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The decisive role of the carbon storage potential in the deployment of the CCS option

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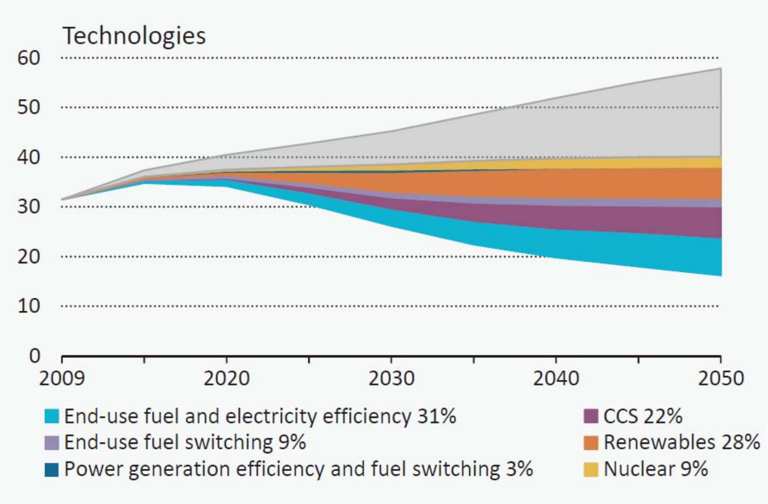
Introduction: The place of CCS technologies in the future climate regime

Over the past decade and while in May 2013 CO_2 concentration in the atmosphere reached record high of 400 ppm, Carbon Capture and Storage (CCS) has increasingly been dealt as a possible, not to say an expected, solution to achieve CO_2 emissions mitigation objectives. Indeed, despite of persistent controversies, in terms of i) a significant and uncertain costs that this technology requires, ii) a too low level of investment and progress as regards a plausible large scale deployment of the technology but also of infrastructures (i.e. transport, shared platform, for example), iii) support of incentives by comparison with other options, as renewables, or iv) the risks of storage for environment and human health that question the social acceptability and the appropriate place of CCS within the portfolio of GHG abatement strategies, CCS technologies are still presented as a solution to reach ambitious climate target. Moreover, in the 2DS of IEA, CCS contributes for 22% of CO2 emissions reduction (*Figure 1*).

Figure 1: Contributions to emissions reductions in the 2DS



Source : ETP 2012, Figure 1.9, p.39

MiniCam model has predicted that a 2.6 W/m² limitation of radiative forcing (a constraint in line with the 2DS) is achievable with 20 Gt of CO2 stirage/year till 2020. In TIAM-FR, in case of the same strong climate constraint, so a 2.6 w/m², without overshoot, 19% of the power generation come from plants with CCS (based on fossil or biomass resources) in 2050. Renewables then represent 50% of the power generation, and nuclear and hydro, 16% and 11% respectively.

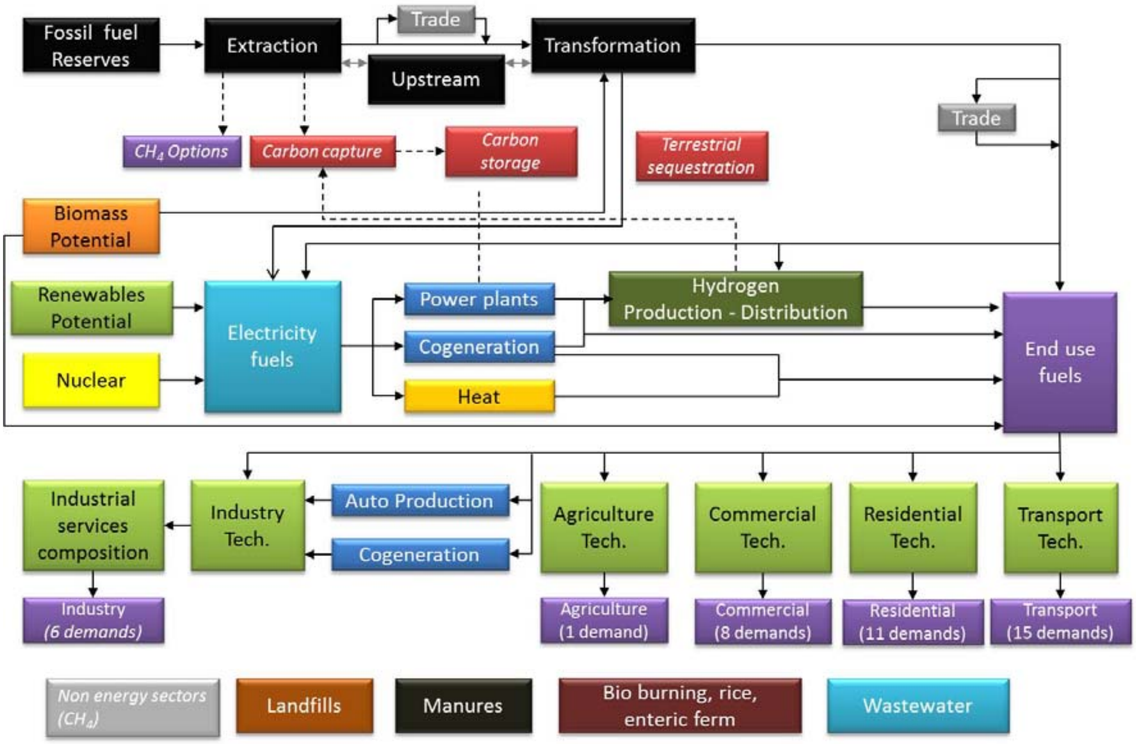
The potential of deployment of CCS is also highly connected to the potential of carbon storage. In TIAM-FR (and ETSAP-TIAM), the assumed level of this potential is not a constraint for the development of this solution but the question is if data are always in line with literature? The question of the location of the sites, in the sense of an offshore and onshore distribution, also impacts the structuring of the CCS sector, in terms of availability, acceptability and cost. The purpose of this analysis is to estimate the CO_2 storage capacity at a regional level based on updated data from available literature and discuss the impact of this potential on the development of the CCS option in a climate context. Then, different scenarios on the availability of storage sinks (particularly offshore/onshore) were conducted in TIAM-FR to evaluate whether CCS deployment is limited.

