JRC Scientific and Technical Reports

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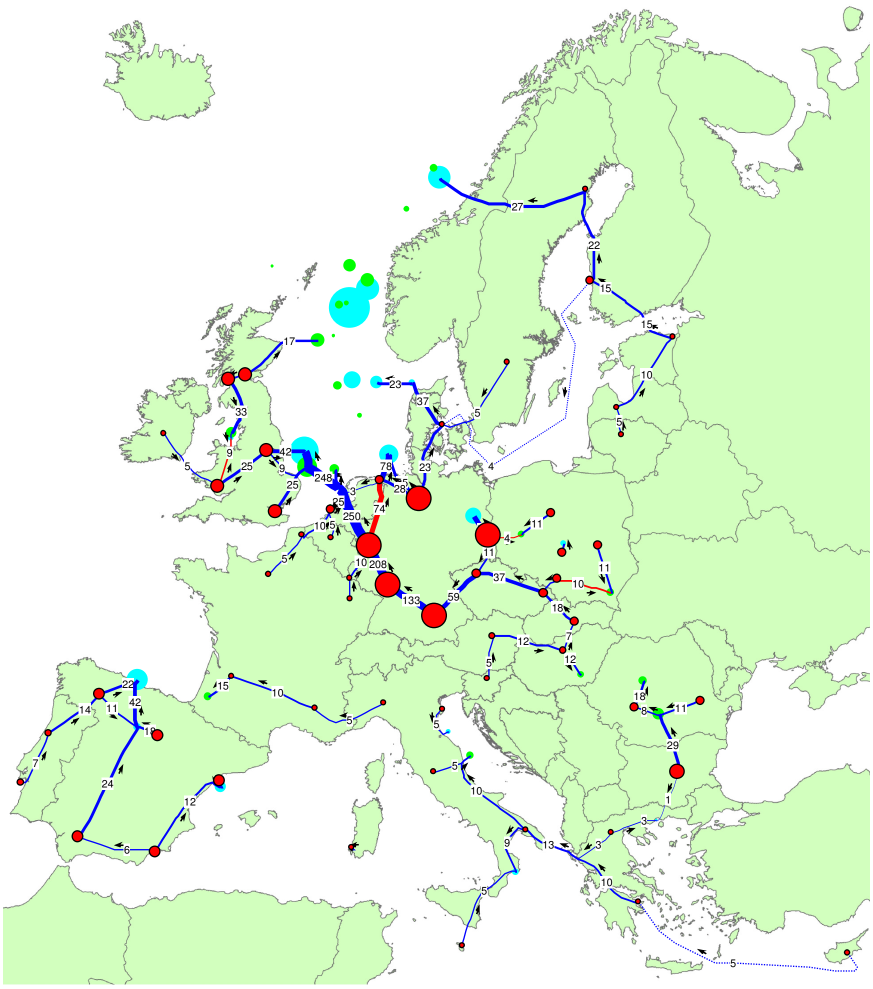

JRC
EUROPEAN COMMISSION

Institute for Energy

EUR 24565 EN - 2010

The mission of the JRC-IE is to provide support to Community policies related to both nuclear and non-nuclear energy in order to ensure sustainable, secure and efficient energy production, distribution and use.

European Commission
Joint Research Centre
Institute for Energy

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JRC61201

EUR 24565 EN
ISBN 978-92-79-17204-5
ISSN 1018-5593
doi:10.2790/24331

Luxembourg: Publications Office of the European Union

Printed in the Netherlands

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Introduction

Fossil fuels will remain the main source for electricity generation in Europe, at least in the short to medium term, despite the significant ongoing efforts to promote renewable energy technologies and energy efficiency including the targets set out by the Climate and Energy package. CO_2 capture and storage (CCS) is considered as one of the most promising technological options for reducing CO_2 emissions from the power generation sector, as well as from other heavy industries, offering a bridge between the fossil fuels dependent economy to the carbon-free future. Today, most elements of the CCS chain of technologies (CO_2 capture, transport and underground storage) have already been commercialised, albeit at a scale much smaller than that required by the power generation sector and other energy-intensive industries. To this end, the European Union (EU) has made the demonstration of CCS technologies a priority in the context of the European Strategic Energy Technology Plan (SET-Plan) to enable the cost-competitive deployment of CCS technologies as of 2020-2025 and to further develop the technologies to allow for their subsequent wide-spread use in all energy-intensive industrial sectors, thus contributing to the decarbonisation of the European society by 2050.

The large scale deployment of CCS in Europe will require the development of new infrastructure to transport, using pipelines and ships, the captured CO_2 from its sources (e.g. power plants) to the appropriate CO_2 storage sites. The physical properties of CO_2 differ from those of, for example, natural gas, creating some technical design issues to overcome. For example, current installations and research in the field of CO_2 pipelines suggest that the most cost-effective option is to transport CO_2 in dense phase above its 'critical point', i.e. above 32 degrees Celsius and above 75 Bar. This would require pipelines to operate at higher pressures than most existing natural gas pipelines, and to operate with low levels of impurities, including water, which can react with CO2 to create carbonic acid that would be corrosive to commonly-used pipeline materials. Despite all the above-mentioned issues, the large scale transportation of CO_2 by pipeline is an established industrial process in the USA with 3,900 km of pipelines transporting 30Mt of CO_2 annually. It is widely accepted that also in Europe most of the CO_2 will be transported by pipelines. Although the use of suitable ships, similar to those used for LNG and LPG, has been proposed as an alternative transport option, this is rather unlikely to be realised on a large scale, at least during the early stages of CCS deployment, due to the state of maturity and transport capacity of this option. Furthermore, the fact that many possible CO_2 sources and sinks will not be directly accessible by ships should not be overlooked. In support of this argument it is noted that only one out of the seven archetypal projects identified by the zero emission fossil fuel power plant Technology Platform (ZEP ETP) in their proposal for a European demonstration programme envisages CO_2 transport by ship.

