ECO_2 project number: 265847

Deliverable Number D5.2: Economic considerations associated with offshore CCS; WP5; lead beneficiary no 18 & 24 (IfW, ECN))

Offshore CCS and Ocean Acidification: A Global Long-Term Probabilistic Cost-Benefit Analysis of Climate Change Mitigation

Reyer Gerlagh [a] and Bob van der Zwaan [b,c,d]

[a] Tilburg University, Economics Department, Tilburg, The Netherlands.
[b] Energy research Centre of the Netherlands (ECN), Policy Studies Department, Amsterdam, The Netherlands.
[c] University of Amsterdam, Faculty of Science, Van 't Hoff Institute of Molecular Sciences, The Netherlands.
[d] Johns Hopkins University, School of Advanced International Studies, Bologna, Italy.

Abstract

Public fear for environmental and health impacts or potential leakage of CO_2 from geological reservoirs is among the reasons why over the past decade CCS has not yet been deployed on a large enough scale so as to meaningfully contribute to mitigate climate change. Storage of CO_2 under the seabed moves this climate mitigation option away from inhabited areas and could thereby take away some of the opposition towards this technology. Given that in the event of CO_2 leakage for sub-seabed CCS the ocean would function as buffer for receiving this greenhouse gas, rather than the atmosphere, offshore CCS could particularly address concerns over the climatic impacts of CO_2 seepage. In this paper we point out that recent geological studies confirm that leakage for individual offshore CCS operations may be highly unlikely from a technical point of view, if storage sites are well chosen, well managed and well monitored. But we argue that on a global long-term scale, for an ensemble of thousands or millions of storage sites, leakage of CO_2 could take place in certain cases and/or countries for e.g. economic, institutional, legal or safety cultural reasons. We investigated what the impact could be in terms of temperature increase and ocean acidification if leakage would nevertheless occur, and addressed the question what the relative roles could be of on- and offshore CCS if mankind desires to divert the atmospheric damages resulting from climate change. For this purpose, we constructed a top-down energy-environment-economy model, with which we performed a probabilistic cost-benefit analysis of climate change mitigation with on- and offshore CCS as specific CO_2 abatement options. One of our main conclusions is that even if there is non-zero leakage for CCS activity on a global scale, there is high probability that both onshore and offshore CCS could – on economic grounds – still account for anywhere between 20% and 80% of all future CO_2 abatement efforts under a broad range of CCS cost assumptions.

1. INTRODUCTION

Although aspects of both the technical and economic, legal, political as well as public acceptance dimensions of CO_2 capture and storage (CCS) require deeper understanding, this technology possesses many features enabling it to become a major mechanism to curb global CO_2 emissions. According to the Special Report on CCS (SRCCS) of the Intergovernmental Panel on Climate Change (IPCC), it is expected that CO_2 artificially injected underground can remain securely stored during at least centuries (IPCC, 2005). The probability of long-term CO_2 storage integrity is deemed very high and storage sites can be found, if well managed and monitored, for which containment is (almost) guaranteed. The Sleipner storage plant is a good example, since in this case CO_2 has been safely stored in a geological formation under the North Sea with quantities of about a million ton of CO_2 per year since 1996. The findings of the recent ECO2 project, which involved experiments at a number of other locations, point towards the same direction, in that safe storage of CO_2 in the underground is possible.

In this paper we take a global long-term economic approach towards CCS deployment and the integrity of CO_2 stored underground. In recent CO_2 storage projects it proved that sometimes mid-term action is required in order to maintain safe containment conditions. During the operation of the Snohvit CCS project, it appeared that the storage capacity of the formation initially chosen proved insufficient, so that mid-course another geological formation was chosen for storage of CO_2. On the basis of reservoir, seismic and geo-mechanical data obtained at the In Salah CO_2 storage project concerns arose about possible vertical leakage of CO_2 into the cap-rock, as a result of which the storage activities at this plant were suspended in 2011. These two examples indicate that not always all features of the planned storage formation can be fully comprehended before a storage project is initiated. We think that it is imaginable that not in all future storage projects, the same adaptive approach would necessarily be adhered to as in these two cases. For example, it could be that not in all countries the same monitoring efforts are deployed, for a number of reasons, such as the lack of the corresponding technical expertise. It could be that not the same safety requirements are followed by lack of political will or absence of necessary safety culture. It could be that for institutional reasons no action is taken upon observed breach of storage containment, for example as a result of unclear agreements over responsibilities and liabilities. There could be economic reasons for initiating CCS projects, e.g. stimulated by a high enough carbon tax, but costs of managing, monitoring and remediating could form the reason why insufficient action is undertaken when seepage is observed. Such economic, institutional, legal or social drivers for possible CO2 leakage phenomena may diverge substantially from one country to the other.