Methods: Model, database and scenarios

The model

This analysis is developed with TIAM-FR, a bottom-up model describing the world energy system in great detail of current and future technologies expressed by region and sector. TIAM-FR, of the ETSAP-TIMES family model, is a geographically integrated model, with 15 world regions[1], on the time horizon from 2005 to 2100. TIAM-FR includes several thousand current and future technologies in all sectors of the energy system (energy procurement, conversion, processing, transmission, and end-uses). *Figure 2* gives a synthetic description of the reference energy system (RES) covering the whole energy chain. The main outputs of the model are future investments and activities of technologies for each time period. Furthermore, the structure of the energy system is given as an output, i.e. type and capacity of the energy technologies, energy consumption by fuel, emissions, energy trade flows between regions, transport capacities, a detailed energy system costs, and marginal costs of environmental measures as GHG reduction targets. An additional output of the model is the implicit price, or opportunity cost (shadow price), of each energy form, material and emission.Indeed, the model tracks emissions of CO_2, CH_4, and N_2O from fuel combustion and processes. Emission reduction is brought about by endogenous demand reductions, technology and fuel substitutions (leading to efficiency improvements and process changes in all sectors), carbon sequestration, including CO_2 capture at the power plant and hydrogen plant level, sequestration by forests, and carbon storage.

Figure 2: Synthetic view of the reference energy system



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[1] Africa (*AFR*), Australia-New Zealand (*AUS*), Canada (*CAN*), China (includes Hong Kong, excludes Chinese Taipei; *CHI*), Central and South America (*CSA*), Eastern Europe (*EEU*), Former Soviet Union (includes the Baltic states, *FSU*), India (*IND*), Japan (*JPN*), Mexico (*MEX*), Middle-East (includes Turkey; *MEA*), Other Developing Asia (includes Chinese Taipei and Pacific Islands; *ODA*), South Korea (*SKO*), United States of America (*USA*) and Western Europe (EU-15, Iceland, Malta, Norway and Switzerland; *WEU*).

More precisely, the global potential of carbon storage is close to 10,000 Gt. If we compare with different models, this level is more optimistic that MERGE (1,466 Gt) and TIMER (5,500 Gt) but more restrictive than REMIND, POLES and E3MG which assume unlimited potential. Different storage options exist in the sense that storage capacities data are classified according to a regional distribution and the storage site type, i.e. deep saline aquifers, coal basins, depleted oil and gas fiels, and so, for all type, to the storage site location, i.e. onshore and offshore (*Figure 3*).

Figure 3: Regional carbon storage potential in TIAM-FR

Gt CO_2	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	WORLD
Enhanced Oil Recovery	3	0	3	1	8	2	15	0	0	38	0	1	0	8	0	77
Depl oil fields (onshore)	3	0	3	1	8	2	23	0	0	56	4	8	0	8	0	113
Depl gas fields (onshore)	11	1	10	0	23	0	168	0	0	150	8	23	0	8	11	411
Depl oil fields (offshore)	2	1	1	0	2	0	0	0	0	8	2	1	0	8	3	26
Depl gas fields (offshore)	4	6	5	0	0	0	0	0	0	38	8	15	0	8	23	105
Enhanced Coalbed Meth recov <1000 m	4	15	8	8	0	1	13	4	0	0	0	12	0	45	6	115
Enhanced Coalbed Meth recov >1000 m	4	15	8	8	0	1	13	4	0	0	0	12	0	45	6	115
Deep saline aquifers (onshore)	1000	500	667	500	1000	250	1000	500	5	500	250	1000	10	1000	250	8432
TOTAL	1029	538	702	518	1039	256	1231	508	5	789	271	1071	10	1128	300	9392

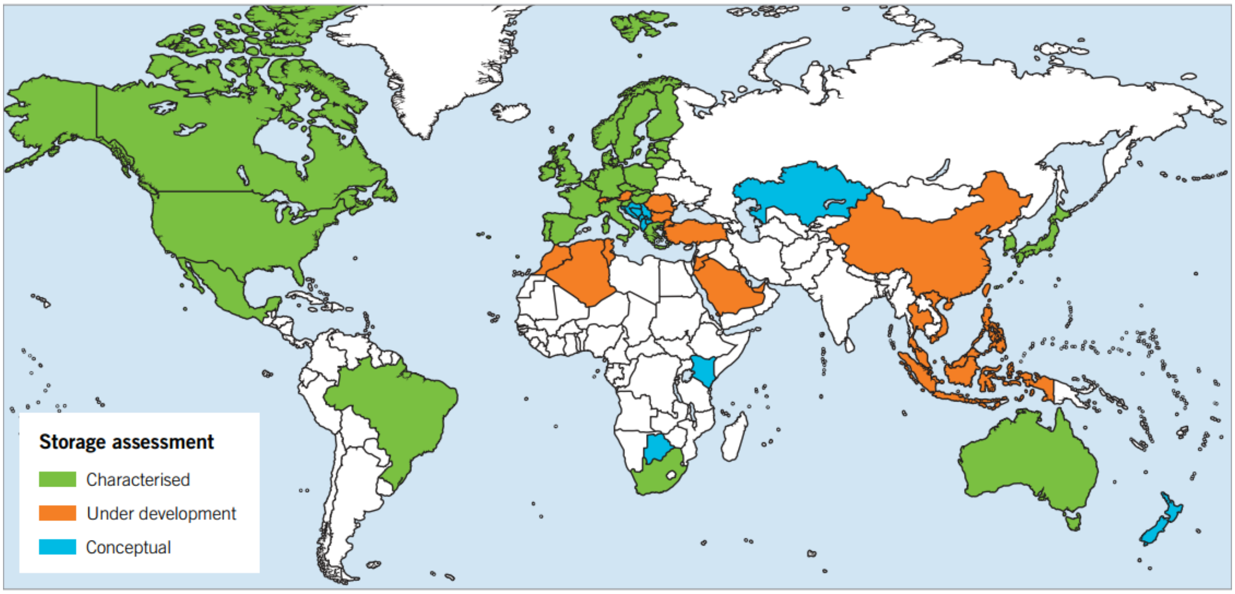
In this context, we verified if current data exist. This concerns regional carbon storage potential but also cost of transport. We developed an onshore/offshore distribution when missing and present the impact of these storage assumptions on the future energy system and on the deployment of CCS technologies, with a specific consideration of the public resistance for onshore CO_2 storage.