There are different views on how the CO_2 transport infrastructure might evolve in Europe. There has been a perception that CCS plants will be built very close to potential storage sites for minimising transport costs. On the other hand, proposals for CCS projects that have become public tend to show that their location is dictated by other factors, such as safety and public acceptance concerns that may require that CO_2 is initially stored offshore; or the presence of old power plants that are suitable for retrofitting or refurbishing with CO_2 capture technologies. Furthermore, the large scale deployment of CO_2 capture facilities in Europe, needed to achieve the decarbonisation of the European society by 2050, combined with the fact that CO_2 storage sites and capacities are not uniformly distributed across Europe, will necessitate the construction of an extended pipeline infrastructure, which will span across Member State borders when countries do not have adequate CO_2 storage potential.

The evolution of the CO_2 transport network in Europe will be dictated by the level of CCS deployment and the degree of coordination for its development. The simplest approach for the development of the CO_2 transport infrastructure would be the construction of numerous pipelines linking individual CO_2 sources with sinks, sized to meet the transport needs of individual capture facilities. This implies that pipelines will be constructed in the context of individual CCS projects and their planning and construction will be synchronous to the development of the CO_2 capture facilities. This approach is however likely to impede the large scale deployment of CCS as it will not permit the expansion and sharing of the built infrastructure with other CO_2 sources, which in turn will be required to develop their own pipelines, resulting in deployment delays due to permitting procedures, and additional costs, since pipeline costs do not scale proportionally with transport capacities. Apparently, this situation would be most detrimental for CO_2 sources that are either of small size or located away from suitable storage sites. Alternatively, the development of integrated pipeline networks, planned and constructed initially at regional or national level and oversized to meet the transport needs of multiple CO_2 sources would take advantage of economies of scale and enable the connection of additional CO_2 sources with sinks in the course of the pipeline lifetime. For example the Pre-Front End Engineering Design Study of a CCS network for Yorkshire and Humber showed that initial investment in spare pipeline capacity would be cost effective even if subsequent developments were not to join the network for up to 11 years. The study also confirmed experience from other sectors i.e. that investing in integrated networks would catalyse the large scale deployment CCS technologies by consolidating permitting procedures, reducing the cost of connecting CO_2 sources with sinks and ensuring that captured CO_2 can be stored as soon as the capture facility becomes operational. In the longer run, such integrated networks would be expanded and interlinked to reach CO_2 sources across Europe and distant storage sites, leading to the development of a true trans-European network, similar to the existing ones for electricity and gas.

The development of a trans-European network will however require:

- Advanced planning for its optimal design, taking into consideration the anticipated volumes of CO_2 that will have to be transported in the medium and long term and the location of CO_2 sources and sinks.

- Coordination of national authorities, in view of the fact that a trans-European integrated network will have an international dimension, hence cross-border issues will need to be addressed.

- Policy intervention in the form of financial support, as the trans-European pipeline network will be originally operated below its nominal capacity in anticipation of its connection with additional CO_2 sources during the lifetime of the investment.

- Other measures, such as the possible development of European CO_2 stream composition specifications, which can be addressed in the review of the Directive for the underground storage of CO_2 (2009/31/EC) to be completed by 31 March 2015[1].

The aim of this report is to describe the potential evolution of the CO_2 transport network on the European scale for the period 2015 – 2050 for the benefit of the Impact Assessment. It is underlined however that the results from any analysis with such broad spatial and long-term coverage are only indicative. This analysis provides a first 'order of magnitude' estimate of the extent of the CO_2 network, the investments required as well as an insight on its international character. The estimates have been made based on a sound methodology, which is described in brief below. The results however depend strongly on the assumptions that have been made, especially in view of the long term horizon of the analysis, the uncertainty of CCS deployment rates and timelines, the lack of robust data on CO_2 storage sites and the variability of pipeline construction costs. The assumptions made for this analysis are described in detail below, followed by the results. It is noted however that the developed methodology can be easily used to assess the development of the trans-European CO_2 network under different sets of assumptions, which may be deemed more appropriate in the future (e.g. when the New Infrastructure Instrument is tabled).

[1] See article 38 paragraph 2 of Directive 2009/31/EC

Methodology

The aim of the analysis is to determine the *optimal* CO_2 transport network in Europe and its evolution over time. The term 'optimal' is used here to indicate that the methodology aims at determining a network configuration that transports predefined volumes of CO_2 to suitable storage sites at the lowest possible cost. The methodology consists of four steps:

- **Step 1 – Identification and clustering of CO_2 sources and sinks.** Locations and sizes of CO_2 sources and sinks are obtained from existing databases, described below. Since there is a large number of possible CO_2 source and sink locations, a mathematical clustering algorithm is used to group the source and sink locations into a number of 'clusters'. Sources and sinks are clustered separately. Each cluster centre becomes a 'node' in the network, either a 'source node' or a 'sink node'. Each node is a point on the map of Europe, which however does not refer to a specific CO_2 source (e.g. an existing power plant) or sink (e.g. an aquifer).

- **Step 2 – Assumptions about the evolution of captured CO_2 emissions and storage capacities.** For each CO_2 source node, an assumption is made regarding the starting date of capture operations, the annual amount of CO_2 captured and its evolution over time. For each sink node, an assumption is made regarding storage capacity, the earliest possible starting date of storage operations, the maximum annual injection rate and its evolution over time.

- **Step 3 – Routing of potential pipelines between nodes.** A large set of possible pipelines between the above-mentioned nodes is determined. For each possible pipeline, the construction costs are estimated taking into account cost differences between onshore, offshore and mountainous areas[2]. Pipelines are restricted to the territory of the European Economic Area (EEA). Although the focus of this analysis is the development of a pipeline network, the possibility of CO_2 transport by ship is foreseen on two long, albeit small capacity, marine routes.

- **Step 4 – Selection of the optimal network and evolution over time.** A state-of-the-art optimisation engine is used to determine the optimal set of pipelines and shipping routes, among the set identified in the previous step. The optimisation criterion is the minimisation of the total net present value (NPV) of CO_2 transport infrastructure investments in Europe, while ensuring that all CO_2 capture plants across Europe have access to transport and storage.

