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Submitted (Author(s))	Filip Neele	15/04/2011
Verified (WP-leader)	Filip Neele	15/04/2011
Approved (SP-leader)	Luuk Buit	18/04/2011

Author(s)		
Name	**Organisation**	**E-mail**
Filip Neele	TNO	Filip.neele@tno.nl
Marielle Koenen	TNO	Marielle.koenen@tno.nl
Ad Seebregts	ECN	seebregts@ecn.nl
Jeroen van Deurzen	ECN	vandeurzen@ecn.nl
Klaas Kerssemakers	Anthony Veder	kkerssemakers@anthonyveder.com
Machiel Mastenbroek	Anthony Veder	mmastenbroek@anthonyveder.com

EXECUTIVE SUMMARY

Introduction

Carbon Capture and Storage (CCS) is identified by national and European governments as part of a portfolio of measures to reduce CO_2 emissions. CO_2 transport is probably the least cost intensive element of the full CCS chain, but may be the most planning and guidance-intensive part during the development of the transport infrastructure. The EU FP7 CO_2Europipe project aims to present a roadmap towards a Europe-wide infrastructure network for the transport and storage of CO_2.

In this report the geographical distribution and timing of CO_2 supply and storage availability is sketched in the period 2020 - 2050. CO_2 captured volumes and available storage capacity are linked to obtain a sketch of a possible future transport network. Some requirements and possible bottle-necks for its development are touched upon. This report will be used in the remainder of the project, which runs until the end of 2011, to formulate the requirements for the development of large-scale CCS infrastructure.

Captured volumes

It is assumed that future capture installations will be located in current industrialised regions. Current emission levels from these regions are used to estimate future captured volumes. Data on CO_2 emission sources is provided by the emission database compiled by the recently concluded EU FP6 project Geocapacity. Sources include large CO_2 point sources like power plants and industry. Emission sources (which represent future capture installations) are grouped together into regional source clusters.

National CO_2 capture efforts are projected from 2020 until 2050. On the short term for the year 2020, the small-scale CCS plans (status October 2009) provide the starting point. On a longer term for the period 2025-2050, energy use scenarios are combined with assumptions on economic growth, energy demand and fuel mix in power generation and in large industry, to obtain the national level of capture efforts. Up to 2030, a PRIMES scenario from the CCS Impact Assessment published in 2008 was used as a starting point. That scenario has been modified up to 2030 for countries like the Netherlands, Belgium, Germany and Norway based on more up to date information from more recent national energy scenarios. For the period after 2030, the scenarios have been extrapolated assuming:

- Continued (and thus increasing) energy saving. E.g., the energy demand increase between 2030 and 2050 is equal to the increase between 2020 and 2030.
- Further increase of renewable energy
- In EU Member States with nuclear power plants phased out, like Germany and Belgium, part of that capacity is replaced by fossil power plants with CCS
- All new coal power plants deploy CCS
- For some EU Member states co-firing of biomass is used for coal power plants. Hence, to some extent deployment of CCS to these power plants results in a negative CO_2 emission.
- Roughly, about 80% of CCS is deployed in power generation; the other 20% is deployed on large point sources in industry.
- The CO_2 emissions in 2050 are about 80% less than the CO_2 emissions in 1990, for the total of the countries involved in this CO2Europipe scenario.

- The largest share of national captured volumes is assumed to be taken by source clusters currently planned for small-scale demonstration projects and / or clusters with currently large emissions.

The development in the captured volumes presented here is from almost 50 Mt/yr by 2020 to more than 1 Gt/yr by 2050. This development is in agreement with projections given by the IEA [2009] for Europe. Focusing on only the countries that are member of the North Sea Basin Task Force (NSBTF), the CO2Europipe captured volumes in 2030 are in the same range as those reported in the 'One North Sea' scenarios (One North Sea, 2010). Compared to the most recent EC Baseline 'Energy Trends to 2030' (EC, 2010), the CO2Europipe capture scenario is somewhat higher. The number of capture installations required to reach such volumes is likely to be more than 300, in all of Europe. This rapid growth of CCS in Europe, and also in other parts of the world, is also foreseen in other road maps published recently, and is the direct result of the ambitious CO_2 emission reduction targets for 2030 and 2050.