The carbon storage database and the carbon transport costs

We first realized a state of the art of regional carbon storage potentials to propose updated and new data in the model, and particularly, we add a new distribution between onshore and offshore potential as regards deep saline aquifers and enhanced oil recovery. Many sources have been used as the North American Carbon Storage Atlas (2012), the United States Carbon Utilization and Storage Atlas – DOE & NETL (2012, 4th edition), IEA, Dooley *et al.* (2005), Hendricks (2004), Ecofys (2004) ZEP (2010), McKinsey & Compagny (2008), USGS World Petroleum Assessment (2000), and various specific national sources. A brief study was done to look into the storage capacities assumed by other Energy models (as MERGE, REMIND, POLES, E3MG, TIMER).

Currently, very few countries have done an assessment of their storage capacity. The following map (*Figure 4*) representing regional initiatives highlights, with a characterized assessment in green, an under development assessment in orange, a conceptual assessment in blue and no assessment in white. This assessment, when done, has not been done for every type of storage. Furthermore, different methodologies and assumptions exist and are used by countries or organisms to assess the storage capacity. Oil and gas fields are completely assessed, data being relatively available. United States Geological Survey (USGS) and (Total Petroleum Systems (TPS) location data were used to determine the onshore/offshrore classification for oil and gas fields. For saline aquifer and coal bed storage, data are extrapolated for whole country, based on few surveyed fields. It is then more difficult to find an onshore/offshore classification. After a review of existing references and estimates, different choices was made according to methodologies following the more relavant and plausible assumptions. Concerning enhanced oil recovery capacity estimation, 96% of world known oil reserve were studied. As regards storage in depleted gas fields, we excluded fields with a capacity less than 50 Mt of carbon (onshore) or 100 Mt CO_2 (offshore) due to economical reasons.

Figure 4: Regional carbon storage potential in TIAM-FR (Gt)



Source: Global CCS Institute Status of CCS 2012

In this study, we selected the global data from IEAGHG (2009b) and then we classified it into regions and storage site by using other sources as, for example, Hendricks; United States Geological Survey (USGS), Total Petroleum System (TPS) and specific national or industrial data. Classifying storage data according to their type and location will provide a deeper insight regarding CCS deployment feasibility under climate constraints. As said previously, storage potential study was done for 96% of known oil reserve in the world and 60% of the gas fields, this is the most suitable given data constraints. Investigating the storage capacities in each reservoir require a huge investment of time, capital and manpower. In most of the regional studies research is performed for selected sites and then extrapolated for the whole region based on assumptions. Aggregating the data from such sources has two major problems: data for each country in that region may not be available, due to different assumptions and methodology in each study the aggregated data may not lead to correct storage capacity estimates. Storage capacities estimated for each country using these references may not be accurate as many small storage sites have been neglected but an uniform methodology has been applied which gives reliable estimates for each region that can be compared and aggregated. For proper planning of the CCS projects, it is important to have the storage potential estimates along with the timeline of their availability. Storage in depleted oil and gas fields can only be started once the production is ceased. Source-sink matching is also an important factor in CCS projects-planning. This issue is analyzed in the literature we have used, but it is not included in this study. However, huge potential of storage lies in the saline aquifers and there are not this problem of source-sink matching as in the case of Oil and Gas reservoirs. Pipeline installation is a labor intensive job. The storage capacity estimates in this study refers to effective storage capacity taking into account geological and engineering constraints. Gas fields having both onshore and offshore reservoirs are classified under ‘Both’ (and in the new database, in ‘Onshore’). Except Hendriks, none of the references have the data for CO_2 storage in depleted oil fields without EOR and in most of the reference storage, depleted oil fields is synonymous to Enhanced Oil Recovery. New data are less optimistic than in other sources. None of the identified references have information about the depth of the storage site so it is not possible to classify the storage estimate as performed by initial sources. We then consider an half and half distribution, as initialy. Deep saline aquifers have the largest storage potential but among all sources, least information is available about storage in saline aquifer. None of the reference sources had storage estimates classified on onshore/offshore location. So the Dooley’s distribution was finally selected for the updated TIAM-FR scenario studies.

In a second step, even if capture is the most important part of the CCS cost, contributing 80% or more, we explore the costs of carbon transport. And due to the new classification for saline aquifer, onshore and offshore, we proposed different cost according to the location of the site. Capex represents the main part of the cost which are specific to the site, due to various characteristics about the pipeline (depending on the material, the volume of transported CO_2, the diameter) and the topography of the area. But essentially, cost variation results from the location, between onshore and offshore and don’t depends on the type of storage site. A cost multiplier by region according to IEA reference (IEA GHG) allows to take into account of regional disparities. TIAM model also integrates a regional coefficient, notably inducing lower costs in Africa (for all type of sites excluded deep saline aquifers), Former Soviet Union (for EOR or gas fields for example), Central and South America (for coalbed methane recovery or oil/gas onshore fields and EOR), Europe, Japan and South Korea (for coalbed methane recovery), etc.

Figure 5: CO2 transport costs

$/t CO_2	TIAM model	McKinsey (2008)	ZEP (2010)
Enhanced Oil Recovery (onshore)	10	5.2	2.77
Enhanced Oil Recovery (offshore)	10	7.8	4.47
Depleted oil fields (onshore)	10	5.2	2.77
Depleted gas fields (onshore)	10	5.2	2.77
Depleted oil fields (offshore)	10	7.8	4.47
Depleted gas fields (offshore)	10	7.8	4.47
Enhanced Coalbed Methane recovery <1000 m	10	5.2	2.77
Enhanced Coalbed Methane recov ery >1000 m	10	7.8	2.77
Deep saline aquifers (onshore)	10	5.2	2.77
Deep saline aquifers (offshore)	10	7.8	4.47

CO_2 transport costs estimates used previously in the TIAM-FR model are bit higher than the transport costs reported in the references used in this study and there is no difference between the cost of onshore and offshore transport. Cited references are here the ZEP (2010) estimates of storage costs for an optimistic approach or McKinsey & Company (2008) estimates. Though these references conclude that it is very difficult to generalize the cost of CO_2 transport as it is project/site dependent, it is convenient to have an average estimate. Then, we investigate different scenarios according to the regional carbon storage potentials, the regional costs of transport, and a possible allowed location of carbon storage, offshore and onshore.