The above procedure is embedded in the *InfraCCS* tool developed by the JRC.

Assumptions

- **Overall assumptions:**
  - The study covers the 27 EU Member States. Norway is included in the analysis only with respect to storage sites, while Norwegian CO_2 sources are not considered.
  - The time horizon of the study is 2050, with snapshots for the years 2015, 2020, 2025 and 2030.

[2] This information is extracted from geographical information systems (GIS).

■ **Assumptions for Step 1:**

- Information on the locations and capacities of CO_2 sinks is obtained from the GeoCapacity database, which has been developed in the context of a research project funded by the 6th Framework Programme for Research and Development of the EU. An objective mathematical clustering of sinks is performed, in order to select the most suitable set of cluster centres so that sinks are on average less than 50 km away from the nearest identified cluster centre. Each of the identified cluster centres becomes a sink node in the analysis. Hydrocarbon fields and aquifers are clustered separately, so a distinction is made between 'hydrocarbon field sink nodes' and 'aquifer sink nodes'. Since the GeoCapacity database does not include any Italian offshore hydrocarbon fields, an additional hydrocarbon field sink node is added in the Adriatic Sea to reflect the present situation.

- It is further assumed that CO_2 storage in onshore aquifers does not materialise in the EU, driven by public concerns, except where onshore storage in aquifers is explicitly foreseen in the CCS projects funded by the European Energy Programme for Recovery (EEPR). This is the case for the three aquifers associated with the projects in Germany, Poland and Spain. It is assumed that these aquifers will be allowed to store CO_2 only from the sources clustered in the same node together with the corresponding CCS EEPR plant. Besides these three EEPR-related onshore aquifers, no other onshore aquifer sink nodes are considered in the analysis. Onshore hydrocarbon fields, which are subject to the same considerations but may be more easily publicly accepted for CO_2 storage than onshore aquifers, are only considered in the analysis in countries that have no offshore storage fields and whose onshore hydrocarbon fields are large enough to accommodate at least all the CO_2 captured from a 400 MW_{net} coal power plant for the duration of its lifetime. This is the case for France, Hungary, Poland and Romania.

- Similar to the clustering of sinks, the CO_2 source nodes up to 2050 are determined objectively by applying a mathematical clustering algorithm to all *current* CO_2 emissions sources, as obtained from the GeoCapacity and the EPER emission databases. This approach implies the assumption that future CO_2 capture plants will typically be located in areas that include already today a cluster of CO_2 emissions, e.g. the Ruhr area in Germany. The clustering algorithm chooses the most suitable set of cluster centres in each Member State (minimum one per Member State), so that, overall, the current EU CO_2 sources are on average less than 100 km away from the nearest identified CO_2 emission cluster centre. As mentioned before, each of the resulting cluster centres becomes a CO_2 source node in the analysis. In addition, the 6 CCS EEPR projects and 6 other projects in advanced stage of conception (Longannet, Kingsnorth, Eemshaven, Hunterston, Meri Pori and Sulcis in Sardinia) are added as source nodes. In cases where one of these 12 plants is very close to one of the identified cluster centres, the latter cluster centre is removed from the analysis, for the sake of simplicity. It is important to note that the clustering exercise is based on the complete GeoCapacity and EPER emissions databases, which include not only power plants but a wider range of point sources of CO_2, such as industrial complexes, refineries, etc. The location of the resulting nodes is therefore also representative of potential capture projects at industrial sites.

- As a result of the clustering exercise, the analysis considers 57 CO_2 source nodes, 24 hydrocarbon field sink nodes (of which 6 onshore), and 19 aquifer sink nodes (of which 3 onshore). The coal field that is envisaged as CO_2 sink in the Sulcis project, is added as a single 'coal field sink node', which brings the total number of nodes to 101.

- **Assumptions for Step 2:**

  - The CO_2 storage capacity in each sink node is the sum of the storage capacities of all sinks in the cluster. Storage capacities are obtained from the conservative estimates of the GeoCapacity project. Annual injection rates of each sink are capped at $1/30^{th}$ of the total capacity of the sink. The starting date of possible injection in hydrocarbon field sink nodes is determined based on the expected depletion of the hydrocarbon reserves in the area. Injection in offshore aquifers is assumed to become possible in 2015. Injection in the onshore aquifers envisaged in the EEPR projects is assumed to become possible as of 2015 as well.

  - The amount of CO_2 captured per country up to 2030 is taken from the 2009 update of the PRIMES Baseline scenario. The amount of CO_2 captured per country in 2050 is determined by scaling up the CO_2 capture volumes of 2030 so that the total amount of CO_2 captured in the EU in 2050 matches the corresponding value from the Eurelectric 'Power Choices' scenario. It is noted that both these scenarios describe only the captured emissions from the power generation sector. Capturing the emissions from other industries would obviously increase significantly the amounts of CO_2 that need to be transported, and hence lead to an expanded CO_2 transport network. Furthermore, it should be noted that the Eurelectric scenario does not assume any cross-border transport of CO_2, except in the Benelux. This is however not incompatible with the model used in the present analysis, where cross-border transport of CO_2 is only performed when it is a cost-minimising solution. Hence, the CO_2 transport network in this analysis could transport more CO_2 than the Eurelectric scenario at a given cost, therefore the use of the Eurelectric scenario in this analysis is a conservative choice.