Storage capacity
The Geocapacity database also provides data on storage capacity and the availability of storage capacity for subsurface storage reservoirs (sinks) for North-West and central Europe. More recent country specific studies, if available, were used in addition to the Geocapacity database, to produce maps of available storage capacity in the period 2020 – 2050.

Storage reservoirs (sinks) include gas fields, oil fields and aquifers. To reduce the uncertainty in the storage capacity estimates and storage availability, sinks were clustered as well, for the different sink types separately. For each sink cluster, storage capacity and injection rate are assessed in the period 2020 – 2050. For the purpose of this project, assumptions are made on the availability and injectivity of storage reservoirs.

CCS scenarios
The CO_2 captured volumes from the source clusters are linked with available injection capacity of the sink clusters, taking into account availability and size of storage capacity, as well as the (estimated) ability of the storage reservoirs to store the yearly produced volumes. This creates a network of transport corridors, covering North-West and Central Europe. South-West and South Europe were not included in the current study, as these are assumed not to become linked to the storage capacity in Central and North-West Europe, due to the large distances involved and the mountain ranges in between.

Three different storage scenarios are used:

- Reference scenario: storage takes place both onshore and offshore. Matching of supply and demand was based on current models and projects for the development of CCS that exist in the Member States;
- Offshore-only scenario: onshore storage was excluded from the assessment to investigate the impact of current public concerns and stringent permitting issues that might result from these concerns;
- EOR scenario: in addition to the offshore-only scenario it is assumed that EOR is economically attractive and will therefore use part of the captured CO_2.

Onshore and offshore storage
Maps are presented of indicative CO_2 transport flows for the timeline 2020, 2030 and 2050, for the three scenarios. For each scenario, the infrastructure network required in 2020 is limited in size and extent. By 2030, each source cluster is assumed to contain one or more capture installations, resulting in an extensive infrastructure network. This is due to the assumption that by then economic growth and more stringent emission caps will necessitate the use of CO_2 capture to sufficiently reduce emission levels in all countries. By 2050, the network is similar to the network in 2030. The potential transported volumes, however, will have become much larger. Transport corridors might involve transporting tens to hundreds of megatonnes of CO_2 annually. In 2030, the total yearly captured volume in North-West and Central Europe is estimated to be of the order of 400 Mt/yr; in 2050 the volume is estimated to be about three times larger (1200 Mt/yr in the same region.

In the reference scenario, most of the West European countries have sufficient national storage capacity to store their CO_2. Belgium and Poland could need to transport part of their CO_2 to the Netherlands and Germany, respectively. Transport from Sweden, Finland and the Baltic States to the North Sea is foreseen. Romania and Hungary do not have sufficient national storage capacity. Storage in Slovakia could be an option for these countries.

Consequences of offshore-only storage
The infrastructure of the two offshore-only scenarios forms a network of transport corridors which are all directed towards the North Sea, where the largest offshore storage options are located. Due to the location of offshore oil fields close to gas fields and aquifers, the infrastructure for the two scenarios is chosen as similar and investigates transporting large volumes from deep within Europe to the North Sea coast, to continue in offshore pipelines to the North Sea gas fields, saline formations and oil fields. Many of the transport corridors should require transport capacities of tens to hundreds of megatonnes annually. The networks in these offshore-only scenarios serve to demonstrate the importance of onshore storage for a large part of Europe. *Discarding onshore storage is likely to render CCS impossible for large parts of Europe*.