In other words, if a global large-scale long-term approach is taken, we argue, it cannot be entirely excluded that CO_2 may once leak from geological reservoirs to the atmosphere. That's why in the present study we stipulate such leakage rates, albeit at a very low level. In the case of slow CO_2 seepage, CCS would constitute a delay of CO_2 emissions rather than a genuine reduction option (see e.g. Wilson *et al*., 2003; van der Zwaan and Smekens, 2009). This problem is pertinent, as the use of CCS itself requires energy – applied to standard electricity generation, for example, it involves a substantial part of the energy content of the fossil fuels used. More fossil fuels are thus required to run a fossil-based power plant equipped with CCS in order to produce the same net output of electricity as a conventional non-CCS plant. Hence, with CCS application more CO_2 is captured and stored underground than the amount of avoided emissions. The climatic consequences of slow CCS-associated CO_2 leakage may thus be non-negligible, as are possibly the economic implications.

Studying the long term through the discipline of economics is challenging, but we nevertheless attempt to answer the question in this paper what the impact on the deployability of CCS is if stored CO_2 would gradually leak over a time frame of 100 years. We also inspect how one would need to evaluate such leakage in an economic framework. In an earlier publication we analysed the economics of CCS with a focus on non-trivial seepage patterns (contrasting exponential with hump-shaped leakage; see van der Zwaan and Gerlagh, 2009). In a subsequent article we analysed more in depth the underlying methodology and discussed the issues that arise with cost-benefit analysis of CCS characterised by CO_2 leakage in a setting that considers both the very long term and aspects of uncertainty (see Gerlagh and van der Zwaan, 2012). Both these papers assumed onshore CO_2 storage only. In the present paper we introduce offshore CCS as complementary option to onshore CCS, as a way to expand, refine and improve our analysis. The main rationale for now focusing on offshore CCS is the idea that if seepage of CO_2 occurs, then in the case of sub-seabed storage the ocean would be the receiving medium, rather than the atmosphere. It is broadly recognized that the damages and costs incurred to the ocean as a result of an increase of the concentration of CO_2 is much lower for leakage into the ocean as opposed to that into the atmosphere (SEI, 2012). The introduction of offshore CCS could improve the attractiveness and deployability of CCS overall.

The costs of CCS as well as public fear over potential groundwater acidification or other environmental pollution are among the reasons why over the past decade CCS technology has not been deployed on a scale large enough to contribute to mitigate climate change. Concerns over potential leakage of CO_2 from geological reservoirs add to the obstacles faced by CCS. Storage of CO_2 under the seabed moves this risk away from inhabited areas and could thereby take away some of the concerns over possible climatic or health impacts of CO_2 leakage. In the event of CO_2 leakage for offshore CCS, the ocean would function as buffer for receiving this greenhouse gas. For the present paper we constructed a top-down energy-environment-economy model, with which we performed a probabilistic cost-benefit analysis of climate change mitigation with generic abatement activity as well as both on- and offshore CCS as two other CO_2 abatement options. With this model we try to answer several questions. First, to what extent can CCS still contribute to CO_2 emissions abatement if on a global long-term scale leakage occurs at relatively low seepage rates. Second, what can under such conditions be the relative roles of onshore versus offshore CCS, given that ocean damages are likely much less than atmospheric damages as a result of CO_2 release? Third, in other words, can moving storage activity from onshore to offshore constitute a stimulus for the large-scale deployment of CCS on purely economic grounds, in addition to the possible improvements in terms of public acceptance that such a shift could entail, in the event that 100% storage integrity cannot be entirely ascertained for the ensemble of all storage sites internationally into the indefinite future? In section 2 we describe the model we use for our analysis and the way in which we apply it for this paper's purposes. In section 3 we report our findings in terms of a series of model run outcomes, while in section 4 we summarize our main conclusions.

2. Model and Methodology

For the purpose of answering these questions we constructed an optimal growth model in which prices in the global economy yield general equilibrium between supply and demand. A representative planner optimizes welfare, which is expressed by the discounted sum of utility per time period. Welfare optimization leads to the Ramsey rule for the intertemporal rate of exchange. This model thus fits in the tradition of top-down integrated assessment models, as initiated by Nordhaus (1994) with the DICE model. Like DICE, our model accounts for damages incurred as a result of climate change and proffers abatement options with which, at a certain cost, emissions of greenhouse gases can be avoided (see the appendix and/or online Support Information for the full details of our model). As in Gerlagh and van der Zwaan (2002), Hoel and Sterner (2007), and Sterner and Persson (2008), our model also includes intangible damages associated with climate change.

Our new model has certain similarities with the DEMETER model, which we previously used for related analysis and has been instrumental for studying several climate-related policy questions (see e.g. van der Zwaan *et al*., 2002, and Gerlagh and van der Zwaan, 2006). Our new model, like DEMETER, simulates the global use of fossil fuels, the CO_2 emissions resulting from their combustion, as well as the means that allow for avoiding these emissions. It includes generic production and consumption behavior and a basic climate module, and is in several ways an extension of DEMETER, since we have refined the simulation of atmospheric and oceanic CO_2 stock build-up as well as the corresponding climate change dynamics, and now explicitly include impacts such as ocean acidification. Over the past years DEMETER has been used specifically for the purpose of studying opportunities and conditions for CCS deployment, including issues such as potential CO_2 leakage (van der Zwaan and Gerlagh, 2009; Gerlagh and van der Zwaan, 2012). We here build on that work.