  - Since PRIMES provides only the total amount of CO_2 captured per country, assumptions are made regarding the geographic locations of the sources of captured CO_2. In the analysis, the captured CO_2 emissions as prescribed in PRIMES, at each point in time, are distributed among a number of CO_2 source nodes within each country (either a subset of source nodes or all source nodes). Source nodes are activated gradually (one at a time), when the allocation of CO_2 emissions from PRIMES to existing nodes exceed 5Mt/y per node. For countries with multiple source nodes, the prioritisation in activating the source nodes is as follows: (i) the 6 EEPR project locations, (ii) the locations of the 6 projects in advanced stage mentioned above, (iii) other locations in order of increasing distance from EEPR project locations (where applicable), (iv) other locations in descending order of current CO_2 emissions. No CO_2 capture is assumed on islands of countries with a continental presence (e.g., France, Spain, Greece) unless foreseen in a project (Sulcis in Sardinia). Furthermore, it is assumed that by 2050 all CO_2 source nodes capture at least 5 Mt/y of CO_2, which is the equivalent of a typical 800 MW_{net} coal power plant.

- **Assumptions for Step 3:**

  - Pipeline investment costs are expressed in Euros 2010 and are based on a statistical analysis of available CO_2 pipeline cost estimates, combined with publicly available assessments of ongoing large natural gas pipeline projects (MedGaz, GALSI, NordStream, Nabucco). It is stressed that the construction costs for both natural gas and CO_2 pipelines, as they appear in the open literature, show large scatter, hence it is difficult to define reference cost values. It is also important to note that the calculation of costs assumes that pipeline investments are 'lumpy': even a pipeline with very small capacity still requires significant investment, while a pipeline with much larger capacity is proportionally cheaper.

- Transport of CO_2 by ship is foreseen on two routes: (i) Finland-Denmark, as foreseen in the Meri Pori project, and (ii) Cyprus-Greece, because of the small volumes and the large depth of the eastern Mediterranean, which makes the construction of a pipeline in this region unpractical. Shipping costs are based on preliminary business cases presented by the industry, and hence represent rough estimates only.

- Cross-border transport of CO_2 takes place only after 2020.

■ **Assumptions for Step 4**

- A discount rate of 7.5% is assumed, which is the average of the typical industrial discount rate for this type of investments (10%) and the European social discount rate according to the DG REGIO guidance for cost-benefit analysis (5%).

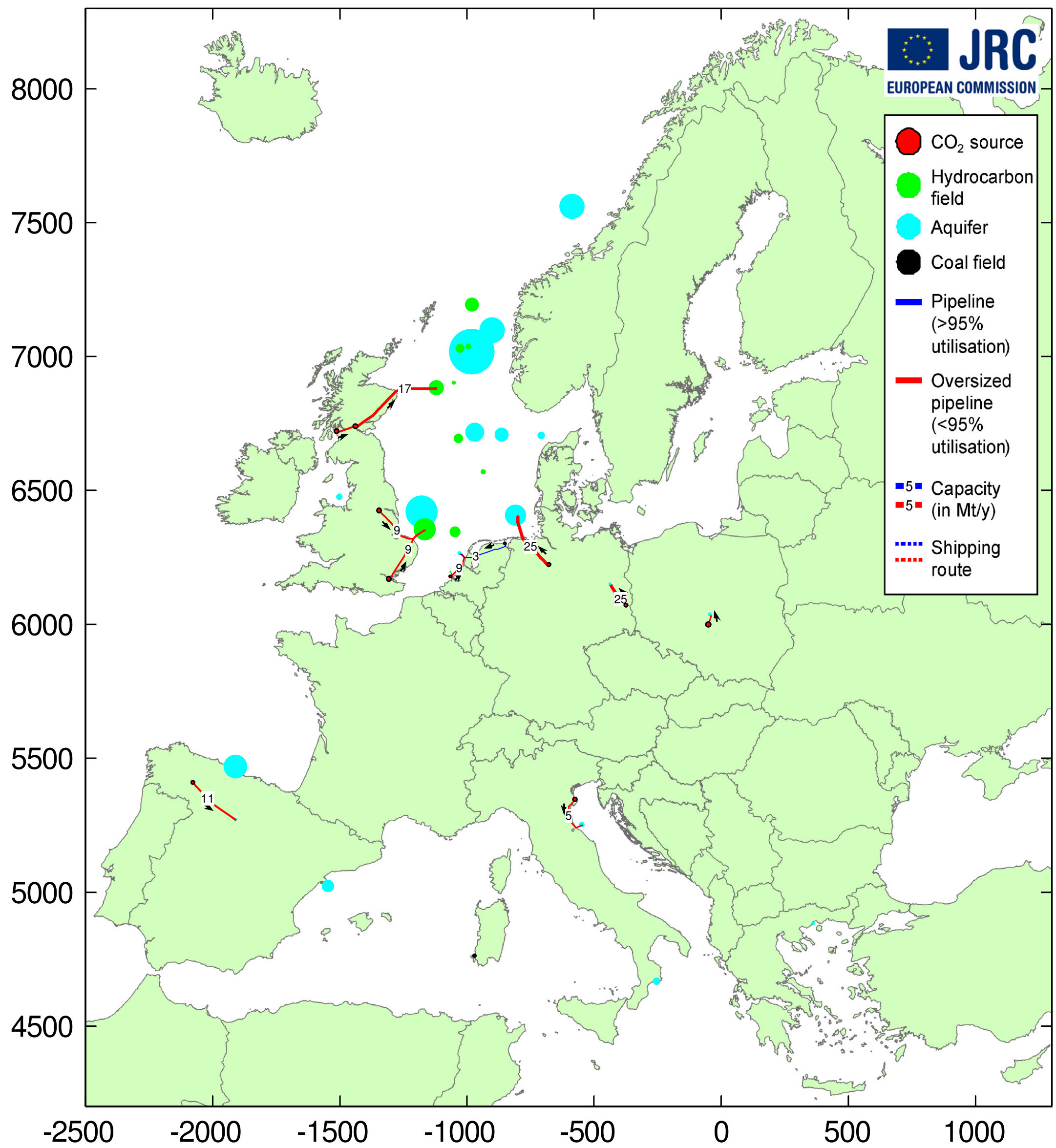
Results

As mentioned above, this analysis assumes that the first elements of the European CO_2 pipeline infrastructure are put in place in 2015 with the start of operation of the 6 EEPR-funded CCS demonstration projects. For all these cases, CO_2 is transported to the sinks by pipeline.

