The feasibility of a Europeanwide integrated CO2 transport network

Citation for published version:
Stewart, RJ, Scott, V, Haszeldine, S, Ainger, D & Argent, S 2014, 'The feasibility of a Europeanwide integrated CO2 transport network' Greenhouse Gases: Science and Technology, vol. 4, no. 4, pp. 481-494. DOI: 10.1002/ghg.1410

Digital Object Identifier (DOI):
10.1002/ghg.1410

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Greenhouse Gases: Science and Technology

The Feasibility of a European Wide Integrated CO_2 Transport Network

R J Stewart[1] (corresponding author)
V.Scott[1] (secondary contact)
R. S Haszeldine[1]
D Ainger[2]
S Argent[2]

Contact Information

[1.] University of Edinburgh
Scottish Carbon Capture and Storage
School of Geosciences
Grant Institute
West Mains Road
Edinburgh
EH9 3JW
Scotland
United Kingdom

[2.] Arup
Rose Wharf
78 East Street,
Leeds,
LS98EE,
England
United Kingdom

Telephone Contact: (+44) 0131 650 5936
Email: jamie.stewart@ed.ac.uk, vivian.scott@ed.ac.uk

ABSTRACT

The European Union's ambition to achieve near-total decarbonisation by 2050 suggests a large role for carbon capture and storage, requiring the transport (mostly by pipeline) of CO_2 from source facilities to appropriate sites for geological storage. Here, a network modelling approach is used to test the scale, structure and estimated costs of an integrated European CO_2 transport network for different amounts of CCS deployment. Models are optimised with the sole objective of creating the least cost pipeline network that joins all sources to sufficient storage for a 25 year period of operation, and assume no restrictions on trans-boundary transport of CO_2, or due to topographical constraints. Results show that extensive CO_2 pipeline networks are required to deliver the CCS contribution to decarbonisation. Sufficient storage is available but is distributed such that even for low levels of CCS deployment, both offshore storage and trans-boundary transport of CO_2 are needed. Scenarios are run to test pipeline infrastructure requirements should onshore CO_2 storage not be permitted, giving an estimated increase in CO_2 transport infrastructure cost of 10-30% (€3-7 billion). Scenarios examining the effect of removing the more speculative storage potential in the Baltic, close to central and eastern European CO_2 source clusters, reinforce the need to experimentally validate theoretical storage capacity estimates especially in the Baltic and North Sea.

Key words: CO_2 pipeline, Carbon Capture and Storage, CCS, energy network modelling,

1. Introduction

The deployment of Carbon Capture and Storage (CCS) is expected to be a core component of measures to enable significant reductions in CO_2 emissions from electricity generation and industrial processes in the European Union (EU). The EU Commission Energy Roadmap 2050[1] presents a range of scenarios for achieving the EU goal of 85-90% cut in CO_2 emissions by 2050 relative to 1990. CCS makes a major contribution of between 19-24% of the overall emissions reductions in all but the very high renewables scenario. These scenarios require deployment of CCS in the period 2020-2030, with CCS applied to all coal and gas power plants by 2030, and around half of the EU's energy-intensive industry by 2050, suggesting a need to transport hundreds of millions of tonnes of CO_2 per year between source facilities and storage.

Compared with the capture and storage elements of the CCS chain, CO_2 transport presents both the least technically challenging and least costly component.[2] However, as storage capacity is not evenly distributed, with some EU Member States relatively undersupplied relative to others (Figure 1) developing an integrated network, of appropriate capacity and at the correct time presents a considerable logistical challenge requiring guidance and planning. As a result, a number of CO_2 source – CO_2 storage matching and CO_2 transport infrastructure modelling exercises have been undertaken in both European macro-regions e.g. the North Sea area[3], and across the EU[4-6]

Here, we present results and analysis building on a foundation of network modelling work to investigate Europe-wide CO_2 pipeline requirements undertaken by the engineering firm ARUP and Scottish Carbon Capture and Storage (SCCS) for the European Commission in 2010[I]. This includes examining the difference in pipeline layout and costs should public concerns restrict CO_2 storage to offshore locations, and presents a new scenario examining the impact of Baltic Sea storage availability on the structure of CO_2 pipeline infrastructure. The implications of the findings for policy-makers are discussed.

2. Methods

2.1 Assessing European CO_2 storage capacity

Although most estimates of CO_2 storage capacities have been made for isolated geological basins or formations, there are a limited number of studies exploring capacity

[I] The original report 'Feasibility Study for Europe-Wide CO_2 Infrastructures' can be found at: http://ec.europa.eu/energy/coal/studies/doc/2010_10_co2_infrastructures.pdf.

estimates on a European scale. [4, 7-10] The most recent and comprehensive is the EU FP6 GeoCapacity project,[7] which compiled earlier GESTCO[10] data with new assessments to cover 25 Member States. GeoCapacity estimated the combined conservative storage capacity of the 25 countries assessed to be 116,000 Mt in both saline aquifers and hydrocarbon fields - sufficient to enable storage of at least 50 years of current EU CO_2 emissions from large point sources.

Around half (52%) of the total storage is located in the UK and Norway North Sea, the major part in saline aquifers offshore Scotland (Figure 2). However, potential capacity does not necessarily make it viable or available for CO_2 storage. Commercial evaluation must include specific geological suitability, practical accessibility, competition for hydrocarbon activities or geothermal heat, and public acceptance of CO_2 storage.

Plans for onshore CO_2 storage in Europe have in many cases met with considerable public opposition. Reasons include health and property-value concerns resulting from a combination of poor communication, mistrust of government and commercial actors, and a lack of perceived benefit to the affected communities.[11,12] In the Netherlands, Austria, and Germany public opposition has resulted in legislation preventing or severely restricting onshore CO_2 storage.[13] While loss of onshore storage (around 25% of the EU's total storage capacity) doesn't prevent sufficient quantities of storage being available for large levels of CCS deployment, it potentially has major implications for the design of CO_2 transport networks.

As with other large scale studies undertaken by multiple actors, the precise methodology (e.g. in the resolution of structures included and the pore-space filling efficiency) of the different national estimates made within GeoCapacity varies between EU Member States. Here, the GeoCapacity dataset was augmented with the addition of more detailed data from a number of regional studies (Scottish offshore;[14] Ireland;[15] offshore Baltic (adapted from *(Shogenova et al, 2009)*[16] and aquifer extrapolations (Austria and Switzerland) to produce a 50km by 50km grid basis storage site dataset. Storage options without the European Economic Area (for these purposes the EU plus Norway) are not considered. There could be possible storage sites in nations bordering Eastern Europe, or in North Africa but these are both little assessed and their use would involve considerable legislative complexity. The data is filtered to include only grid squares that have storage capacities of 50 Mt or above – consistent with required capacity for a full commercial scale CCS project (e.g. upwards of 5Mt CO_2/yr from a coal power plant) operating for several decades. This filtering reduces the number of sites significantly but only reduces the total capacity by 2-3%.

2.2 Forecasting future CCS deployment

Power plants burning fossil fuels produce 54% of EU electricity supply,[17] resulting in around 35% of current total EU CO_2 emissions. The EU ambition for a 85-90% reduction in emissions by 2050 calls for the near-total de-carbonisation of electricity generation by around 2030, to enable the subsequent decarbonisation of transport and heating through electrification. Renewable and nuclear power generation, and improved energy generation and energy use efficiency are all expected to contribute, but fossil fuel burning generation is expected to retain a major role.[1] CCS is proposed to de-carbonise this fossil power capacity, and is the only option available to decarbonise energy intensive industries.

