. The time for putting in place a framework which can assure this is rapidly approaching.

Low carbon industry with high employment

The development of a European CO_2 storage industry has the potential to maintain, transfer and grow existing European expertise and employment. Development of required CO_2 storage and injection capacity will necessitate extensive seismic surveying, characterisation, injection testing, drilling and monitoring. The anticipated scale of the industry will generate skilled employment, attract investments to on- and offshore activities and generate income for the European economy, but only if policies are enacted now to attract investment to the CO_2 storage sector.

Injectivity is the critical parameter

The analysis of key performance indicators (KPI) has revealed injectivity of storage sites to be the major driver of CO_2 storage deployment. Lower injectivity has outsized effects on the number of storage sites to be deployed under all capture scenarios. Under the scenarios run, the lower injectivity scenario resulted in a doubling of the cost and scale of CO_2 storage deployment.

Reaching material rates of injection is absolutely necessary for the successful deployment of CCS. The role injection capacity plays in realising CCS is often underestimated. To date national CO_2 storage capacity efforts such as the Norwegian CO_2 storage atlas have focused on storage capacity and not injectivity. More effort is needed to quantify the injectivity of prospective CO_2 storage sites. This will require investments in injection testing.

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