Since the New Infrastructure Instrument will cover the new financing period 2013-2020, the first snapshot of this analysis is the most relevant for the Instrument and the Impact Assessment. In 2020, 36 Mt of CO_2 are captured from power plants in 6 EU Member States, which correspond to 2.5% of the CO_2 emissions from the EU power sector. The resulting CO_2 transport network in 2020 is shown on the map below. In Germany, the UK and the Netherlands, additional source nodes (beyond the initial EEPR projects) start capturing CO_2, and pipelines are constructed to transport the CO_2 to a number of offshore locations in the North Sea. It is interesting to observe that nearly all pipelines are at this stage 'oversized', in order to accommodate the additional CO_2 quantities anticipated in the following years[3]. For example, the pipeline from the German EEPR project to the aquifers in the Brandenburg region is designed with a capacity of 25 Mt/y, while the initial flow from the demonstration project is only 1-2 Mt/y. The 25 Mt/y pipeline will be fully utilised by 2030. Oversizing is a result of pipeline economics as it is optimal to build a large pipeline from the beginning, rather than building a small pipeline, which subsequently needs to be expanded.

[3] It is noted that oversized pipelines are shown in red, while pipelines operating at full capacity are shown in blue in the figures that follow.

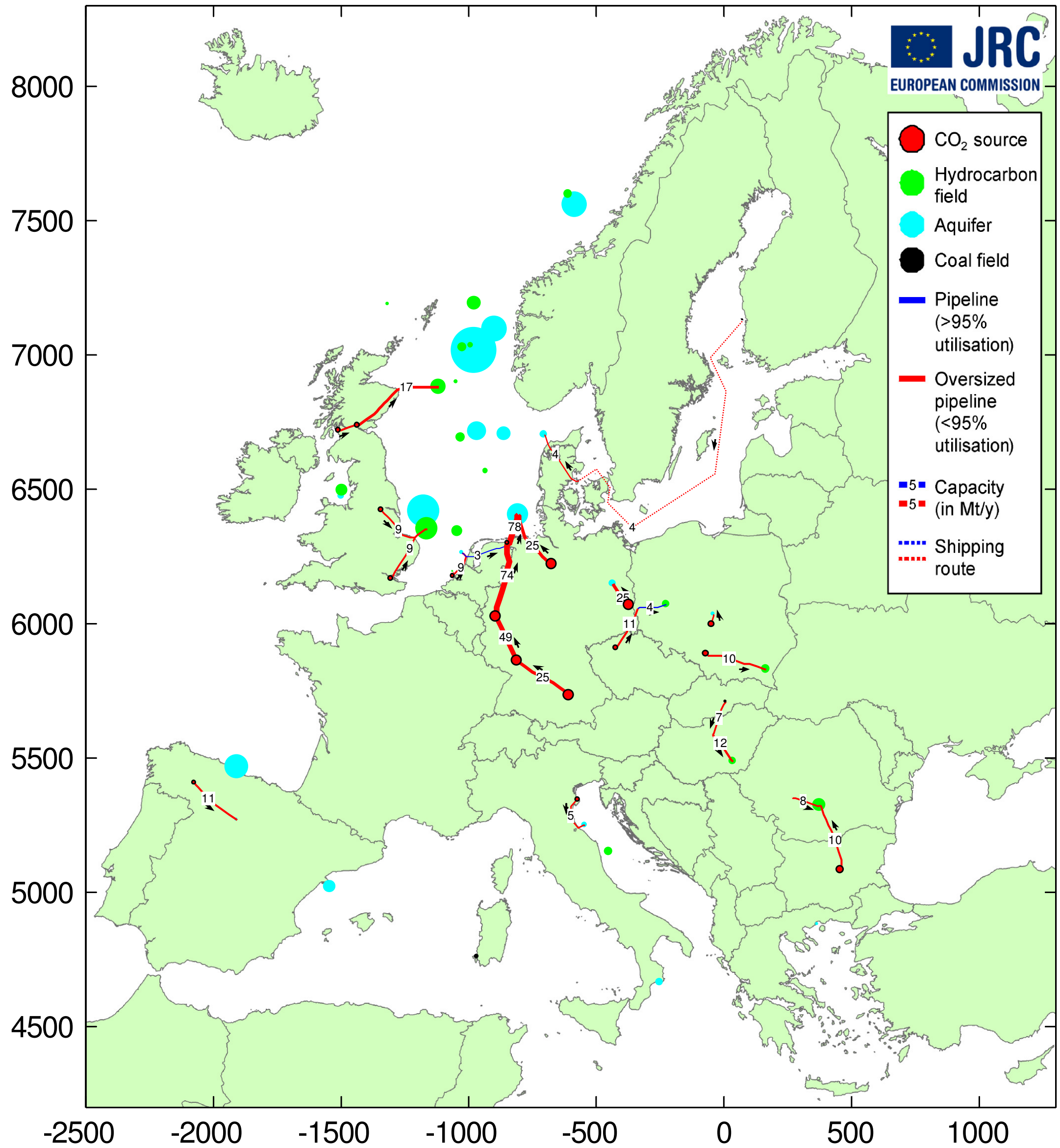
YEAR 2020 - 2005km network - 2.5 billion EUR cumulative investment



As it was mentioned above the period relevant for the Impact Assessment stretches until 2020. Therefore, for the sake of completeness of the analysis, exceptionally for the 2020 snapshot an alternative run of the model was exercised where figures from PRIMES Reference scenario were used. This alternative run showed exactly the same outline of the pipelines stretching across Europe for the same length of 2005 km. The only change is that the cumulative investment drops to €2.2 billion (instead of €2.5 billion) as some of the pipes do not need oversizing for the future. The fact that these two different runs produce similar results in 2020 results mainly from the fact that EEPR projects are already under development. They will initiate the network that could evolve further post 2020. This evolution will depend however on investment made before this date.