Much of the EUs current fossil power plant fleet is ageing, and due to the stricter pollutant regulations of the EU Industrial Emissions Directive is set to be retired or replaced before 2020. How, when, and where, this generation capacity is replaced is subject to market, technology and policy uncertainty. As part of the development of the EU Energy 2050 Roadmap,[1] multiple energy and market system modelling studies were performed to produce future energy generation options consistent with the EU's CO_2 emissions reductions ambitions.

Here, eight of these undertaken by Government: EU energy trends to 2030 – Primes BL, -25,[18] Industry: Eurelectric "Role of Electricity" Scenario[19]& Eurelectric "Power Choices" Scenario,[20] and environmental NGOs: European Climate Foundation 2050 Roadmap - BL,40,60,80[21] were analysed to give broad coverage of the range of different energy systems and corresponding degrees of CCS deployment envisaged. These were amalgamated and combined with details on current and planned industrial emission sources and used to develop three (low, medium, high) CCS deployment scenarios for both 2030 and 2050, reflecting the wide range of predicted levels of CCS deployment. These CCS deployment scenarios cover a range of 50 Mt (low), 120Mt (medium) and 350Mt (high) of CO_2 captured per year in 2030, and 280Mt (low), 600Mt (medium) and 800Mt (high) of CO_2 per year in 2050.

2.3 Modelling Method

Figure 3 illustrates the platform database on which the infrastructure modelling was based. Storage capacities and potential capture quantities are aggregated onto a European 50x50km grid system. Each grid square filled by colour represents CO_2 storage capacities in both saline aquifers and hydrocarbon fields combined. Potential capture quantities for the different CCS deployment level scenarios are aggregated within each 50x50km square and in Figure 3 (and subsequent figures) are represented by circles scaled to the quantity of CO_2 captured. These provide the two input datasets which the modelling seeks to connect with minimum total cost.

Geo-referenced databases of CO_2 storage capacities and capture quantity scenarios, enable hydraulic models to be used to identify potential pipeline pathways. Evolutionary network optimisation methods such as genetic algorithms (GAs) and more recently developed 'ant colony optimisation algorithms' (ACOAs) have been used extensively in the design and operation of fluid distribution systems.[22,23] They solve tasks by multi agent co-operation using indirect communication through modifications in the environment.

Here, the proprietary commercial model used extensively by ARUP for optimising water and gas pipeline networks, phone lines and electric grids is used to model source to store CO_2 pipeline routeing. The fully functioning hydraulic model (based on ACOASs) allows use of both small diameter 'gathering systems' and large diameter 'trunk mains' to identify the least cost scenario for transporting the required quantities of CO_2 between sources and storage. Although in the process industry where security of supply is paramount, ring mains are used, here due to the significant cost saving (thought to be up to half the cost) and the potential to vent or locally store CO_2 in the event of a pipeline breakage, trunk mains are considered to be sufficient.

The costing equation used within the algorithm does not impose any limit to pipeline sizes. It is assumed that for notional pipe diameters larger than those typically constructed, twinned pipes could be constructed at similar costs. Considering this, a range of pipeline diameters from 1 to >80 inches are modelled to accommodate different flow rates. Although the pipe cost equations used do not account for system design pressure, a standardised flow velocity of 2.77m/s was used. This was assumed to ensure surge pressures remained below the short term over pressure limits of the pipeline and that erosion, losses and wear are kept to a minimum. The optimisation algorithm used within the Arup proprietary model uses 'minimum total network cost' (total in €) as its objective function, while matching all input sources to a sink of sufficient capacity for a minimum capacity of 25 years of continuous operation. The optimisation used can be described as 'near optimal' as only a solution within 5-10% of the least cost solution was found. It is thought that this 5-10% sub-optimality is however suitable given the scope of the work. Better optimisation is possible from the algorithm given a longer project duration and scope.

A number of assumptions are made to make the process manageable. No restrictions on the selected optimal routes are made by the presence of other infrastructure or population centres, topography is assumed flat and unbroken by waterways, and the complexity of transiting national boundaries is not considered. The possibility of CO_2 shipping as an alternative transport method, for instance connecting isolated coastal sources with distant storage is not included. The relative practicality of developing one storage site over another and possible rate of injectivity limitations[4] is not considered.

As such, the results presented below should be considered as indicative of the scale, general layout and corresponding costs of possible CO_2 pipeline network developments required for different levels of CCS deployment, rather than identifying specific pipeline routes or connecting specific sources to specific storage.

3. Results

Twelve different CO_2 transport demand scenarios are analysed: low, medium, and high CCS deployment with and without onshore storage availability (6 scenarios) for 2030, and the same for 2050. These results do not seek to determine exact pipeline pathways but instead to inform on their overall structure.

3.1 All storage available

Figure 4 shows the results for all storage (on and offshore) equally available for the low, medium and high CCS deployment scenarios in 2030 and 2050. All these share two key features. First, due to the lesser distance and hence cost, the vast majority of storage occurs onshore. Almost no use is made of the huge storage potential available in the central and northern North Sea, with offshore storage only being utilised where it is adjacent to CO_2 sources – e.g. from the UK, Denmark and the Netherlands to the central and southern North Sea. Second, even for high levels of CCS deployment, trans-EU CO_2 transport is not required. Isolated, relatively simple regional clusters are sufficient to link sources to storage, with only one major cluster located principally in and around Germany. This is also where most of the requirement for trans-boundary transport (with associated legal and planning complexity) is seen, with CO_2 moving between Germany, Belgium, the Netherlands, Luxembourg and Denmark.

3.2 Offshore storage only

Figure 5 shows the results when storage is restricted to offshore sites. These scenarios contrast strongly with the both on-and-offshore storage available results above. All levels of CCS deployment require trans-EU CO_2 pipeline transporting CO_2 from inland sources northwards to storage in the southern North Sea and Baltic. A number of countries have sufficient offshore domestic storage (Spain, Italy – for only lower deployment levels, Denmark, Ireland and the UK), but a large western network, and a number of south to north trunk lines in central and eastern Europe, are required to connect sources in other Member States to storage. However, the picture presented is perhaps unrealistic as for instance either capacity replacement with alternative generation, or using multiple smaller local stores or CO_2 shipping might present a more viable solution for sources in south-eastern Europe than many thousands of kilometres of pipeline north to the Baltic. Despite this, the overall layout is instructive – with NW Europe (including western Germany) utilising North Sea storage, and eastern Germany, Poland and other central and eastern Member States connecting to the Baltic (Section 3.3 below considers an alternative scenario without storage available in the Baltic).

In both storage availability options, and all deployment scenarios, almost none of the 2030 pipeline routes become redundant in 2050. Figures 6 & 7 show the calculated lengths of different diameters of pipeline for the medium CCS deployment scenarios with and without onshore storage in 2030 and 2050. These show the shift to larger diameter pipeline resulting from the need to transport all captured CO_2 offshore. Taken together, this suggests that from a technical perspective pipeline can be developed with no regrets. It also makes a strong case for a degree of strategic oversizing or, given that capital investment of double capacity might prove difficult to justify without certain return, designing trunk routes with additional wayleave space to enable straightforward parallel expansion. While seemingly large, the overall pipeline lengths and capacities calculated are an order of magnitude lower than that of the EU's current natural gas transport network (144,000km)[24] suggesting that deployment at this scale is technically achievable.