Unlike with DEMETER, we have now substantially simplified the simulation of energy-transition dynamics, as we do not explicitly represent in our new model the replacement of fossil fuels by mitigation options such as renewables, nor do we assume that the costs of mitigation reduce according to learning-by-doing phenomena. Rather, we keep the energy economy relatively simple, by allowing for a shift away from fossil fuels in a more stylistic way. The social optimizer can choose between either continuing with the use of fossil fuels but experiencing the damages emanating from climate change, or shifting away from them to avoid these impacts but at a given abatement cost. An additional degree of freedom for the social planner (like in DEMETER) is that CCS can be introduced as a means to decarbonize fossil fuels, which would permit their continued usage but under additional abatement costs.

New in our current approach is that we represent two types of CCS options, one for which storage of CO_2 takes place onshore, the other one offshore. We make several key assumptions for these options, in an attempt to let our model reflect stylistically some of the main features of mitigation through CCS. First, both these types of CCS are characterized by an energy penalty of 30%, which yields lower levels of CO_2 avoided versus the levels of CO_2 stored. Second, we assume that the costs of onshore CCS amount to 50 €/tCO_2 (median) with a lognormal uncertainty range of 17-150 €/tCO_2 (2.5% and 97.5% probability levels). Similarly, we assume for offshore CCS costs of 75 €/tCO_2 (median) with a lognormal uncertainty range of 25-225 €/tCO_2 (2.5% and 97.5% probability levels).[1] The difference between the costs of these two types of CCS reflects the fact that for offshore CCS additional and more advanced technology is required to perform geological injection of CO_2 through a layer of hundreds (or possibly thousands) of meters of sea or ocean water. Third, we differentiate between safe and unsafe storage sites, but assume that the type (i.e. safety level) of any particular storage site is unknown in advance. We suppose that the majority of CO_2 stored geologically will stay underground forever: for both types of CCS we assume that this immobilized quantity amounts to 70% (median) with an uncertainty range of 40-85% for all injected CO_2.

Fourth, we stipulate that for unsafe storage sites, CO_2 stored onshore leaks with a rate of 0.33%/yr (median) with a lognormal uncertainty range of 0.15-0.6%/yr.[2] The reason for this is not because we think that CO_2 cannot be stored safely underground: quite on the contrary, we think that sites can be found for which storage will be permanent. Rather, we leave open the possibility that as a result of economic, institutional or political reasons, and/or given the prevailing safety culture, storage activities in some regions or countries may not necessarily be subjected to measures required for long-term secure containment. Likewise, we suppose that from unsafe offshore storage sites CO_2 leaks with a rate of 0.5%/yr (median) with a lognormal uncertainty range of 0.2-0.8%/yr. As described in the introduction, such leakage levels are highly speculative. But on the basis of the fact that injecting, monitoring and remediating is possibly more challenging for offshore than onshore CO_2 storage, we justify our choice for slightly higher leakage rates for the former than for the latter.

[1] From here on we specify uncertainty ranges as 2.5-97.5% probability intervals.

[2] The average expected leakage is thus 30% unsafe storage times 0.33%/yr, which equals 0.1%/yr leakage.

Fifth, we assume that CO_2 (emitted or leaked) incurs two types of damage to the environment (atmosphere or ocean) in which CO_2 is released, tangible and intangible. We assume that a 3C temperature increase lead to a tangible damage cost of 2% (median) of GDP with a lognormal uncertainty range of 0.5-8%. The intangible damages from this temperature rise add another 1% cost of GDP (median), with a higher lognormal uncertainty range of 0.125-8.0% to reflect the higher uncertainty for these intangibles.[3] The tangible costs resulting from an increase in ocean acidification corresponding to a decrease in the pH parameter equivalent to 550 ppmv atmospheric CO_2 concentration increase amount to 0.1% of GDP. Given the large uncertainties in this respect, we assume a very wide probability distribution of 0.01-1.0% for these costs. Similarly, for intangible costs resulting from a corresponding drop in the pH-value amount to 1.0% of GDP, with a lognormal uncertainty range of 0.2-5.0%. Intangible damages are scaled for the base year (2020) and their value relative to output increases with income if the elasticity of marginal utility exceeds 1. We assume a median value for the elasticity of 1.5, with a range of 0.5-4.5. The pure rate of time preference is set to 1%/yr (range 0.5-2%/yr). This means that our model is calibrated consistent with a robust decline in returns on capital when economic growth slows down, as argued in Piketty and Zucman (2014). The assumed declining returns imply a robust carbon price, robust optimal emission abatement levels, and moderate climate change as the median outcome.