The scenario specification

Finally, we realized an impact analysis of these new potential by comparison with previous data to discuss whether CCS deployment can be limited by assumed storage conditions. To analyze possible alternative development paths of CCS technologies in a future low carbon regime, we investigated a climate scenario with a strength constraint in line with the 2° C objective, over the period 2005-2100. More precisely, we investigated a 2.6 W/m² limitation of radiative forcing scenario, without overshoot. A sensitivity analysis is carried out considering different assumptions about regional carbon storage potential, or more specifically, as follows:

- *Clim_Ini*: with initial data of the model;
- *Clim_Doo*: with Dooley’s assumptions;
- *Clim_HenL*: with Hendricks’ assumptions, Low scenario;

- *Clim_HenB*: with Hendricks' assumptions, Best scenario;
- *Clim_HenH*: with Hendricks' assumptions, High scenario;
- *Clim_Misc*: with data issued from the literature review and reports.

We also specify a scenario allowing to exclude onshore storage due to a hypothetic policy considering public resistance to the onshore storage. This scenario limits the carbon storage to the offshore sites. According to IEA reports, carbon transport cost is around 8-10 \$/tonne of transported carbon; this considers a 250 km of pipeline. In TIAM model, carbon transport cost are assumed to be 10 \$/tonne of transported carbon, we then implement a specific scenario where carbon transport cost are assumed to be 20 \$/tonne of transported carbon, assuming a longer pipeline. Otherwise, carbon transport costs are assumed to be the McKinsey ones (Figure 5) applying with IEA regional coefficients.

Results

Considering the climate context, we first analyse the penetration of carbon capture technologies in the power generation according to the assumptions of carbon storage potential. Indeed we particularly examine the share of electricity generated by plants with CCS in the various scenarios that we implemented. As previously mentioned, plants with CCS generate close to 20% of the world electricity in 2050, in a strong climate context, in TIAM-FR included initial values of carbon storage potential (*Clim_ini*). They generate close to 24% in 2100. In *Clim_Misc* and *Clim_Doo*, where the global carbon storage potential is also around 10,000 Gt[2], the share of electricity generated by plants with CCS represents 18.5% and 23.7% respectively in 2050, and 22.6% and 23% in 2100. The comparison with the *Clim_Hen* scenarios - where the global carbon storage potential is lower - is interesting in the sense that, in the *Best* and *High* cases, CCS technologies remain an important solution to reach ambitious climate target, with 21.7% and 24.2% respectively in 2050, and 17.4% and 23.6% respectively in 2100. Note that the share is higher in 2050 (by comparison with 2100), particularly in the *Clim_HenB* scenario where the plants with CCS "only" generate 17.4% of the world electricity. However, the level of power generation increase in this scenario, from 9.853 TWh in 2050 to 15.498 TWh in 2100. In the *Clim_HenL* scenario (with an assumption of lower potential of carbon storage, i.e. 572 Gt CO_2 against 1,706 and 5,864 Gt CO_2 respectively in the *Best* and *High* scenarios), CCS represents 10.5% of the power generation in 2050 and 6.79% in 2100. In other terms, 4,648 TWh of electricity are produced by plants with CCS in 2050 and and 7,430 TWh in 2100, two time less than in the scenario *Clim_HenB.*

Figure 6: Electricity mix (%) by scenario

Scenario	Period	Coal	Gas and Oil	**CCS**	Nuclear	Hydro	Geo and Tidal	Solar PV	Solar Thermal	Wind
Clim_ini	2050	0.3	2.2	**19.5**	15.4	10.7	1.4	32.9	5.5	11.1
	2100	0.0	0.0	**23.9**	13.1	9.0	10.1	27.9	5.1	10.3
Clim_Doo	2050	0.3	1.0	**23.7**	14.6	10.3	1.2	32.2	5.4	10.6
	2100	0.0	0.1	**23.0**	13.2	9.1	10.0	29.0	5.2	9.9
Clim_HenL	2050	0.2	5.4	**10.5**	16.0	11.3	1.8	35.4	6.7	11.9
	2100	-	4.9	**6.8**	10.8	11.5	8.9	37.4	4.2	13.9
Clim_HenB	2050	0.3	1.4	**21.7**	14.6	10.4	1.4	33.4	5.4	10.6
	2100	-	1.2	**17.4**	13.0	11.1	9.9	29.6	5.1	11.9
Clim_HenH	2050	0.3	0.7	**24.2**	14.5	10.2	1.1	32.2	5.3	10.6
	2100	0.0	0.0	**23.6**	13.3	8.8	9.8	28.9	5.2	10.0
Clim_Misc	2050	0.3	2.9	**18.5**	14.6	10.4	1.5	34.2	5.4	11.2
	2100	0.0	0.1	**22.6**	13.1	9.7	10.0	28.8	5.2	9.9

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[2] For the detailed distribution of the carbon storage potential by region, type and location, see the Annex.

Note: CH4 options and biomass (except with CCS)are not included in this table, due to minor importance (less than 1%).

The development of intermittent solutions is important in these climate scenarios. According to the scenario, they represent between 48 and 54% of the electricity production in 2050 and between 43 and 55% in 2100; the higher development being in the *Clim_HenL* scenario where the CCS is less used. As for CCS, this large scale exploitation requires to invest in infrastructures and in storage solutions. The latter also concerns solar thermal where options exist to store the heat energy of the solar thermal power plants but the performance is still too low.

What’s happen when the cost of carbon transport is twice higher (expressing to take into account of higher length of pipeline)?