3.3 Assessing the importance of developing Baltic storage

As a region less explored and developed by the hydrocarbons industry than the North Sea, the potential CO_2 storage capacity of the Baltic is less well-established.[25] Projects such as the BASTOR project[26] are currently undertaking more detailed preliminary analysis of potential Baltic subsurface storage targets.

Here, we undertake a model run for the 2050 high CCS deployment scenario in which the option of CO_2 storage in the Baltic is removed. In this scenario, shown in Figure 8, almost all CO_2 sources with the exception of those in Spain, Ireland and Scotland are connected via a single trans-EU network to storage in the southern North Sea. This involves pipeline crossing the Benelux (Belgium, Netherlands and Luxembourg) and

Germany to connect to CO_2 source clusters in Poland and further east. The overall increase in pipeline length (from 20041km to 20189km) is negligible, but as shown in Figure 9 the lengths of the different pipeline diameters used change. While there is no simple trend shown across the range of diameters, there is a more than doubling in the lengths of very large (>80") pipeline diameters sections from just under 1000km to 2000km reflecting the need for major pipelines accessing the North Sea to be extended to accommodate CO_2 from central and eastern Europe. The resulting difference in pipeline costs between these two scenarios (€2 billion) is discussed below.

3.4 Estimated costs of CO_2 transport infrastructure

Table 1 presents details on the lengths, overall capital cost estimates (2010 costings) and capital cost per tonne of CO_2 transported[II] in € for the different pipeline networks generated for the low, mid and high CCS deployment scenarios in 2030 and 2050. While the overall cost of pipeline increases for higher deployment, the cost per tonne CO_2 is less as better economy of scale is achieved through the use of larger diameter pipes with higher CO_2 flows

As expected from Figures 4 and 5, the availability of only offshore storage requires greater pipeline length (between 11-33% increase) over scenarios with both on and offshore storage being available, resulting in an increase to the overall capital cost

[II] Cost per tonne estimates based on linear pipeline costs of €37,500/km/inch of diameter, booster stations at €4.5million per MW and computed flow rates of CO_2 across the whole design life. Economies of scale are incorporated in the cost model. It is assumed that twice the flow is gained for approximately 30% extra cost. The impact of these economies of scale on the optimisation algorithm in the hydraulic model is to select a smaller number of larger diameter as opposed to a large number of small diameter pipes.

estimates by around half as much (40-65%) again. Lastly, with no offshore storage available in the Baltic, the 2050 high deployment scenario requires larger diameter pipeline to accommodate sources in central and eastern Europe in pipeline accessing storage in the North Sea (Figure 8). This results in a 10% total cost increase of an additional €2 billion giving a total of network cost of €21,824 million over the high deployment all offshore storage available scenario.

4. Discussion

4.1 Comparison with other CO2 transport studies

The results presented here broadly corroborate those of other EU CO_2 transport scenario studies,[3,5,6,27] producing similar pipeline routes and pipeline network locations. This is largely to be expected as used inputs of source and storage locations derived from similar sources to those used here. However, none of these studies include the possibility of storage in the Baltic and consequently make greater use of potential storage initially in the southern North Sea (producing similar results to the no Baltic storage scenario shown in Figure 8), with later extension to the northern North Sea in the case of the One North Sea scenario and Morbee et al offshore storage only 2050 scenario. We also note that some Scandinavian CO_2 sources not included in this work are connected to storage offshore Norway in the other studies.

The total pipeline network lengths calculated by Morbee et al of 11,200km for all storage available (this study 12,000-15,000km) and 17,000km for offshore storage only (this study 14,000-20,000km) broadly agree. The calculated estimated costs are less similar.

Overall, *Morbee et al (2012)*[6] produce a higher estimated total network costs for 2050 of €16 billion for both on and offshore storage available for use (this study €8-13 billion), and €36 billion should storage be restricted to offshore sites only (this study €10-20 billion – €22 billion if the Baltic is not included in available storage). The higher costs of *Morbee et al* arise from the more sophisticated costing model in their work. While this study assumes a fixed cost irrespective of topography or off- or onshore location, Morbee et al modify costs to the terrain, increasing the per km cost by 50% for mountainous regions, and by 100% for offshore pipeline. This additionally explains some of the differing pipeline route choices in the offshore only scenarios where the Morbee et al networks connecting sources in Italy to storage in the North route away from directly crossing the Alps.

Overall, the similarities between the results of these studies present a compelling need for strategic EU CO_2 transport planning. All show that even with all onshore storage available, offshore storage is still vital to accommodating the expected volumes of CO_2, and all require at least some trans-boundary movement of CO_2 between Member States. Should onshore storage options be heavily restricted, all studies agree that trans-EU pipeline networks encompassing multiple Member States are required to access sufficient offshore storage. Further, for both on and offshore storage, all highlight the need to connect the industrial sources of western Germany to the North Sea through Belgium and the Netherlands (see additional discussion below).

4.2 Implications for achieving CCS deployment

Compared to the expected investment costs for CO_2 capture and (to a lesser extent) storage facilities, the predicted cost of CO_2 transportation is a relatively small.[28] The costs presented here are those for basic materials, and do not include costs associated with processes such as planning and land-access, and possible re-routing of other infrastructure. However, even assuming the modelled estimates are a significant underestimation of real-world costs, the ~€10-20 billion cost of a pipeline network capable of transporting hundreds of millions of tonnes of CO_2 per year, is much smaller than the many tens of billions of € that would need investing in the deployment of CO_2 capture and storage facilities.

The primary issue therefore, is less one of technical or cost constraints, but of predicting the scale and timing of any deployment such that appropriate transport infrastructure can be planned and built.[2] Here, the prescient example is the US, where initial CO_2 pipeline taking CO_2 from natural sources to oilfields undergoing CO_2-Enhanced Oil Recovery (EOR) has provided a basis to develop growing (approaching 6000km total) pipeline networks linking CO_2 captured from gas processing and other facilities to meet demand from EOR activity[III]. By contrast, excepting a few cases where existing redundant natural gas pipeline might be re-used[IV], the EU is reliant on early CCS projects to establish initial transport and storage infrastructure, adding both expense and complexity.