Storage capacity used
The cumulative amount of CO_2 that is likely to be stored between 2020 and 2050 is small compared to the total storage capacity. While the total volume of CO_2 stored by 2050 in this study is 18 Gt, the available storage space is of the order of 300 Gt. Dependent on the scenario, 13-25% of the gas field capacity has been filled, and 4-5% of the aquifer capacity. The use of oil fields is limited to the EOR scenario. Based on current knowledge of storage capacity, abundant capacity would be available if CCS is to play a role in emission reduction strategy also after 2050.
Since aquifers take care of 60-80% of the total amount of CO_2 to be stored, aquifer exploration is one of the more urgent issues in the near future.

Transport network construction effort
The total length of trunk pipeline required for the scenario with both onshore and offshore storage is about 22.000 km by 2050. The total transport distances for the offshore-only scenarios are about 50% longer. Countries with the largest amount of pipeline to be constructed are Germany, Norway and Poland. This is mainly due to the large flows to be transported, requiring several parallel pipelines in some cases. As

several countries do not have sufficient national storage capacity, cross border transport is required, from the moment CCS is initiated there. For the reference scenario, cross border transport would start around 2030, while it would already be needed in the start-up phase in 2020 for the two alternative scenarios. *This shows that international cooperation would be important in an early stage if CCS is to be established at a large scale. This cooperation is required to ensure compatibility of CCS transport infrastructure, as well as to ensure that sufficient transport capacity is available.*

The largest effort in the construction of pipelines is expected between 2020 and 2030 since the larger part of the network needs to be in place by 2030. The rate of construction would need to be 1200 – 1500 km/yr in the region considered. This effort is large, but not beyond the current European pipeline construction capacity. Cooperation among the countries is required, starting at the earliest construction efforts, at several levels, such as technical and regulatory levels. Construction bottlenecks are expected to arise due to permit-requiring issues.
Furthermore, at the capture side, the equivalent of 240 capture installations producing 5 $MtCO_2$/yr each are needed by 2050 in order to capture about 1200 Mt/yr. The construction rate for these installations is about 10 annually in the region considered.

Ship transport
Transport of CO_2 can be realized by pipeline or ship. Ship transport would be an alternative in an early phase of a CCS project, during pipeline construction. Also small-scale projects with a remotely located storage site can have use of ship transport, rather than constructing pipelines. Ship transport of CO_2 is favourable for sources that are located close to the coast or to a waterway, for easy access to ship loading facilities. Due to its flexibility, ship transport is also an option for sources that produce low or fluctuating volumes of captured CO_2. Storage sites that are amenable to supply by ship include oil fields and reservoirs that are either small or located far from a CO_2 trunk line. Ship transport can also be used during the start-up of CCS in a cluster of sinks, during the construction of a pipeline network.

Conclusions
1. CO_2 storage capacity is not a limiting factor in the development of large scale CCS infrastructure.
2. Available storage capacity is, however, not evenly distributed over the area considered, with the larger part located in the North Sea.
3. It is essential that storing CO_2 onshore storage is possible, if CCS is to be feasible throughout Europe.
4. Transport infrastructure construction efforts will be considerable, but lowest when onshore storage is possible.
5. International cooperation and alignment of infrastructure developments is required for an efficient CCS transport infrastructure in Europe.

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Project summary

The CO2Europipe project aims at paving the road towards large-scale, Europe-wide infrastructure for the transport and injection of CO_2 captured from industrial sources and low-emission power plants. The project, in which key stakeholders in the field of carbon capture, transport and storage (CCTS) participate, will prepare for the optimum transition from initially small-scale, local initiatives starting around 2010 towards the large-scale CO_2 transport and storage that must be prepared to commence from 2015 to 2020, if near- to medium-term CCS is to be effectively realized. This transition, as well as the development of large-scale CO_2 infrastructure, will be studied by developing the business case using a number of realistic scenarios. Business cases include the Rotterdam region (Netherlands), the Rhine-Ruhr region (Germany), the Kårstø project with offshore pipeline to the Utsira saline aquifer storage from the Norwegian coast and the development of CCS in the Czech Republic and Poland.