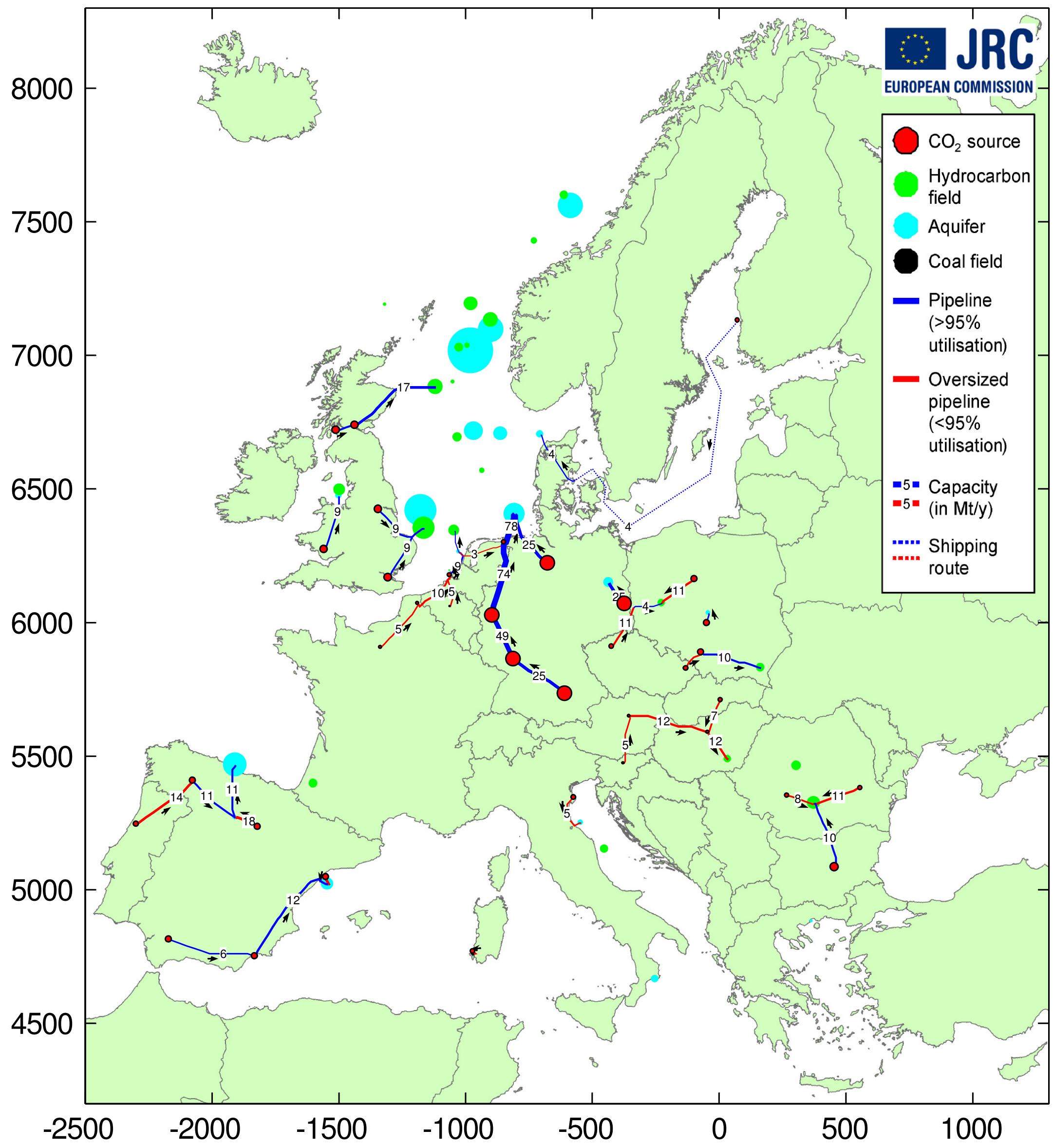
In 2025, the amount of CO_2 captured increases to 113 Mt (i.e. 8% of the CO_2 emissions of the EU power sector of that year) with CCS projects in 13 Member States. Elements of a trans-European pipeline network start to be put into place with the construction of a number of regional connections, e.g. a large oversized pipeline collecting CO_2 throughout the southern and western parts of Germany as well as the northern part of the Netherlands, and bringing it to the offshore aquifers in the North Sea. Furthermore, a CO_2 transport chain by ship is set up from Meri Pori (Finland) to Denmark. In Denmark, the CO_2 is fed into a pipeline and transported to Danish offshore aquifers. This pipeline is designed to also transport captured CO_2 from Danish sources as of 2030. Smaller-scale international CO_2 pipelines are also being constructed between Germany, Poland and Czech Republic, as well as between Slovakia and Hungary, and between Bulgaria and Romania.