[III] Studies suggest there is potential for CO_2-EOR in the oilfields of the North Sea *(SCCS, 2009)*, but sourcing sufficient volumes of CO_2 requires demonstration projects to proceed. A few CCS demonstration with CO_2-EOR storage project proposals have been put forward but none have proceeded to date.
[IV] For example the Feeder 10 gas pipeline in Scotland[29]

CCS demonstration projects have the potential to significantly influence the structure of future CO_2 transport networks by providing a hub for initial regional clusters.[30] However, the 2007 European Council aim to demonstrate CCS at commercial scale in up to 12 projects by 2015 across the EU has suffered numerous setbacks with only a handful of candidate projects remaining, none of which have reached a final investment decision (2013). More generally, there remains a disconnect between broader energy infrastructure planning and the expectation that CCS will be required.[31] A recent study into planned gas power plant in the EU found that many were unlikely to be located in sites which would enable efficient (geographically close) connection to promising storage locations.[32]

In the light of this, should significant CCS deployment in the 2020s and 2030s still be desired, a number of smaller scale strategic interventions should be considered in the immediate future. This includes the identification and creation of 'priority corridors' as 'projects of common interest' for CO_2 pipeline as suggested in the European Commission's Energy Infrastructure Package.[33] As illustrated by these and other EU CO_2 transport network study results, some pipeline corridors seem likely to be used in all CCS deployment scenarios. The most compelling are those connecting source clusters in western Germany to storage either in or offshore of the Netherlands. Here, there is a strong case to undertake a more detailed examination of possible pipeline (or indeed shipping) [V] routes, potential coordination with other energy infrastructure, and the legal

[V] The potential for transporting CO_2 using barges on the Rhine and Meuse has been explored by studies such as https://www.globalccsinstitute.com/sites/default/files/publications/25491/co2-liquid-logistics-shipping-concept.pdf and regulatory frameworks that would be required including bi- or multi-lateral negotiations enabling the transfer of CO_2 between these territories.

In terms of the planning of future sources – the results highlight the structures necessary for connecting sources distant to viable (existing or permitted) storage. The current 'CCS readiness' feasibility requirements focus primarily on allowing for the integration of CO_2 capture equipment – consideration of the realities of connecting a source to storage should be given more attention. This is especially the case in Member States in which policy suggests that onshore storage might not be allowed – such that implementation on CCS depends on action elsewhere to provide access to storage.

Lastly, we suggest that confirmation of the storage potential of major saline aquifers, especially in the Baltic region, should receive a high priority. Fossil fuels are likely to remain the major source of generation in central and eastern Europe so establishing the viability and capacity of Baltic formations is essential to planning CCS deployment in the region. Such activity is likely too speculative to be undertaken solely by industry – EU Member State Governments and industry need to actively work together to undertake these strategic investigations to allow both political and commercial choices to be appropriately informed.

5. Conclusions

Least-cost optimised modelling of the pipeline capacity and layout that would be needed to connect expected CO_2 point sources to CO_2 storage shows that extensive CO_2 pipeline networks will be required by both low and high levels of CCS deployment if CCS is used to help deliver the EUs climate mitigation ambitions. Here, assuming that achieving the overall least-cost prevails over other considerations the calculated networks are found to be around an order of magnitude less in overall length to the present natural gas distribution network. Sufficient storage is available but is distributed in such a way that even for low levels of CCS deployment, the modelled networks require both offshore storage and trans-boundary transport of CO_2. While larger capacity networks able to support high levels of CCS deployment are more expensive, they are more cost efficient in terms of capital outlay per tonne of CO_2 transported. In all the scenarios explored, common pipeline corridors are identified suggesting that forward thinking planning should consider oversizing of some early pipeline wayleaves to enable efficient future capacity expansion.

There is significant financial value (€3-7 billion) in gaining acceptance of at least some onshore CO_2 storage, but offshore storage capacity is sufficient to meet demand. Rejection of onshore storage due to public concern considerably increases the length of CO_2 pipeline networks and their expected capital cost. However, some of the output networks suggests trans-EU pipeline to connect isolated source clusters to very distant offshore storage. Here, we suggest that subsequent analyses should explore mixes of on and offshore storage permissions in different Member States, examine the potential to relocate some CO_2 sources closer to (offshore) storage, and consider the inclusion of the potential to deploy CO_2 shipping (both at sea and on major waterways) to compliment pipeline.

Overall, these results strongly suggest that it is vital that storage exploration and appraisals of potential major storage locations in saline aquifers in the North Sea, Baltic and elsewhere are started immediately to accurately inform government and industry on storage destination options. Furthermore, EU wide coordination of CO_2 transport planning, as well as resolution of legal issues surrounding trans-boundary transport and liability are essential to establish industry confidence and enable the delivery of CCS consistent with the EU's emissions abatement ambitions.

References:

1. European Commission (EC), 2011. Energy Roadmap 2050, http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf

2. Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., & Haszeldine, R.S. 2013 Last Chance for CCS. *Nature Climate Change*. v3 pp (105-111)

3. North Sea Basin Task Force (NSBTF), 2010. One North Sea http://nsbtf.squarespace.com/storage/OneNortSea_Fulldoc_Final_LoRes.pdf

4. IEAGHG, 2005. Building the cost curve for CO_2 storage: European Sector. International Energy Agency Greenhouse Gas, 2005/02

5. CO_2 Europipe, 2011. Towards a transport infrastructure for large-scale CCS in Europe http://www.co2europipe.eu/Publications/CO2Europipe%20 %20Executive%20Summary.pdf

6. Morbee,J., Serpa, J. and Tzimas, E. 2012. Optimised deployment of a European CO_2 transport network. *International Journal of Greenhouse Gas Control*, v **7**, March 2012.

7. GeoCapacity, 2009. Assessing European Capacity for geological Storage of Carbon Dioxide. http://www.geology.cz/geocapacity

8. Joule 11, 1993. http://cordis.europa.eu/fp7/home_en.html

9. CASTOR, 2007. European Castor Project on the capture and geological storage of CO_2www.co2castor.com

10. GESTCO 2004.Geological Storage CO_2 from Combustion of Fossil Fuel, Summary Report http://www.geus.dk/programareas/energy/denmark/co2/GESTCO_summary_report_2ed.pdf

11. Shackley, S. et al, 2009. The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. *International Journal of Greenhouse Gas Control* **3(3),** pp348 2009.

12. Oltra, C., Upham, P., Riesch, H., Boso, A., Bruntsing, S. & Dutschke, E. 2012 Public responses to CO2 storage sites: Lessons from five European Cases. *Energy and Environment*, **23**.

13. IEA CCS, 2011. Legal and regulatory review http://www.iea.org/Papers/2011/ccs_legal.pdf

14. SCCS. Opportunities for CO_2 Storage around Scotland. 2009 http://www.geos.ed.ac.uk/sccs/regional-study/

15. Sustainable Energy Ireland (SEI), 2008. Assessment of the Potential for Geological Storage of CO_2 for the Island of Ireland. http://www.sei.ie/uploadedfiles/InfoCentre/1153_SEI%20Full%20Report.pdf

16. Shogenova, A., Sliaupa, S., Vaher, R., Shogenov, K. & Pomeranceva, R. 2009 The Baltic Basin: structure, properties of reservoir rocks, and capacity for geological storage of CO_2. *Estonian Journal of Earth Sciences*, **5(8)**, pp 259-267

17. European Commission Eurostat (ECEurostat), 2012. Electricity production and supply statistics, http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Electricity_production_and_supply_statistics

18. European Commission (EC), 2009. EU energy trends to 2030 http://ec.europa.eu/clima/policies/package/docs/trends_to_2030_update_2009_en.pdf

19. Eurelectric (Eure P-Ch), 2007. Power Choices http://www.eurelectric.org/PublicDoc.asp?ID=60627

20. Eurelectric (EureRoE), 2007. The Role of Electricity
http://www2.eurelectric.org/content/Default.asp?PageID=730

21. European Climate Foundation (ECF), 2010. Roadmap 2050.
http://www.roadmap2050.eu/attachments/files/Volume1_ExecutiveSummary.pdf

22. Dorigo, M., Birattari, M., Stutzle, T. 2006
Ant Colony Optimization: Artificial Ants as a Computational Intelligence Technique. IRIDIA- Technical Report Series ISSN 1781-3794

23. Maier, H., Simpson, A., Zecchin, A., Foong, W.K., Phang, K., Seah, H.,and Tan, C. 2003. Ant Colony Optimization for design of water Distribution Systems. *Journal of water resources planning and management*. 2003.