The project has the following objectives:

1. describe the infrastructure required for large-scale transport of CO_2, including the injection facilities at the storage sites;
2. describe the options for re-use of existing infrastructure for the transport of natural gas, that is expected to be slowly phased out in the next few decades;
3. provide advice on how to remove any organizational, financial, legal, environmental and societal hurdles to the realization of large-scale CO_2 infrastructure;
4. develop business case for a series of realistic scenarios, to study both initial CCS projects and their coalescence into larger-scale CCS infrastructure;
5. demonstrate, through the development of the business cases listed above, the need for international cooperation on CCS;
6. summarise all findings in terms of actions to be taken by EU and national governments to facilitate and optimize the development of large-scale, European CCS infrastructure.

The present report contributes to item 1 in this list, with a description of the required infrastructure for the large-scale transport of CO_2 across North-West and Central Europe. The results presented in this report provide an outlook on the long-term transport infrastructure and represent part of the input needed to address the other items in the list.

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Project partners

Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek- TNO	Netherlands
Stichting Energieonderzoek Centrum Nederland	Netherlands
Etudes et Productions Schlumberger	France
Vattenfall Research & Development AB	Sweden
NV Nederlandse Gasunie	Netherlands
Linde Gas Benelux BV	Netherlands
Siemens AG	Germany
RWE DEA AG	Germany
E.ON Benelux NV	Netherlands, Belgium, Luxemburg
PGE Polska Gruppa Energetyczna SA	Poland
CEZ AS	Czech Republic
Shell Downstream Services International BV	Netherlands, United Kingdom
CO2-Net BV	Netherlands
CO2-Global AS	Norway
Nacap Benelux BV	Netherlands
Gassco AS	Norway
Anthony Veder CO_2 Shipping BV	Netherlands
E.ON New Build and Technology Ltd	United Kingdom
Stedin BV	Netherlands

1 INTRODUCTION

Carbon Capture and Storage (CCS) can significantly contribute to the European CO_2 emission reduction objectives. CCS consists of CO_2 capture at the source, transport by pipeline or ship to a storage location and subsequent underground storage in depleted hydrocarbon fields or aquifers. The CO_2Europipe project has the aim to investigate the efforts required to build a large-scale European transport infrastructure and to sketch the requirements for its development.

This report presents an outlook on the transport infrastructure for CO_2 in northwest and central Europe, in the period 2020 – 2050. The infrastructure is based on the most up to date databases and on current national CCS plans and storage feasibility studies. National scenarios of CCS developments were used as a basis in matching the gradually growing captured streams with storage capacity that gradually becomes available. The geographical distribution and timing of emission points (capture locations) and available storage capacity largely dictates the shape of the transport network**. The aim of this project is to identify likely transport corridors and to estimate the order of magnitude of transported volumes in a future CCS infrastructure.** The future infrastructure is not designed in detail. CO_2 point sources and storage locations have been grouped together into clusters, connecting capture clusters to storage clusters. No individual sources or storage locations have been considered.

Whereas transport is considered to be the lowest cost element of CCS, it may be the element that needs most planning and guidance during its development. Recently, several outlooks on the transport infrastructures required for CCS have been published and realistic networks were published for various regions (e.g., BERR, 2007; Haszeldine et al, 2009; ICF, 2009). Most studies conclude that infrastructure development is feasible in principle, but that significant hurdles exist at the regulatory level, rather than the technical level. The focus in this study is on the countries in North-West and central Europe. In order to establish a more complete overview of CO_2 streams, several countries were added. These countries include Sweden, Finland, Denmark, Estonia, Lithuania, Romania, Bulgaria, and Hungary. Southern Europe is not included, as it is assumed that these will not connect to the storage capacity in the area considered. Transport distances would probably become too large and the cost of crossing the mountains ranges in Central Europe would be prohibitive.