Figure 7: Electricity mix (%) by scenario with higher costs of carbon transport (twice higher)

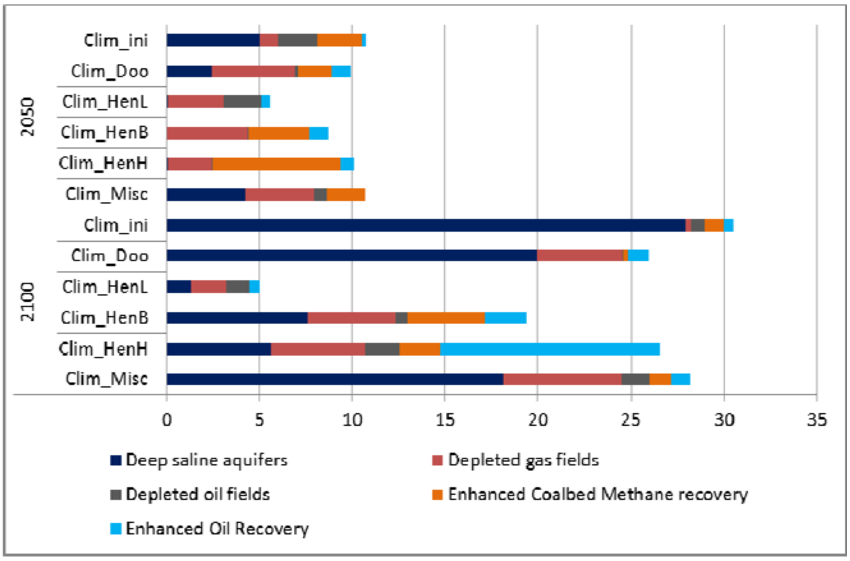
Scenario	Period	Coal	Gas and Oil	**CCS**	Nuclear	Hydro	Geo and Tidal	Solar PV	Solar Thermal	Wind
Clim_Doo_2	2050	0.3	1.0	**22.0**	15.0	10.2	1.4	33.2	5.3	10.7
	2100	0.0	0.1	**22.3**	13.2	9.2	10.0	29.4	5.2	10.0
Clim_HenL_2	2050	0.2	5.5	**9.9**	15.8	11.3	2.2	35.4	6.6	12.3
	2100	-	4.9	**6.8**	10.9	11.5	8.9	37.1	4.4	14.0
Clim_HenB_2	2050	0.3	1.4	**21.1**	15.0	10.4	1.5	33.6	5.2	10.7
	2100	0.0	1.2	**17.4**	12.9	11.2	10.0	29.5	5.0	12.0
Clim_HenH_2	2050	0.3	0.9	**22.8**	15.0	10.3	1.3	32.6	5.4	10.6
	2100	0.0	0.0	**22.8**	13.2	9.1	10.0	29.2	5.2	9.9
Clim_Misc_2	2050	0.3	1.1	**22.0**	15.0	10.2	1.2	33.3	5.3	10.7
	2100	0.0	0.1	**21.2**	13.4	10.1	10.3	28.7	5.3	10.2

Note: CH4 options and biomass (except with CCS)are not included in this table, due to minor importance (less than 1%).

It is interesting to note that the impact on CCS of an increase of the carbon transport cost is limited. Indeed, the electricity mix is almost the same. And, more precisely, the power generation from CCS plants remains around 10,000 TWh in 2050 and 19,000 TWh in 2100 in all scenarios, except in the *Clim_HenL_2* scenario with the lowest storage potential.

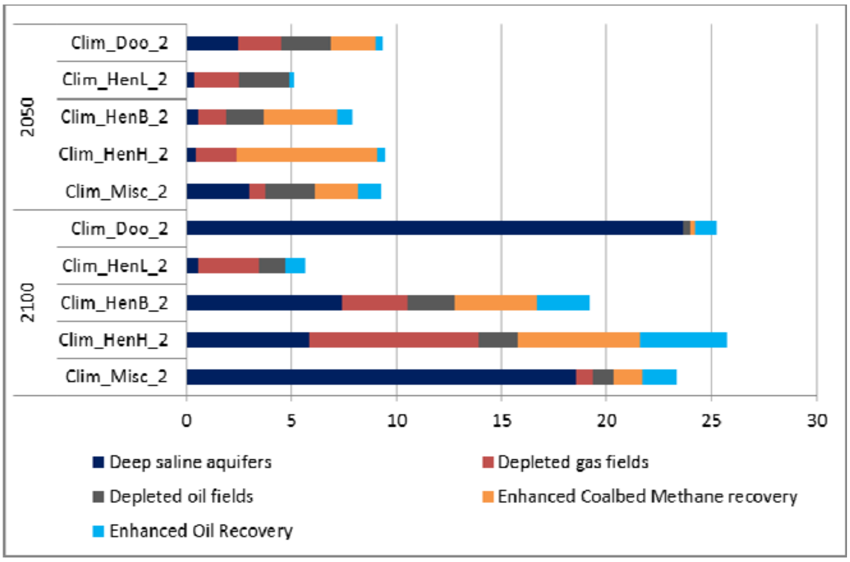
The question is now the one of the carbon storage and more precisely, the type of carbon storage site. Indeed, the development of the CCS option in terms of power plants equipped with capture technologies, requires to store carbon in specific sites. As said previously, storage capacities data are classified according to a regional distribution and the storage site type, i.e. deep saline aquifers, enhanced coalbed methane (ECBM)reservoirs, depleted oil and gas fiels. This level of CCS development implies the storage of 10 Gt per year of carbon in 2050 (6 Gt/y in the *Clim_HenL* scenario) in 2050 and between 26 and 37 Gt/y of CO2 in 2100 (5 Gt/y in the *Clim_HenL* scenario and 19 Gt/y in the *Clim_HenB* scenario).

Figure 9: Carbon storage by site and by scenario (Gt CO2)



In *Clim_Hen* scenarios (Low, Best, High), in 2050, the carbon is essentially stored in depleted basins and for enhanced recovery, and the storage in deep saline aquifers is inexistent, unlike in the othe scenario, and especially in the *Clim_ini* and *Clim_Misc* scenarios, where this type of site represent 47 and 40% of the carbon storage respectivelu. In 2100, this site represent 92, 77 and 64% respectively in *Clim_ini*, *Clim_Doo* and *Clim_Misc*, and more precisely, respectively 28, 20 and 18 Gt/y of stored CO2. In 2100, storage by EOR is largely developed in the *Clim_HenH* scenario, with 12 Gt/y and 45% of the carbon storage.