24. Euro Gas, 2011. Statistical Report 2011
http://www.eurogas.org/uploaded/Statistical%20Report%202011_091211.pdf

25. Baltic Offshore Oil Exploration Watch, (BOOEW) 2012.
Lithuania Green Movement (Lithuania), Green Federation Gaja (Poland), Baltic Resource Information Centre (Russia), 2012.
www.ccb.se/documents/Linaspres.ppt

26. SLR Consulting, 2013. Update on the BASTOR Project
http://www.cgseurope.net/UserFiles/file/Espoo%20workshop%202013/presentations/04_Baltic%20Sea%20Storage%20Potential_Vernon.pdf)

27. European Commission Joint Research Centre (ECJRC), 2010. The evolution of the extent and the investment requirements of a trans-European CO_2 transport network.
http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15100/1/ldna24565enn.pdf

28. ZEP, 2011. The costs of CO_2 Capture, Transport and Storage
http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html

29. Brownsort, P. 2013. Industrial CO_2 Source Clusters in Scotland. Scottish Carbon Capture and Storage:
http://www.sccs.org.uk/news/2013/IndustrialCO2SourceClustersInScotland.pdf

30. Scott, V., 2012. What can we expect from Europe's Carbon Capture and Storage demonstrations? *Energy Policy* (in print - accepted Nov 2012)

31. Heitmann, N., Bertram, C., Narita, D. 2012. Embedding CCS infrastructure into the European electricity system: a policy coordination problem. *Mitigation and Adaptation Strategies for Global Change*
August 2012, **v17**, Issue 6, pp 669-686

32. Littlecott, C. & Attal, E. 2012. The CCS challenge: practical potential for gas carbon capture and storage in Europe in 2030.
Green Alliance: http://www.green-alliance.org.uk/grea_p.aspx?id=6334

33. European Commission Energy (ECE). Energy Infrastructure priorities for 2020 and beyond.
http://ec.europa.eu/energy/infrastructure/strategy/2020_en.htm (2011)

All Storage Available

Scenario	Total Length (km)	Total Cost (€m)	Cost per Tonne CO2 transported (€)
2030 Low	6879	2074	1.45
2030 Medium	9719	4011	1.16
2030 High	12384	7592	0.78
2050 Low	11775	6785	0.89
2050 Medium	14334	10901	0.65
2050 High	15013	12667	0.58

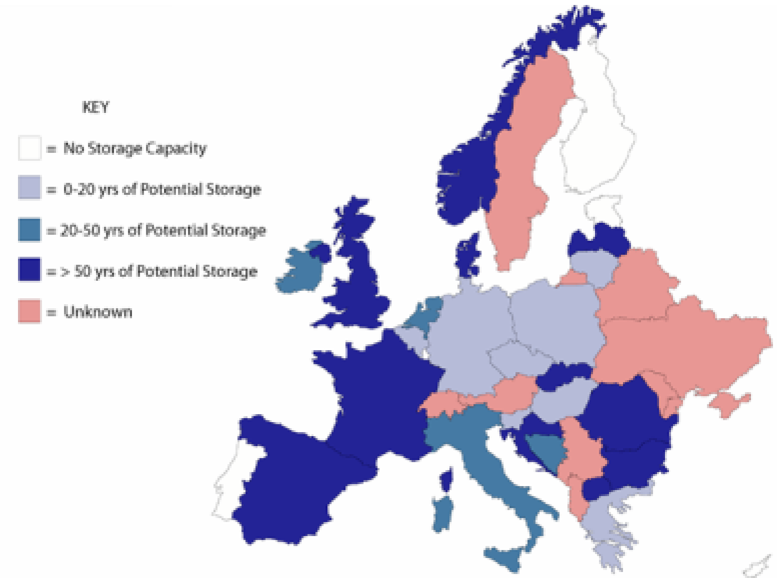
Offshore Storage Only

Scenario	Total Length (km)	Total Cost (€m)	Cost per Tonne CO2 transported (€)
2030 Low	8971	3434	2.40
2030 Medium	10829	5747	1.66
2030 High	14908	11206	1.15
2050 Low	13746	9560	1.25
2050 Medium	18635	16439	0.98
2050 High	20041	19781	0.90