Of course, a model like ours requires many more assumptions, regarding for example population growth, GDP and income growth, baseline fossil fuel use and associated CO_2 emissions (energy and non-energy related) as well as the radiative forcing contributions from other greenhouse gases, return on capital investments and the intertemporal elasticity of marginal utility, as well as the costs of generic abatement activity. For the details behind the parameter values we assumed for these variables we refer to the appendix / online Support Information to this article. We ran 100 scenarios with parameter values that span the indicated uncertainty ranges. In the next session we report our results in case we run our model in a cost-benefit mode for all these scenarios, both for a set of generic emissions-, climate- and ocean-related parameters, and for several variables related to the use of CCS and potential leakage of CO_2.

[3] All modeled climate-change-induced atmospheric damage costs are incurred with a delay of at least decades. We thus abstract from possible immediate (tangible and intangible) seepage costs associated with onshore CCS, resulting from e.g. drinking water pollution, fear and/or social unrest.

3. Simulations and Interpretations

3.1. CO_2 emissions and climate impacts

Figure 1 shows the results of our Monte Carlo analysis for CO_2 emissions until the year 2100. In almost all cases emissions peak before the middle of the century (only a handful of scenario runs involve emissions that still rise after 2050), while more than half of the 100 scenarios yield emission reduction profiles from already in or before 2020 (cf. the 50% probability line), and only about 10% of them reach their highest emission level after 2040 (cf. the 90% probability line). Around 90% of the scenarios yield zero-level emissions before 2100: our cost-benefit analysis thus implies that the assumed level of climate change damages does no longer allow increases in the atmospheric concentration of CO_2 after 2100 in the majority of cases. In Figure 2 we see that the concentration of CO_2 in the atmosphere has reaches its peak in more than half of the scenarios before 2050. For only few of the cases this concentration keeps on rising after this century, while emissions start declining during this century for all scenarios except one (see Figure 1). For all cases depicted in Figures 1 and 2 we see a stark deviation from business-as-usual, for which both emissions and concentrations of CO_2 rise rapidly during the entire 21st century.

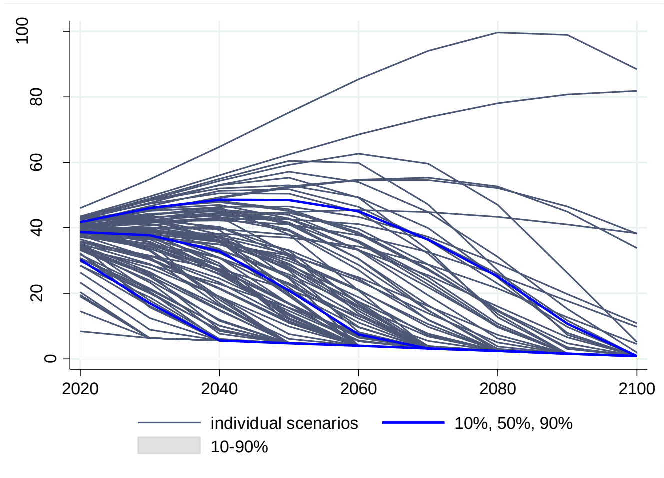

Figure 1. *Annual emissions ($GtCO_2/yr$).*

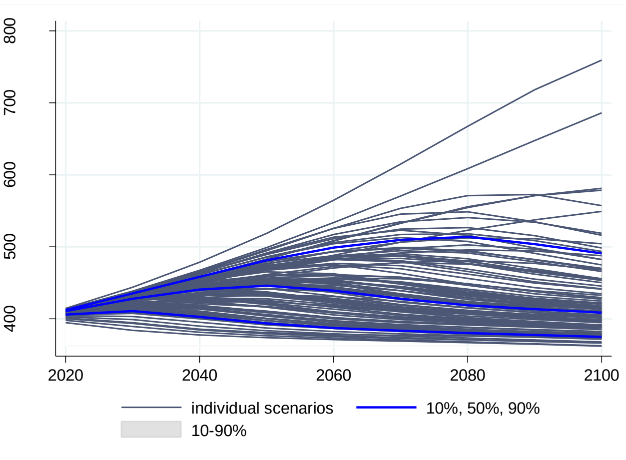

Figure 2. *Atmospheric CO_2 concentration (ppmv).*

Figure 3 (note the time scale is until 2300) shows that the global stabilized temperature increase stays below the internationally agreed 2ºC limit in about 50% of the cases, whereas a subset thereof yields a temporary overshoot (during only several decades) slightly above 2ºC around the end of this century. In slightly under 90% of the scenarios the global average temperature discontinues to rise after 2100. The share of scenarios for which the temperature increase stays always below this target is around 40%. All scenarios reach their temperature peak before 2300 (but in one case this peak is as high as about 5 ºC). Some 10% of the scenarios stabilize with a temperature increase of around 1ºC or lower, with a peak of this increase occurring well before the end of the 21st century of at most