Figure 10: Carbon storage by site and by scenario with higher costs of carbon transport (Gt CO2)

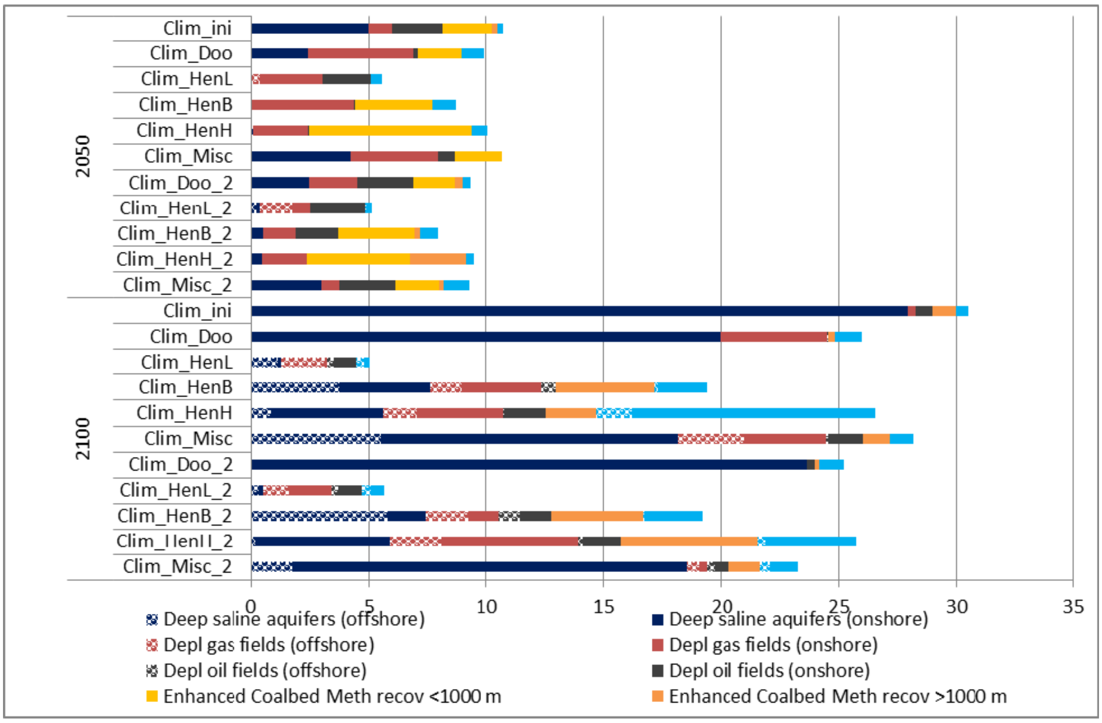


While a higher cost of carbon transport does not really imply a limitation of the CCS development, it is interesting to note that the situation is different concerning the type of storage site. Indeed, in 2050, storage in deep saline aquifer is more developed to the detriment of depleted gas fields in *Clim_Hen* scenarios. In 2100, the most important impact is the less development of EOR, especially in

Clim_HenH, with 17 Gt/y of stored carbon against 10 Gt/y in the scenarios implementing a higher transport cost.

The storage site, whatever the type between deep saline aquifers or depleted oil/gas fields, are essentially located onshore. As regard deep saline aquifer, the carbon is not stored in offshore site before the end of the time horizon. This is the same concerning depleted fields, except in the *Clim_HenL* and *Clim_HenL_2* scenarios, where carbon is stored depleted fields, onshore and offshore.

Figure 11: Carbon storage by site with onshore/offshore classification (Gt CO2)



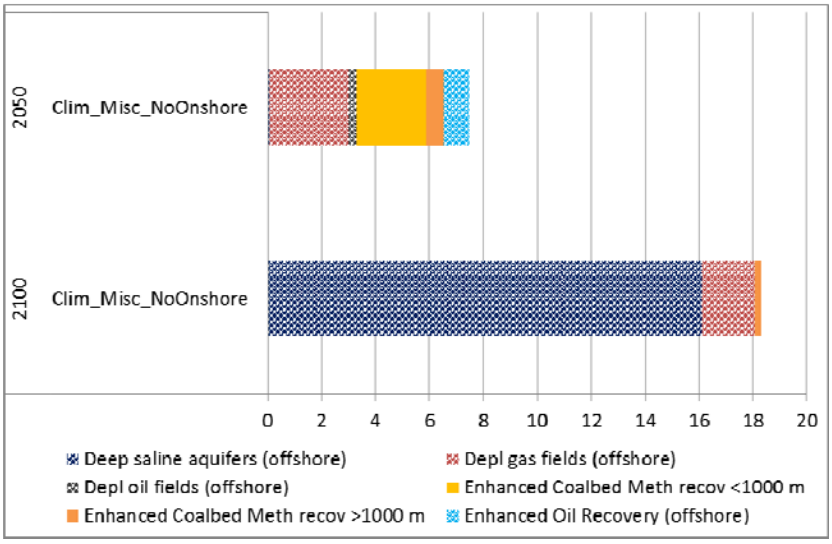
The question of carbon storage involves public resistance due to worries concerning leakage, and by consequence, due to health issues, sand the fact that once CO_2 leaks from the storage reservoir, efforts made to fight climate change would be lost. Considering this problem of social acceptability, we implemented a scenario where onshore storage could be prohibited in the *Clim_Misc* scenario.

Figure 12: Electricity mix (%) in the case of prohibited onshore storage

Scenario	Period	Coal	Gas and Oil	**CCS**	Nuclear	Hydro	Geo and Tidal	Solar PV	Solar Thermal	Wind
Clim_Misc_NoOnshore	2050	0.3	4.1	**13.2**	15.1	11.1	1.6	35.6	6.2	11.8
	2100	0.0	2.7	**13.2**	12.8	9.9	10.0	34.2	4.1	12.0

While plants with CCS generate, in *Clim_Misc*, 18.5% in 2050 and 22.6% in 2100 of the world electricity (5,773 TWh in 2050 and 11,904 TWh in 2100), the contribution of plants with CCS is limited to 13.2% of the power mix, in the Clim_Misc_NoOnshore scenario, i.e. without the development of onshore projects of carbon storage. This implies to store 7.5 Gt/y of carbon in 2050 until 18.31 Gt/y in 2100.