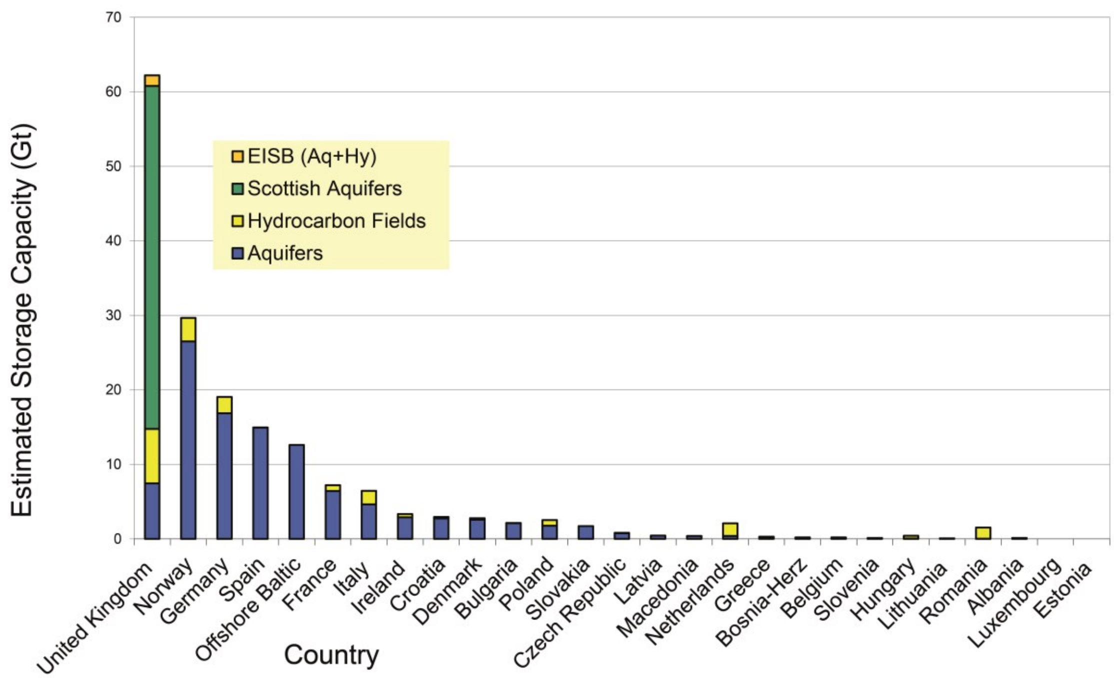
Offshore Storage Only- No Baltic

Scenario	Total Length (km)	Total Cost (€m)
2050 High	20189	21824

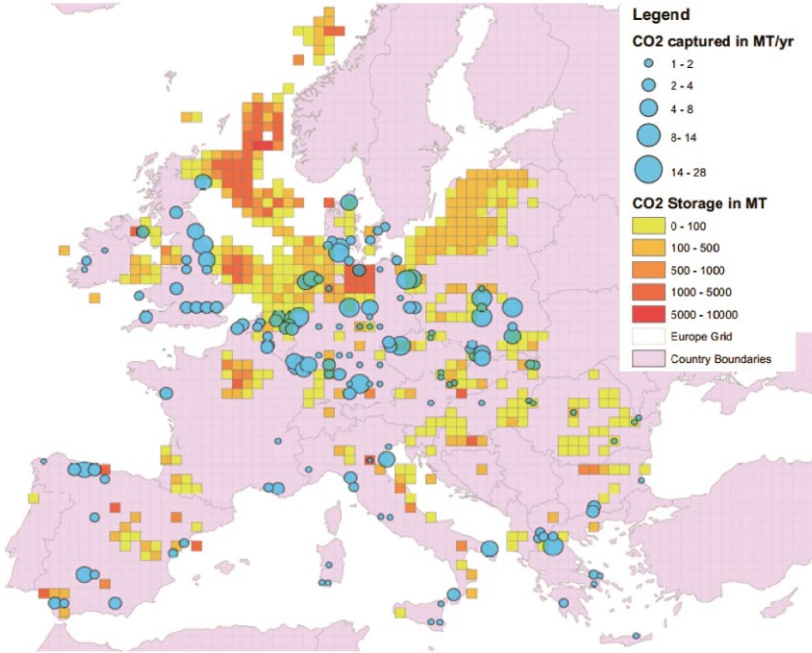
*Table 1***:** *Summary of CO_2 pipeline network length, and capital cost estimates costs for the 2030 and 2050 CCS deployment scenarios. Operating and construction costs, costs associated with adverse terrain, sub-sea and trans-boundary are not included. The cost of compressor stations is included in overall pipeline costs.*

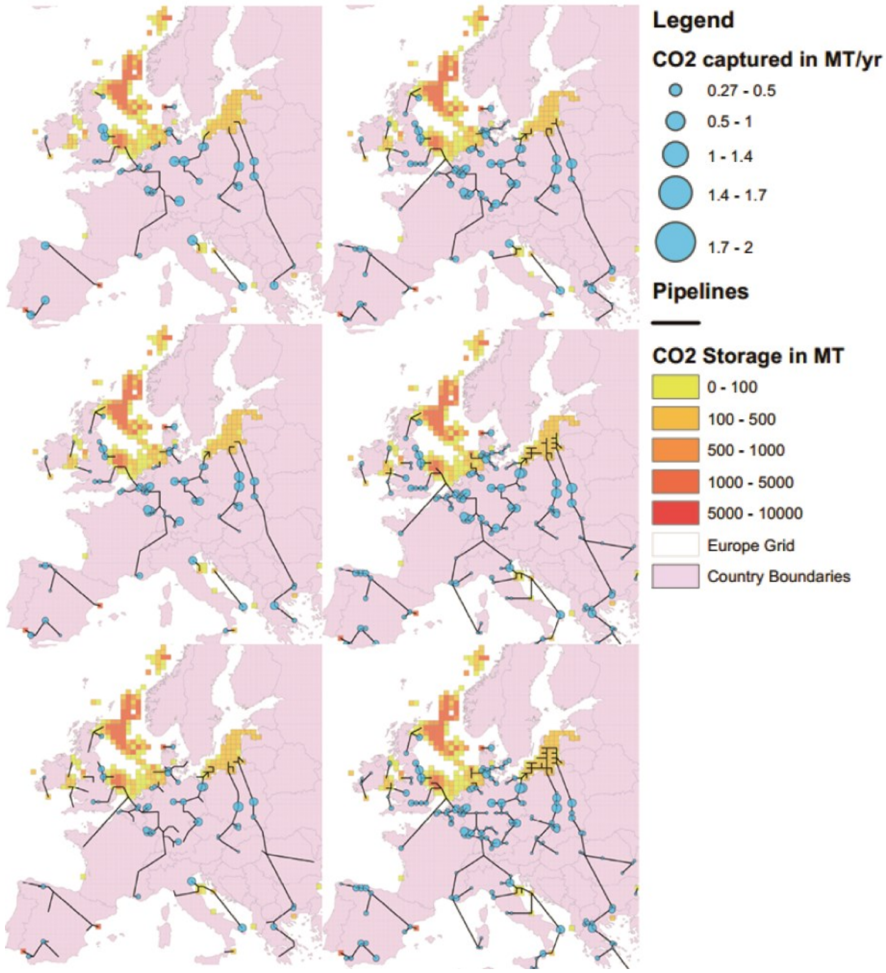


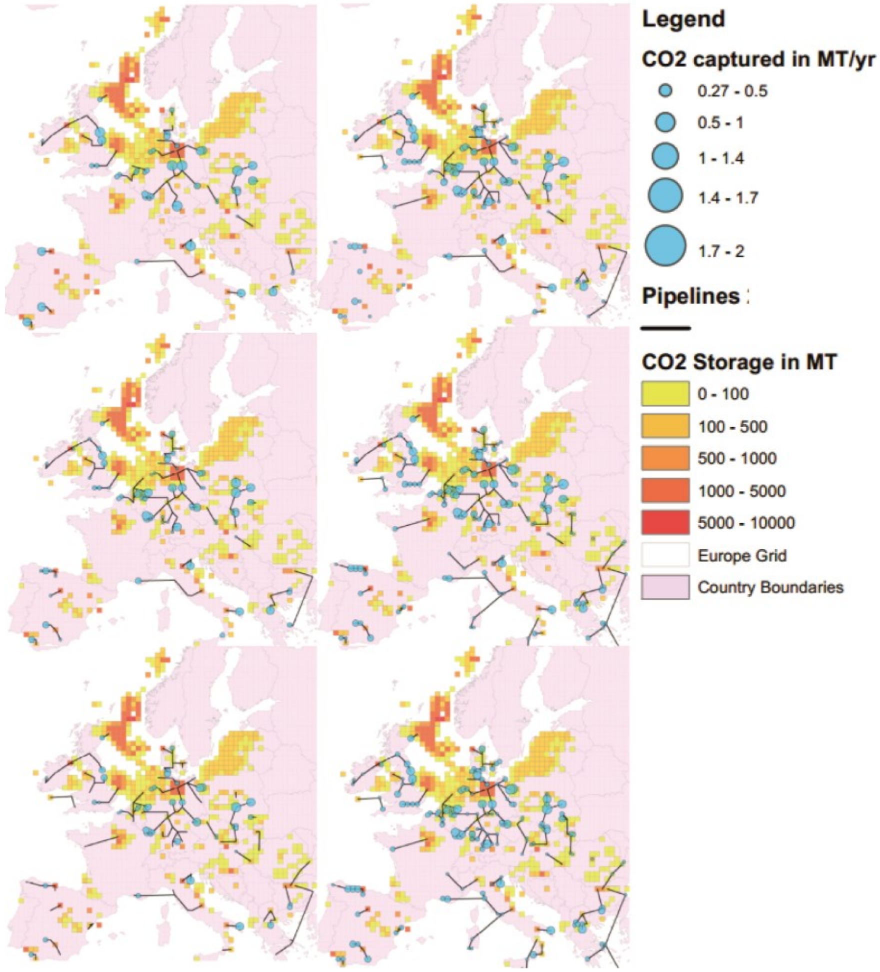
KEY
= No Storage Capacity
= 0-20 yrs of Potential Storage
= 20-50 yrs of Potential Storage
= > 50 yrs of Potential Storage
= Unknown