1.5ºC. For around 10% of the scenarios we find temperature increase peaks that are above 3.5ºC, which typically take place around the end of the century. In Figure 4 (note the time scale is again until 2300), we see for these scenarios the corresponding oceanic acidification increase, as expressed by measure of pH decrease, since much of the CO_2 released into the atmosphere is absorbed by the surface layer of our planet's oceans. As one can observe from this Figure, the pH decrease amounts to at most 0.1 for around 90% of the scenarios. In about 10% of the cases we see that the pH parameter dips deeper than a change of 0.1, and in one case even by as much as 0.3. For all scenarios we see that after a minimum of the pH value around or before 2100, it increases again during the subsequent two centuries: as a result of large-scale emission abatement activity, the pH decrease patterns revert into positive changes from 2100 onwards.

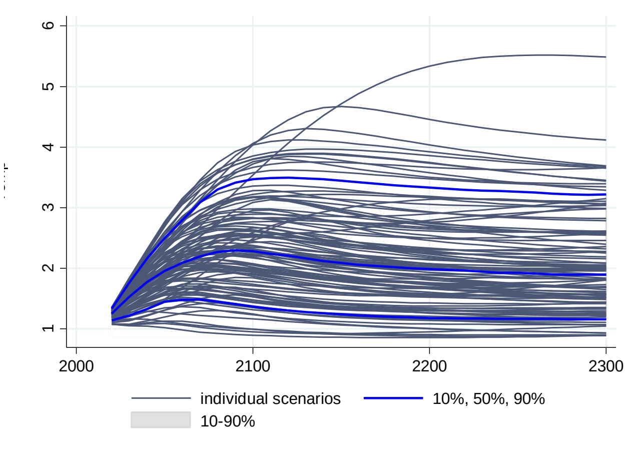

FIGURE 3. *Global temperature increase (°C).*

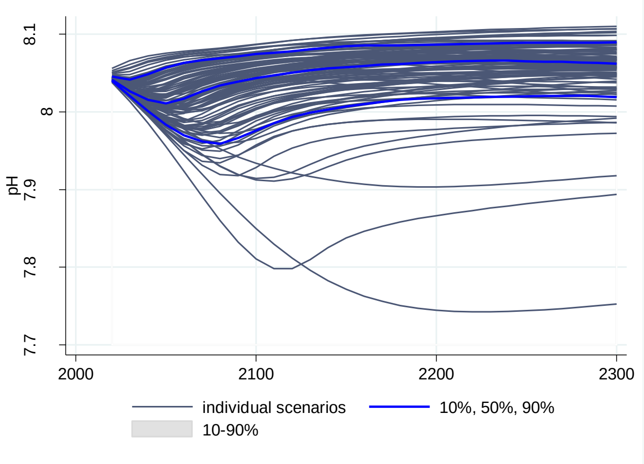

FIGURE 4. *Ocean acidification (pH).*

3.2. Onshore versus offshore CCS

We find that CCS is massively deployed as CO_2 abatement option in order to manage global climate change. CO_2 is stored both onshore and offshore. In Figures 5 and 6 we see that in some 50% of our scenarios we have a substantial level of around 20 GtCO_2 of storage per year around the end of the century, both for onshore and offshore CCS. In the majority of cases we see already 10 GtCO_2 is geologically stored every year by the middle of the century, and for about 10% of the cases even as much as 40 GtCO_2 annually by 2100, with again no large differences between onshore and offshore CCS. Hence, under our current set of assumptions, we observe substantial storage activity for both types of CCS, with onshore CCS benefiting from its lower deployment costs and leakage rate, while offshore CCS profiting from the lesser damage costs it incurs.