Figure 13: Carbon storage by site in Clim_Misc_NoOnshore (Gt CO2)



In 2050, the carbon is mainly stored in depleted gas fields and ECBM (<1000m) while in 2100, offshore deep saline aquifers have to be used to the carbon storage.

Conclusion

Giving the challenge of mitigating the effects of climate change and so reducing the level of carbon emissions, this study highlights the role of carbon storage in the development of CCS which, currently, is the only technology that can capture at least 90% of the emissions from the world's largest CO_2 emitters. This is particularly important in a world where fossil is not yet an outdated and disappearing source of energy. Even if the first challenges that needs to be addressed is the large-scale developpement of CCS, this option can not throw off the need to store captured carbon or develop a chain of applications where the carbon would have an economic value. This study focuses on the carbon storage side and discusses, through detailed and updated data on storage potential (with onshore and offshore classification) and cost of carbon transport, whether the potential may be a limit to the development of CCS. We then investigated various scenarios with different levels of carbon storage potentials and we examine the impact on the CCS development of an increase of the carbon transport cost. Finally, we analyse the consequence of the prohibition of the onshore storage.

First, except in the *Clim_HenL* scenario where the carbon storage potential is very low (i.e. 512 Gt), in a global manner, the development of CCS technologies seems to not be impacted by the level of carbon potential. However, it is interesting to note that in the case of lower level of carbon storage potential, in other words in the case of *Clim_Hen* scenarios, the development of CCS is lower at the end of the period than in the other scenarios. It could be interesting to extend the time horizon to determine if the constraint of potential can be then saturated. Otherwise, the question of the type of storage site appears to be more important. Second, a twice higher cost of carbon transport does not limit the penetration of carbon capture technologies but it impacts the choice of the site. Particularly, a higher transport cost appears to be detrimental to the storage in depleted gas fields and to the EOR at the end of the period. Finally, the carbon storage is mainly operated in onshore site. A limitation of the onshore storage, due to public resistance for example, could have an important impact on the penetration of the CCS option. Higher costs and lower potential can limit the contribution of CCS to the global warming and then implies to accentuate the efforts and the investments on other options, as renewables or nuclear.

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Annexes

Annex A : Carbon storage by type and by region in TIAM-FR model

Carbon storage (Gt)	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	1.3	0.0	2.5	0.8	3.1	1.5	13.2	0.0	0.0	32.4	0.4	0.0	0.0	6.8	0.0	62
EOR (Offshore)	1.3	0.0	0.0	0.0	4.4	0.0	1.8	0.0	0.0	5.1	0.0	1.1	0.0	0.7	0.4	15
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	10.5	0.8	10.0	0.0	22.5	0.0	168.0	0.0	0.0	150.0	7.5	22.5	0.0	7.5	11.3	411
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	3.8	6.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	37.5	7.5	15.0	0.0	7.5	22.5	105
Coaldbed Meth. Rec. <1000m	3.8	15.0	7.5	8.0	0.0	1.3	12.5	4.0	0.0	0.0	0.0	12.0	0.0	45.0	6.0	115
Coaldbed Meth. Rec. >1000m	3.8	15.0	7.5	8.0	0.0	1.3	12.5	4.0	0.0	0.0	0.0	12.0	0.0	45.0	6.0	115
Deep saline aquifer (Onshore)	337	151	534	455	773	227	211	250	0	469	125	402	5	750	85	4772
Deep saline aquifer (Offshore)	663	349	133	45	227	23	789	250	5	31	125	598	5	250	165	3659
TOTAL	1029	538	702	518	1039	256	1231	508	5	789	271	1071	10	1128	300	9392

Annex B : Carbon storage by type and by region in Hendricks (2004) – Low scenario

Storage site	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	0.5	0.0	0.0	0.2	0.8	0.1	1.7	0.0	0.0	5.1	0.0	0.1	0.0	0.8	0.0	9
EOR (Offshore)	0.5	0.0	0.0	0.0	0.5	0.0	0.2	0.1	0.0	0.8	0.0	0.1	0.0	0.1	0.3	3
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	15.2	0.1	6.7	4.0	9.9	2.9	71.3	4.1	0.0	92.6	0.0	2.9	0.0	7.8	5.0	223
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	7.4	7.2	0.7	0.3	10.9	0.0	26.1	1.9	0.0	70.6	0.0	19.1	0.0	1.9	23.2	169
Coaldbed Meth. Rec. <1000m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Coaldbed Meth. Rec. >1000m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Deep saline aquifer (Onshore)	2.1	1.1	1.8	1.5	2.9	0.4	0.9	1.4	0.0	1.1	0.0	0.3	0.0	1.7	0.4	15
Deep saline aquifer (Offshore)	4.0	2.4	0.4	0.2	0.9	0.0	3.2	1.4	0.2	0.1	0.0	0.5	0.0	0.5	0.9	15
TOTAL	34	12	13	7	35	5	126	9	0	234	6	32	0	28	33	572

Annex C : Carbon storage by type and by region in Hendricks (2004) – Best scenario