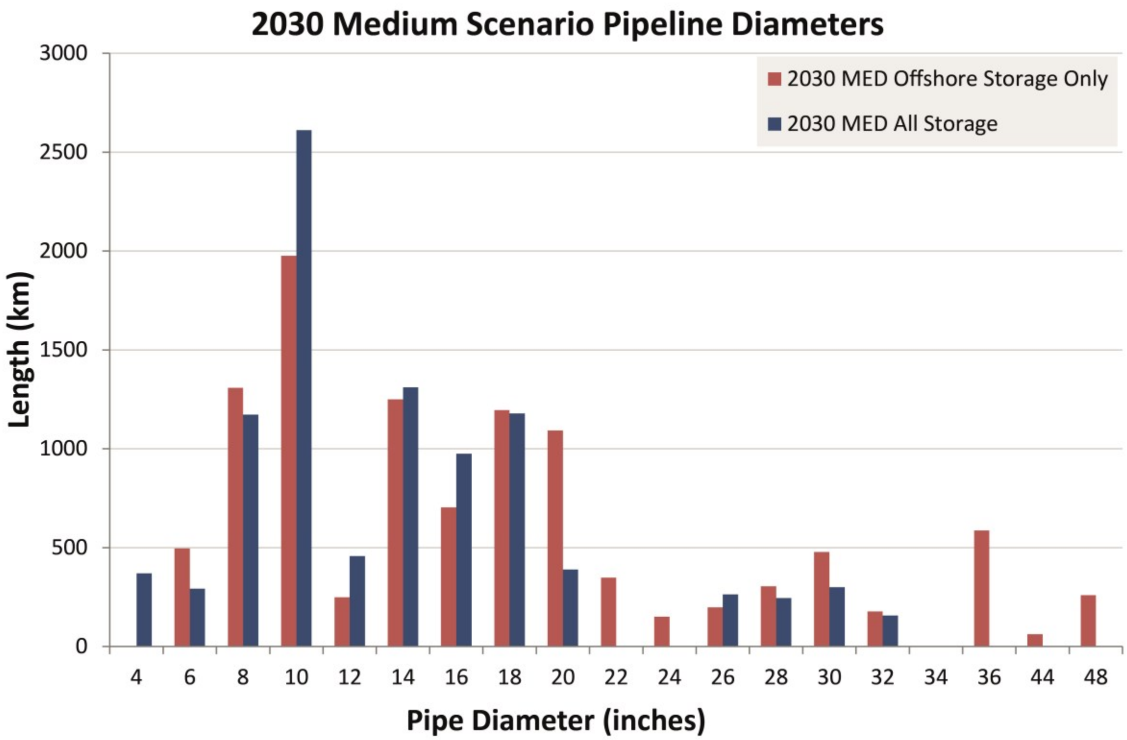


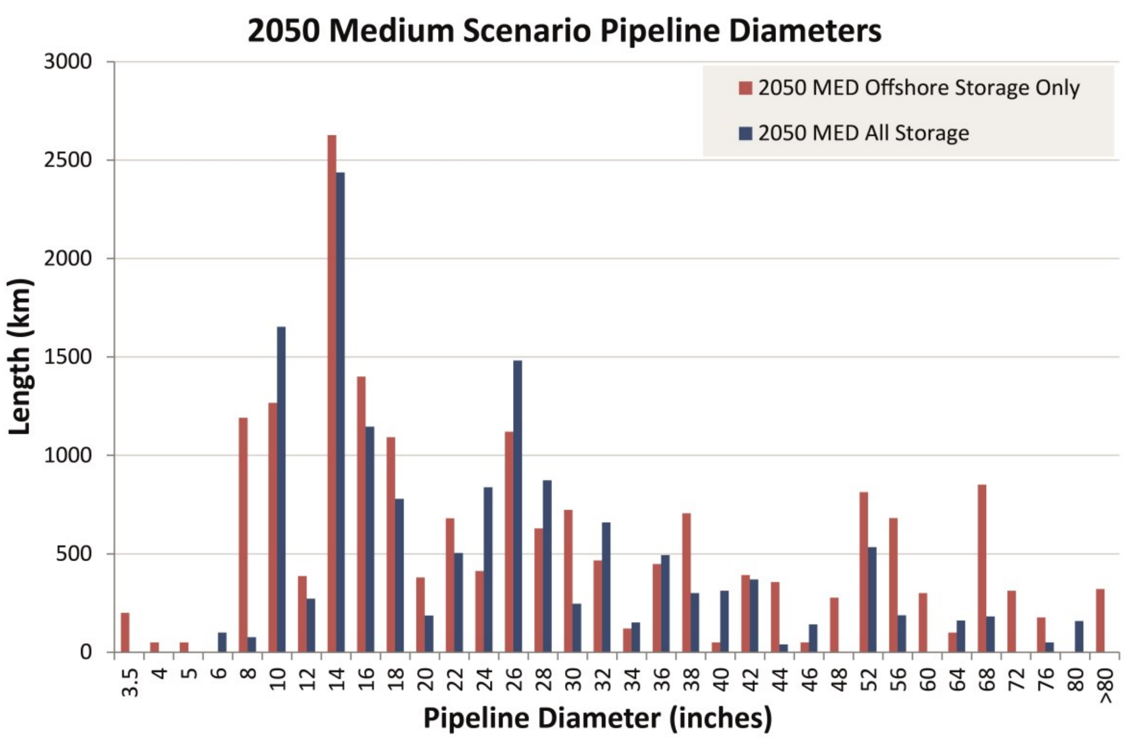
Estimated Storage Capacity (Gt)
70
60
50
40
30
20
10
0
EISB (Aq+Hy)
Scottish Aquifers
Hydrocarbon Fields
Aquifers
United Kingdom
Norway
Germany
Spain
Offshore Baltic
France
Italy
Ireland
Croatia
Denmark
Bulgaria
Poland
Slovakia
Czech Republic
Latvia
Macedonia
Netherlands
Greece
Bosnia-Herz
Belgium
Slovenia
Hungary
Lithuania
Romania
Albania
Luxembourg
Estonia
Country