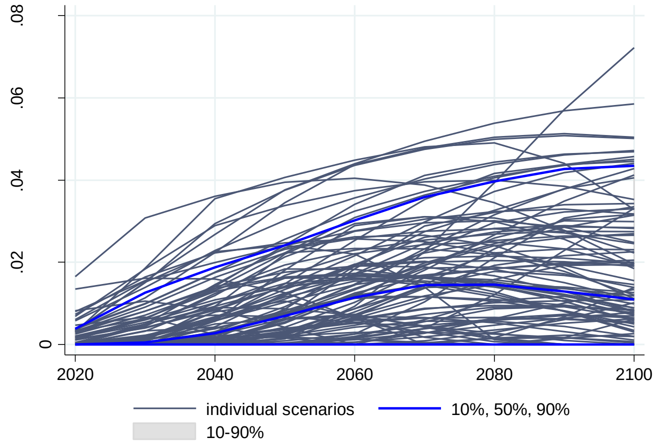

FIGURE 5. *Annual storage of CO_2 onshore (1000 $GtCO_2$/yr).*

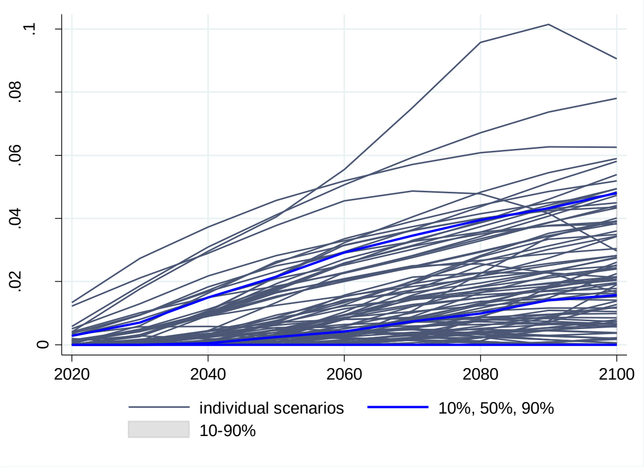

Figure 6. *Annual storage of CO_2 offshore (1000 $GtCO_2$/yr).*

Figures 7 shows that if the minimum value of the costs of the two CCS options is 20€/tCO_2 or lower, some 80% of overall CO_2 abatement takes place through CCS, rather than other options such as renewables. Even at a 50€/tCO_2 minimum CCS cost it is expected that CCS's contribution to total mitigation efforts is still large, on average about 30%, but there is a non-zero probability that it is close to 0% and could be as high as 60%. At CCS costs between 100€/tCO_2 and 150€/tCO_2, the use of CCS is significantly curtailed, but can still amount to a level contributing by approximately 20% to overall climate mitigation. In Figure 8 we indicate under what cost conditions which of the two CCS types dominates. If the injection of CO_2 offshore is at most 10% more expensive than onshore injection, then there is at least a 50% probability that offshore CCS is the preferable option, accounting for at least 60% of all CCS deployment. For cost differences of 30%, onshore CO_2 storage becomes more attractive, with over 50% chance that onshore CCS accounts for more than 60% of all CCS. The explanation for the fact that relatively higher offshore CCS costs can be permitted is the lower level of damages incurred to the environment in the case of leakage of CO_2 into the ocean, in comparison to the case in which leakage occurs into the atmosphere.

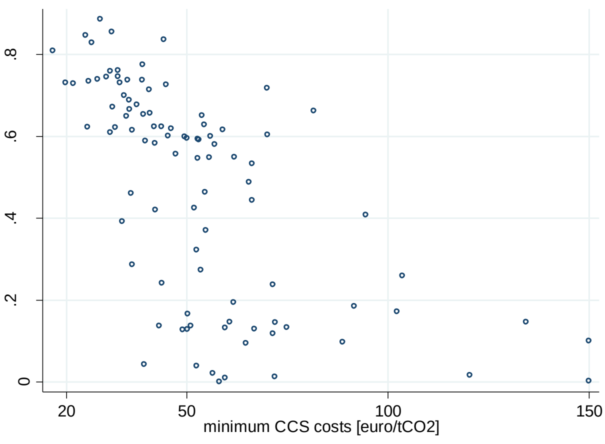

FIGURE 7. *Share CCS in overall emissions abatement.*

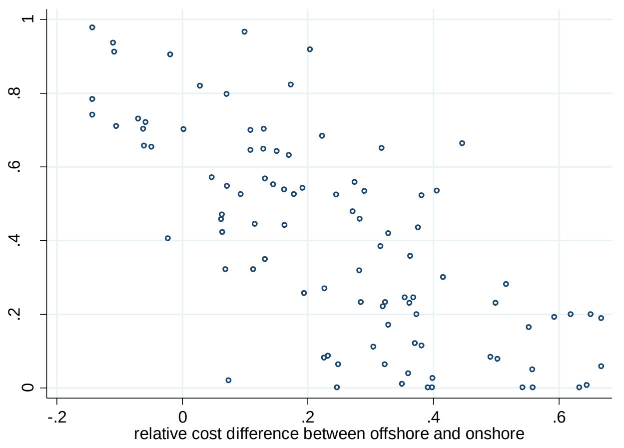

FIGURE 8. *Share offshore CCS in total CCS.*

Figures 9 expresses the conclusion derived from Figure 8 in a different way. As can be seen, if offshore storage is around 50% more expensive than onshore storage, at least 80% of all CO_2 capture and storage takes place through onshore CCS. As can also be observed, if offshore storage is at most as costly as onshore storage, then at least 80% of all CO_2 capture and storage takes place through offshore CCS. If offshore CCS is in between 0% and 50% more expensive than onshore CCS, then there is a good probability (approximately 75%) that a more balanced breakdown exists between offshore and onshore CCS, with a share of at least 20% for each of these two alternatives. Figure 9 also shows that in at most 10% of the scenarios we have an onshore leakage rate of more than 7%/decade. Figure 10, finally, describes the maximum amount of cumulative CO_2 emissions allowed under different global carbon price regimes, in the context of our cost-benefit framework. For example, as one can see in this Figure, if the carbon price exceeds 50 €/tCO_2 in 2020, then the cumulative amount of emissions allowed for the remainder of the century is very likely to stay within an overall budget of 1 TtCO_2.