YEAR 2025 - 5607km network - 5.8 billion EUR cumulative investment



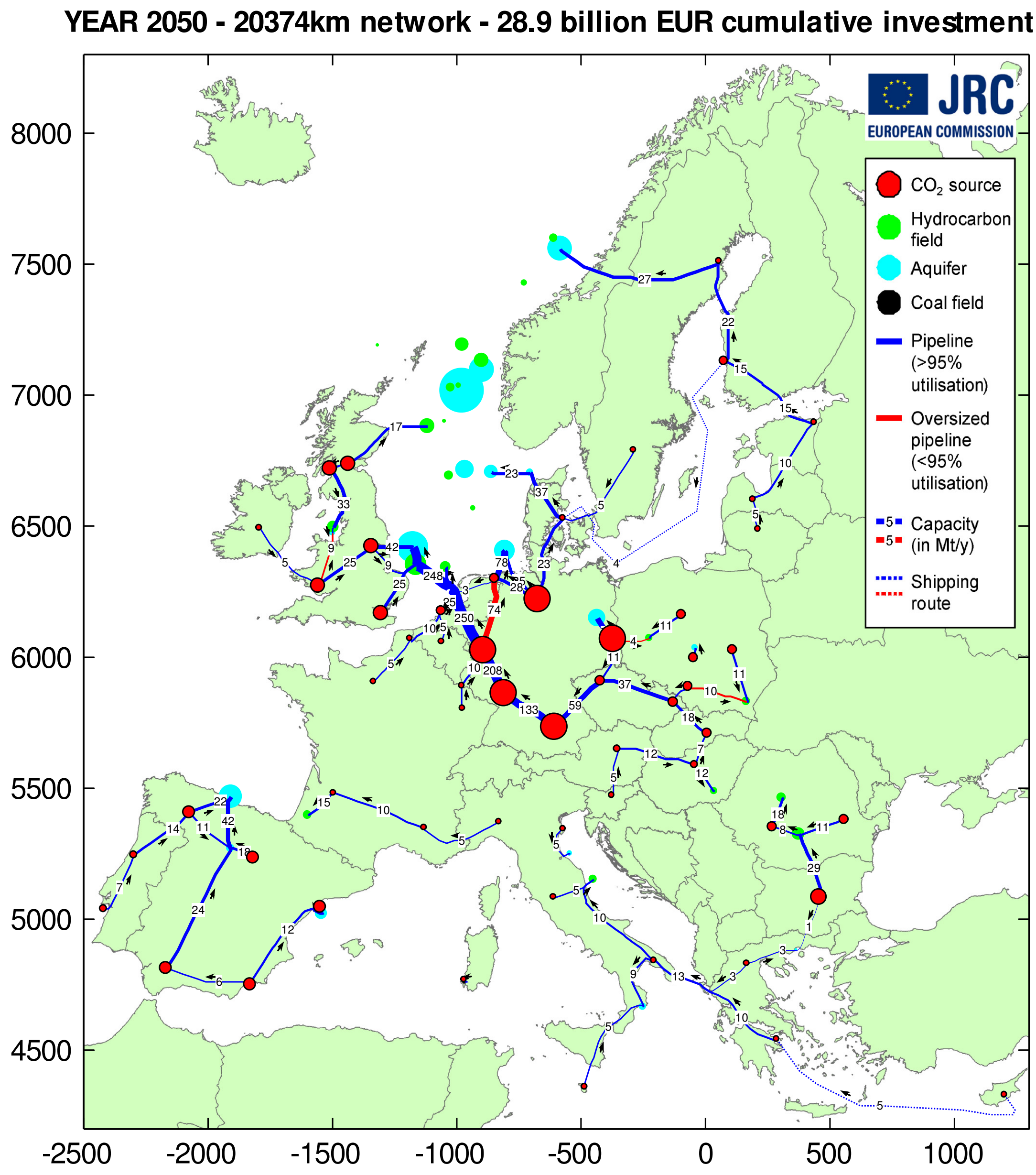
In 2030, the amount of CO_2 captured increases to 272 Mt (i.e. 25% of the CO_2 emissions of the EU power sector) and pipelines are present in 18 Member States. Many of the oversized pipelines built before 2025 are now operating at full capacity, and new oversized pipelines are built, which will be become fully utilised in the ramp-up towards 2050. Regional networks in central and eastern Europe continue to expand. In the south of Europe, a large expansion of CO_2 pipelines appears in the Iberian Peninsula, while the Sulcis project starts to operate in Sardinia. Belgium and France are linked to offshore depleted gas fields in the Netherlands.

YEAR 2030 - 8803km network - 9.1 billion EUR cumulative investment



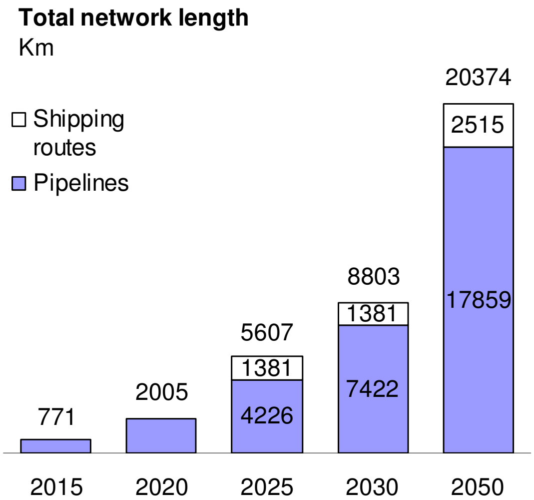
By 2050, most of the large power plants in Europe capture and store the CO_2 generated, approximately 900 Mt, which corresponds to approximately three quarters of the CO_2 emissions of the European power sector. Storing this quantity requires a major expansion and integration of the CO_2 transport infrastructure, as shown in the figure below. In continental western Europe, a large backbone is constructed, bringing CO_2 from central and eastern parts of Europe through Germany and the Netherlands to the hydrocarbon fields and aquifers in the southern part of the North Sea. The backbone extends to Slovenia and Hungary. Furthermore, Denmark becomes a transit point through which CO_2 from northern Germany, Sweden and Finland is transported to aquifers in the central North Sea. In an almost equally cost-effective alternative scenario, the excess CO_2 that cannot be stored locally in Poland could be transported to Denmark as well, instead of feeding into the backbone to the

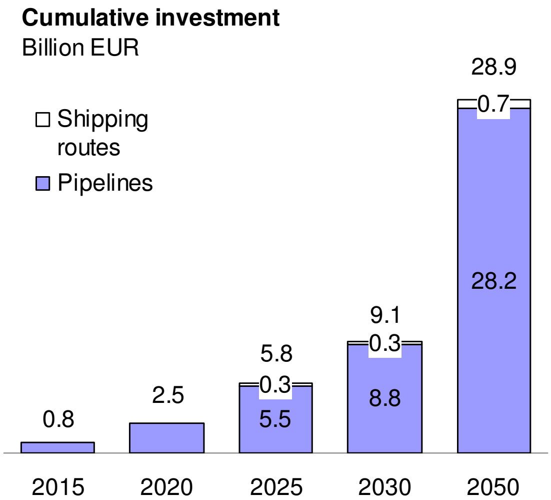
Netherlands. As mentioned before, it is assumed that all Member States deploy CCS technologies by 2050, which leads to the construction of a number of extensive regional networks. Ireland is connected to the UK and a pipeline is built to access the aquifers in the southern North Sea. Cyprus is connected to Greece by ship, which, like Malta, is now connected to Italy. Under the assumptions of the analysis, CO_2 from the north of Italy is stored in southwest France. Obviously, if the model allowed onshore storage in Italy, then this CO_2 would instead be stored in depleted hydrocarbon fields in northern Italy. Finally, the amount of CO_2 captured in Scandinavia has reached a sufficiently large value, so that pipeline transport (to Denmark and to Norway) becomes economical complementing the existing shipping route. A trunk line collecting CO_2 from the Baltic states also feeds into this network.