Storage site	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	6.2	0.0	0.4	3.0	10.4	0.9	21.8	0.4	0.0	62.0	0.0	1.0	0.0	6.2	0.1	112
EOR (Offshore)	8.1	0.5	0.3	0.5	8.6	0.0	2.9	0.6	0.0	9.3	0.0	1.4	0.0	0.5	4.0	37
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	37.6	0.3	14.7	11.7	28.3	6.8	197.3	13.4	0.0	260.4	0.0	9.8	0.0	13.7	15.4	609
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	17.8	17.3	0.8	0.4	25.0	0.0	73.5	5.2	0.0	85.7	0.0	34.9	0.0	2.1	38.8	302
Coaldbed Meth. Rec. <1000m	3.8	5.7	4.3	79.0	1.0	0.4	12.5	1.0	0.1	0.0	0.0	9.5	0.0	15.9	0.5	133
Coaldbed Meth. Rec. >1000m	3.8	5.7	4.3	79.0	1.0	0.4	12.5	1.0	0.1	0.0	0.0	9.5	0.0	15.9	0.5	133
Deep saline aquifer (Onshore)	16.2	8.5	13.9	12.2	23.4	3.1	7.0	10.6	0.0	9.1	0.0	2.6	0.0	13.0	3.5	123
Deep saline aquifer (Offshore)	31.8	19.6	3.4	1.2	6.9	0.3	26.0	10.6	1.9	0.6	0.0	3.8	0.0	4.3	6.8	117
TOTAL	129	58	45	188	114	13	376	43	2	491	6	81	0	87	73	1706

Annex D : Carbon storage by type and by region in Hendricks (2004) – High scenario

Storage site	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	42.4	0.2	3.1	23.0	67.3	5.1	132.4	2.1	0.0	405.8	0.0	6.0	0.0	44.5	1.1	733
EOR (Offshore)	85.0	5.0	3.2	3.4	72.9	0.0	19.3	3.0	0.0	61.1	0.0	10.9	0.0	4.8	39.9	309
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	73.4	0.7	18.3	31.3	72.6	8.5	457.8	33.5	0.0	540.7	0.0	24.9	0.0	23.0	29.1	1314
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	47.9	40.7	1.3	1.1	89.8	0.0	292.6	14.1	0.0	117.7	0.0	65.7	0.0	3.3	135.6	810
Coaldbed Meth. Rec. <1000m	23.0	27.1	25.5	420.4	5.9	2.1	75.1	6.0	0.3	0.0	0.0	57.0	0.0	95.1	2.9	740
Coaldbed Meth. Rec. >1000m	23.0	27.1	25.5	420.4	5.9	2.1	75.1	6.0	0.3	0.0	0.0	57.0	0.0	95.1	2.9	740
Deep saline aquifer (Onshore)	72.8	38.0	62.2	54.8	105.2	13.8	31.3	47.8	0.0	40.9	0.0	11.6	0.0	58.2	15.8	552
Deep saline aquifer (Offshore)	143.4	88.3	15.5	5.5	30.9	1.4	117.2	47.8	8.4	2.7	0.0	17.2	0.0	19.4	30.9	528
TOTAL	515	228	158	961	459	35	1223	160	9	1233	6	259	0	358	261	5864

Annex E : Carbon storage by type and by region in Dooley et al. (2005)

Storage site	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	6.4	0.0	0.0	3.2	8.0	0.0	19.4	0.0	0.0	28.7	0.0	1.5	0.0	10.2	0.2	78
EOR (Offshore)	8.3	0.0	0.0	0.5	6.7	0.0	2.6	0.0	0.0	4.3	0.0	2.2	0.0	0.8	7.1	32
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	42.3	0.2	3.5	7.1	25.3	7.3	187.0	5.3	0.0	143.5	0.0	6.4	0.0	31.8	11.5	471
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	20.0	10.8	0.2	0.2	22.4	0.0	69.7	2.0	0.0	47.2	0.0	22.9	0.0	4.9	28.8	229
Coaldbed Meth. Rec. <1000m	3.7	14.7	1.9	7.4	1.9	1.9	9.2	3.7	0.0	0.0	0.0	12.9	0.0	29.4	1.9	88
Coaldbed Meth. Rec. >1000m	3.7	14.7	1.9	7.4	1.9	1.9	9.2	3.7	0.0	0.0	0.0	12.9	0.0	29.4	1.9	88
Deep saline aquifer (Onshore)	117	205	1001	330	187	106	370	187	0	224	0	121	0	2732	73	5654
Deep saline aquifer (Offshore)	231	477	249	33	55	11	1386	187	0	15	0	180	0	909	143	3876
TOTAL	437	723	1261	390	317	130	2076	389	0	526	6	368	0	3762	271	10655

Annex F : Carbon storage by type and by region in miscellaneous sources

Storage site	AFR	AUS	CAN	CHI	CSA	EEU	FSU	IND	JPN	MEA	MEX	ODA	SKO	USA	WEU	World
EOR (Onshore)	5.2	0.0	1.7	3.8	3.9	0.6	19.1	0.4	0.0	55.3	4.6	0.0	0.0	15.4	0.0	110
EOR (Offshore)	5.4	0.3	0.0	0.0	5.6	0.0	2.6	0.5	0.0	8.8	0.0	0.9	0.0	1.6	4.0	30
Depl. Oil Fields (Onshore)	2.6	0.0	2.5	0.8	7.5	1.5	22.5	0.0	0.0	56.3	3.8	7.5	0.0	7.5	0.4	113
Depl. Gas Fields (Onshore)	17.0	0.0	12.0	7.0	29.0	5.0	202.0	0.0	0.0	31.0	0.0	8.0	0.0	33.0	0.0	344
Depl. Oil Fields (Offshore)	1.5	0.8	0.5	0.2	1.5	0.0	0.0	0.0	0.0	7.5	2.3	1.1	0.0	7.5	3.0	26
Depl. Gas Fields (Offshore)	15.0	18.0	0.0	1.0	14.0	0.0	53.0	1.0	0.0	114.0	1.0	38.0	0.0	7.0	56.0	318
Coaldbed Meth. Rec. <1000m	3.4	15.0	2.0	6.4	2.5	0.3	9.5	2.5	5.0	0.0	0.0	12.0	0.0	30.5	0.3	89
Coaldbed Meth. Rec. >1000m	3.4	15.0	2.0	6.4	2.5	0.3	9.5	2.5	5.0	0.0	0.0	12.0	0.0	30.5	0.3	89
Deep saline aquifer (Onshore)	7	204	22	331	1545	16	443	32	0	9	50	483	0	1738	26	4907
Deep saline aquifer (Offshore)	13	475	6	33	455	2	1657	32	47	1	50	717	0	578	51	4117
TOTAL	74	728	49	389	2067	25	2418	70	57	283	112	1279	0	2449	142	10142