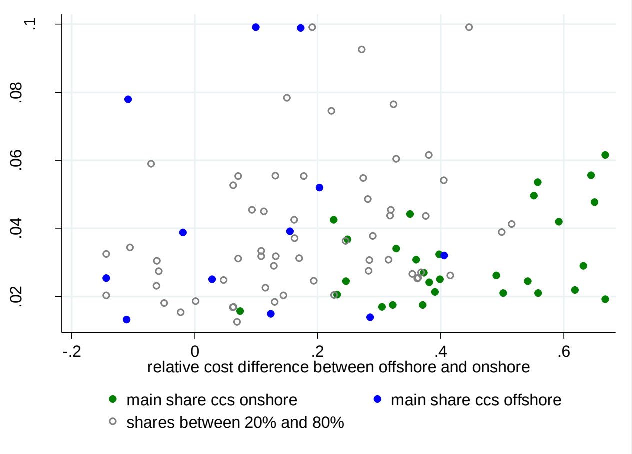

FIGURE 9. *Onshore leakage rate (share/decade).*

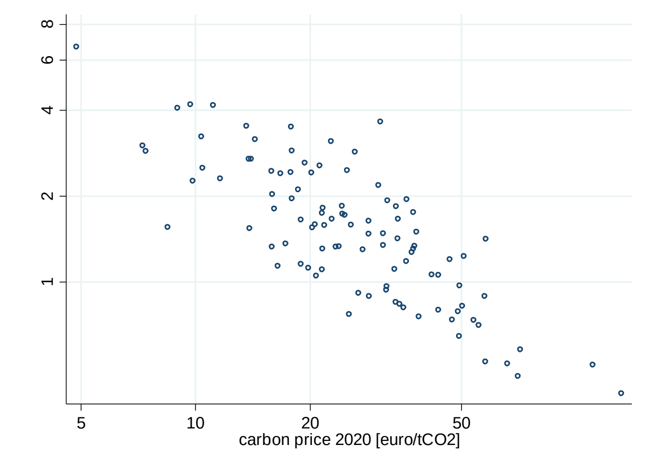

FIGURE 10. *Cumulative CO_2 emissions.*

4. CONCLUSIONS

The findings reported in this article are different from the conclusions we made in our earlier work on the economics of CCS and leakage of CO_2 (van der Zwaan and Gerlagh, 2009; Gerlagh and van der Zwaan, 2012). We have here attempted to shed light on the possible attractiveness of offshore geological CO_2 storage, and have inspected what the economic benefits could be of complementing onshore CCS with offshore CCS. As was shown in section 3, we find that by allowing for offshore CO_2 storage one could possibly significantly stimulate the usefulness of CCS from a benefit-cost perspective, and thus expand its implementation on such grounds. Offshore CO_2 injection may also substantially reduce public opposition to CCS, which currently plays a sizeable role in impeding its deployment onshore. On the basis of both these perspectives, one may conclude that partly moving CCS from onshore to offshore may be a beneficial path to take to render CCS practically more feasible and realistic as climate mitigation option.

In short, our argument goes as follows. First, it may well be that CO_2 abatement through offshore CCS is more expensive than via onshore CCS – we assume by around 25€/tCO_2, i.e. 50% in relative terms – given that it is harder to undertake geological CO_2 injection activity under the seabed through a deep ocean than directly in open air at the surface of the underground. Second, while not all uncertainty is yet resolved in this domain, it seems very likely that zero-leakage storage sites can be found, operated, maintained and secured (onshore as well as offshore) from a natural scientific point of view. But based on economic, political, institutional and safety cultural arguments one may reason that on a large global scale in which thousands or millions of CO_2 storage sited are being operated, leakage may ultimately not be zero. In such a context, one may claim that offshore leakage is potentially higher than onshore leakage, since the injection process is technologically more requiring and remediation is practically less trivial. We hypothesize that leakage rates could be 50% higher for offshore than for onshore CCS.

One may have different opinions on these two assumptions, and over time they may prove not to hold out. But our main point can be drawn despite these relatively negative hypotheses: even under these conditions, as we demonstrate, offshore CCS may be as interesting from an economic perspective as onshore CCS. As a result, the prospects for CCS could be significantly boosted if one were to shift part of the CCS activities from onshore to offshore territory. The reason for this finding is that there is high likelihood that the damages from CO_2 leakage into the atmosphere are much more costly than those from seepage into the ocean. Hence, if the circumstances are one day such that a possibility exists for CO_2 leakage, then it becomes much less costly to let the leakage occur into a medium in which the damage costs are relatively modest (whether tangible or intangible) than into one for which these costs are almost certainly high.