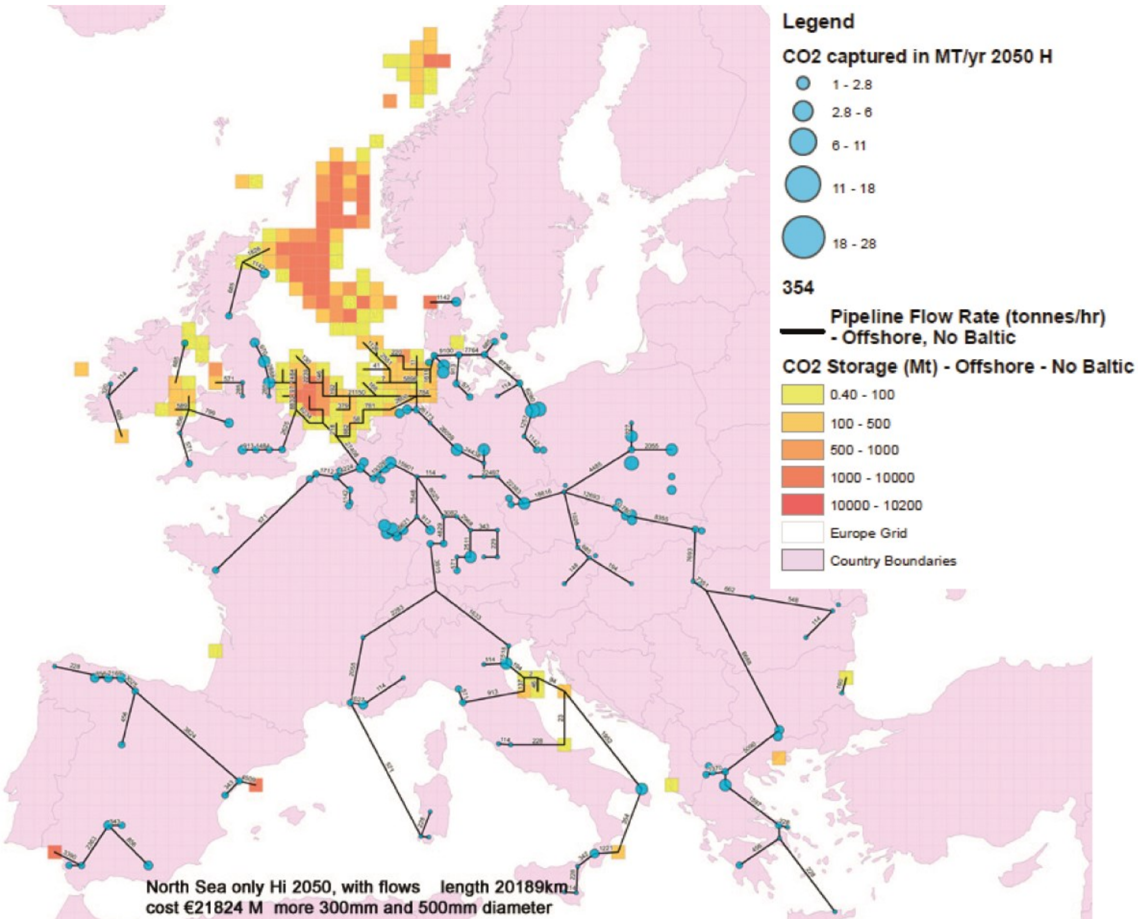

Legend
CO2 captured in MT/yr
1 - 2
2 - 4
4 - 8
8- 14
14 - 28
CO2 Storage in MT
0 - 100
100 - 500
500 - 1000
1000 - 5000
5000 - 10000
Europe Grid
Country Boundaries

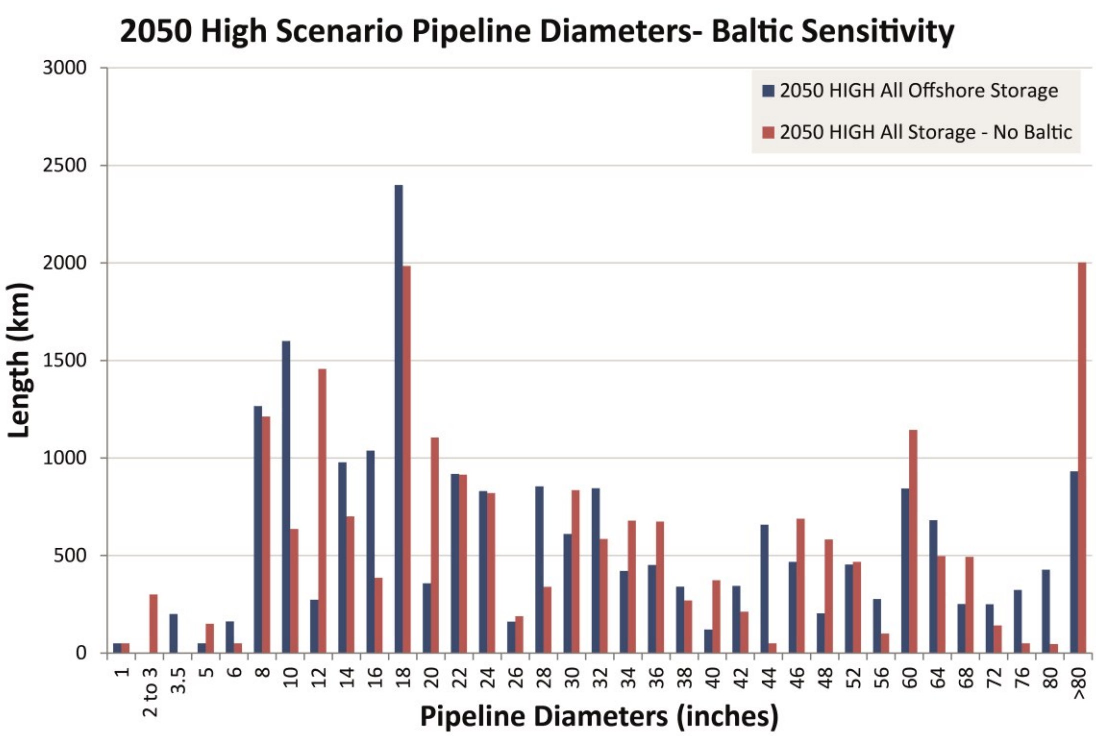

Legend
CO2 captured in MT/yr
0.27 - 0.5
0.5 - 1
1 - 1.4
1.4 - 1.7
1.7 - 2
Pipelines
CO2 Storage in MT
0 - 100
100 - 500
500 - 1000
1000 - 5000
5000 - 10000
Europe Grid
Country Boundaries


Legend
CO2 captured in MT/yr
0.27 - 0.5
0.5 - 1
1 - 1.4
1.4 - 1.7
1.7 - 2
Pipelines
CO2 Storage in MT
0 - 100
100 - 500
500 - 1000
1000 - 5000
5000 - 10000
Europe Grid
Country Boundaries


2030 Medium Scenario Pipeline Diameters
2030 MED Offshore Storage Only
2030 MED All Storage
Length (km)
Pipe Diameter (inches)
0
500
1000
1500
2000
2500
3000
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
44
48


2050 Medium Scenario Pipeline Diameters
2050 MED Offshore Storage Only
2050 MED All Storage
Length (km)
Pipeline Diameter (inches)
0
500
1000
1500
2000
2500
3000
3.5
4
5
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
52
56
60
64
68
72
76
80
>80


Legend
CO2 captured in MT/yr 2050 H
1 - 2.8
2.8 - 6
6 - 11
11 - 18
18 - 28
354
Pipeline Flow Rate (tonnes/hr) - Offshore, No Baltic
CO2 Storage (Mt) - Offshore - No Baltic
0.40 - 100
100 - 500
500 - 1000
1000 - 10000
10000 - 10200
Europe Grid
Country Boundaries
North Sea only Hi 2050, with flows length 20189km
cost €21824 M more 300mm and 500mm diameter


2050 High Scenario Pipeline Diameters- Baltic Sensitivity
2050 HIGH All Offshore Storage
2050 HIGH All Storage - No Baltic
Length (km)
3000
2500
2000
1500
1000
500
0
1
2 to 3
3.5
5
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
52
56
60
64
68
72
76
80
>80
Pipeline Diameters (inches)