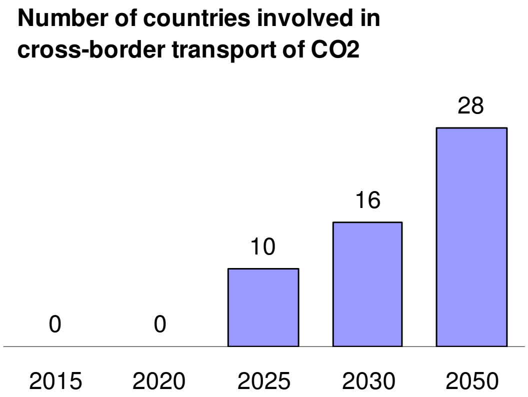
Conclusions

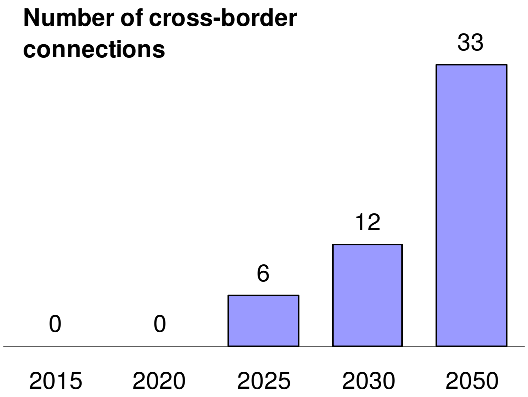
This note presents the results of a model-based optimisation of the potential evolution of a trans-European CO_2 transport network to facilitate the large scale deployment of CCS, as described in the 2009 Baseline scenario of the PRIMES model. The key figures of the network deployment over time are summarised in the following graphs. The size of the network grows steadily until 2030, to 8800 km, requiring around 9 billion euros of cumulative investment; followed by a step-change towards 2050, leading to a total investment of around 29 billion euros. This is based on a relatively conservative scenario of CCS deployment, as the amount of CO_2 captured in 2050 does not meet the ambition for the decarbonisation of the European society by 2050. Scenarios compatible with the European vision for a decarbonised society by 2050, which will necessitate the capture of almost all CO_2 emissions from both the power and the industrial sectors, would obviously be associated with a more extensive and hence more expensive CO_2 transport network.





The analysis also highlights the benefits of European coordination if Europe is to achieve the optimal (cost-minimising) solution for CO_2 transport. The following graphs summarise the number of countries involved in cross-border CO_2 transport, as well as the number of border-crossings. By 2030, 16 EU Member States may be involved in cross-border CO_2 transport. International coordination is therefore crucial for the development of an optimised trans-European CO_2 transport network.





Important notes

- The above results should only be seen in the context of the assumptions made for the execution of such a broad analysis. Use of alternative scenarios for the evolution of captured CO_2 quantities in Europe or different hypotheses for the availability of onshore aquifers for CO_2 storage will produce a different set of results.

- The error margin of optimisation is of the order of 25%. This is the possible deviation that should be considered in the reported pipeline lengths and implicitly on costs.

- The locations of CO_2 emission sources and sinks have been considered in the analysis with an accuracy of ±100 km, which may induce additional deviations in the reported lengths. Furthermore, points on the map should not be identified with specific CO_2 sources or sinks.

- Since cost estimates for CO_2 pipelines and CO_2 shipping show large scatter, the real costs may differ from the results of this analysis, which is based on 'typical' cost values.

European Commission

EUR 24565 EN – Joint Research Centre – Institute for Energy
Title: The evolution of the extent and the investment requirements of a trans-European CO_2 transport network
Author(s): Joris Morbee, Joana Serpa, Evangelos Tzimas
Luxembourg: Publications Office of the European Union
2010 – 12 pp. – 21.0 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-17204-5
doi:10.2790/24331

Abstract

The large-scale deployment of carbon capture and storage (CCS) in Europe will require the development of new infrastructure to transport – using pipelines and ships – the captured CO_2 from its sources (e.g. power plants) to the appropriate CO_2 storage sites. This report describes the potential evolution of the CO2 transport network on the European scale for the period 2015-2050, in terms of physical size and capital cost requirements. These estimates have been made based on an innovative and sound methodology. The results however depend strongly on the assumptions that have been made, especially in view of the long-term horizon of the analysis, the uncertainty of CCS deployment rates and timelines, the lack of robust data on CO_2 storage sites and the variability of pipeline construction costs.

The size of the network grows steadily until 2030, to 8800 km, requiring around 9 billion euros of cumulative investment; followed by a step-change towards 2050, leading to a total investment of around 29 billion euros. This is based on a relatively conservative scenario of CCS deployment, as the amount of CO_2 captured in 2050 does not meet the ambition for the decarbonisation of the European society by 2050. Scenarios compatible with the European vision for a decarbonised society by 2050, which will necessitate the capture of almost all CO_2 emissions from both the power and the industrial sectors, would obviously be associated with a more extensive and hence more expensive CO_2 transport network. By 2030, 16 EU Member States may be involved in cross-border CO_2 transport. International coordination is therefore crucial for the development of an optimised trans-European CO_2 transport network.

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LD-NA-24565-EN-N

EUROPEAN COMMISSION

Publications Office

ISBN 978-92-79-17204-5