In the probabilistic cost-benefit framework that we use for our study, and under the range of stylistic assumptions that we have had to make in order to perform this type of global economic analysis, we find that if offshore storage is at most as costly as onshore storage, then there is a very high probability that at least 60% of all CO_2 capture and storage takes place through offshore CCS. At a 50€/tCO_2 cost of CCS we expect that CCS's contribution to total mitigation efforts is typically about 30%, whereas with CCS costs between 100€/tCO_2 and 150€/tCO_2, the use of CCS is significantly diminished but can still amount to a contribution of around 20% to overall climate mitigation. If the injection of CO_2 offshore is at most 10% more expensive than onshore injection, then offshore CCS is the preferable option, accounting typically for at least 60% of all CCS deployment.

5. Acknowledgements

The research leading to the results reported in this article has received funding from the European Community's Seventh Framework Programme through the ECO2 project ("Sub-seabed CO2 Storage: Impact on Marine Ecosystems", grant agreement n° 265847). Valuable suggestions and feedback on the various versions of this article and/or the underlying analysis is acknowledged from many colleagues of the ECO2 consortium, including especially Matthias Haeckel and Gernot Klepper.

References

Gerlagh, R. and B.C.C. van der Zwaan (2002), "Long-term Substitutability between Environmental and Man-made Goods", *Journal of Environmental Economics and Management*, 44, 329-345.

Gerlagh, R., and B.C.C. van der Zwaan (2006), Options and Instruments for a Deep Cut in CO_2 Emissions: Carbon Capture or Renewables, Taxes or Subsidies?, The Energy Journal, 27, 3: 25-48.

Gerlagh, R. and B.C.C. van der Zwaan (2012), "Evaluating Uncertain CO_2 Abatement over the Very Long Term", *Environmental Modeling and Assessment*, 17, 1/2, pp.137-148.

Ha-Duong, M., and D.W. Keith (2003), Carbon storage: the economic efficiency of storing CO_2 in leaky reservoirs, Clean Techn Environ Policy, 5:181-189.

Hoel, M. and T. Sterner (2007), Discounting and Relative Prices, Climatic Change 84: 1573-1480.

IPCC (2005), Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, Working Group III, Cambridge University Press, Cambridge UK.

Keller, K., D. McInerney, D.F. Bradford (2008), Carbon dioxide sequestration: how much and when?, Climatic Change, 88(3-4), 267-291.

Keppo, I. and B.C.C. van der Zwaan (2012), “The Impact of Uncertainty in Climate Targets and CO_2 Storage Availability on Long-Term Emissions Abatement”, *Environmental Modeling and Assessment*, 17, 1/2, pp.177-191.

Kharaka, Y.K., D.R. Cole, S.D. Hovorka, W.D. Gunter, K.G. Knauss, B.M. Freifeld (2006), Gas-water-rock interactions in Frio Formation following CO_2 injection: implications for the storage of greenhouse gases in sedimentary basins, Geology, 34, 7.

Klusman, R. W. (2003), Evaluation of leakage potential from a carbon dioxide EOR/sequestration project, Energy Conversion and Management, 44(12), 1921-1940.

Nordhaus, W. (1994), Managing the Global Commons: the Economics of Climate Change, MIT Press, Cambridge Massachusetts.

Piketty T. and G. Zucman (2014), Capital is Back: Wealth-Income Ratios in Rich Countries, 1700-2010, Quartlery Journal of Economics, 1255-1310.

SEI (2012), Valuing the Ocean, K. Noone, R. Sumaila, R.J. Diaz (eds.), Stockholm Environment Institute, Stockholm, Sweden.

Shaffer, G. (2010), Long-term effectiveness and consequences of carbon dioxide sequestration, Nature Geoscience, 3(7), 464-467.

Sterner, T. and U.M. Persson (2008), An Even Sterner Review: Introducing Relative Prices into the Discounting Debate, Review of Environmental Economics and Policy, 2, 1, 61-76.

Teng, F., and D. Tondeur (2007), Efficiency of Carbon storage with leakage: Physical and economical approaches, Energy, 32(4), 540-548.

UN (2009), Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2008 Revision, United Nations, New York.

van der Zwaan B.C.C., R. Gerlagh, G. Klaassen, L. Schrattenholzer (2002), Endogenous technological change in climate change modelling, Energy Economics, 24:1-19.

van der Zwaan B.C.C., and R. Gerlagh (2009), Economics of Geological CO_2 Storage and Leakage, Climate Change, 93, 3/4, 285-309.

van der Zwaan B.C.C. and K. Smekens (2009), CO_2 Capture and Storage with Leakage in an Energy-Climate Model, Environmental Modeling and Assessment, 14, 135-148.

Wilson, E.J., T.L. Johnson, D.W. Keith (2003), Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage, Environmental Science and Technology, 37, 16.