Section 2 describes the emission and capture scenarios that were developed to generate the projected captured CO_2 streams, for industrialised regions in each country. Section 3 presents the storage capacity distribution, both geographically and through time, in north-west and central Europe. Section 4 explains the matching process between CO_2 sources and sinks and the structure of the transport infrastructure. Section 5 discusses the implementation of parts of the network with ship transport. Section 6 presents a preliminary discussion of the infrastructure, interpreting the results in terms of construction efforts and cost.

2 EMISSION AND CAPTURE SCENARIO

This section describes the emission and capture scenarios used for the source – sink matching. The captured CO_2 emissions involve both large point sources in the power generation sector and in industry. The potential for CCS is largest in the power generation sector. Large centralized hard-coal and lignite fired power plants and future biomass plants (possibly as co-firing option in coal-fired plants) constitute the main part of the CCS potential in power generation.

2.1 Emission and capture scenario; methodology and background

An emission scenario has been developed for the EU-27 and in particular for the relevant Member States (MS) within Northwest Europe (NWEU, including Norway): the 'CO2Europipe Policy Scenario' (CPS), which is based on EU policy developments since 2007. As a basis it uses a PRIMES scenario policy variant striving to meet the EU targets (EC, 2008).[1] The variant is closest to meeting the EU 2020 targets of 20% greenhouse gas (GHG) reduction, 20% share of renewable energy, and 20% cumulative energy saving targets. In the CPS scenario the original figures in 2030 were changed for some of the Member States, and the scenario was extrapolated up to 2050.

The adaptation takes into account:

a. Recent political changes in Germany and Belgium regarding nuclear phase-out. Both Member States will postpone the nuclear phase-out. In addition, Germany will investigate the life-time extension of these nuclear power plants. As a result, some new fossil fuelled power plants in the original PRIMES scenario were removed. Postponing the nuclear phase-out reduces the potential for CCS.
b. A country-specific scenario for the Netherlands based on a recently completed new Dutch reference projection (ECN/PBL, to be published in 2010).
c. A country specific scenario for Norway[2].

Some key points relevant for the emission and capture scenario in this study are:

- The potential for CCS has been investigated for the power generation and the industry sector. Only large point sources in each of these sectors have been considered for CCS.
- The geographical coverage was restricted to Norway and the EU Member States in Northwest and Central Europe. This includes the countries represented by the CO2Europipe project partners plus Romania, Bulgaria, Hungary, Slovakia, Estonia, Lithuania and Finland.
- The potential for carbon capture is calculated for the years 2020, 2030 and 2050. For the year 2020, most is based on the current and more or less confirmed plans for large demonstration projects for CCS. Although plans have been observed to

[1] At the time of performing the actual source and sink matching work in WP 2.2 work (second half of 2009), the new EU Baseline and Reference scenarios, e.g. see (EC, 2010), were not available.
[2] Et klimavennlig Norge; Departementenes servicesenter Informasjonsforvaltning, 2006

change frequently in this time fram`e, an effort has been made to be accurate and actual. The country-specific information from CO_2Europipe partners has been taken into account as much as possible.

- Results are only indicative. They are plausible within the context of the background scenarios and assumptions made, given the uncertainty in the long-term background scenario and the current policy developments within the EU and various EU Member States.

An overview of the methodology is outlined in Figure 2.1.

The remainder of this section is organised as follows:

1. The current policy developments are outlined, with regard to CCS in the EU and individual Member States (Section 2.2).
2. The method used for clustering of the sources is described (Section 2.3).
3. The current plans for CCS in the next 10 to 15 years are sketched. These plans form the basis for the CCS potential estimated for the year 2020 (Section 2.4).
4. The CPS scenario is sketched for the years 2030 and 2050 with the relevant assumptions (Section 2.5).
5. The resulting amounts of emitted and captured CO_2 are presented on a national basis (Section 2.6).

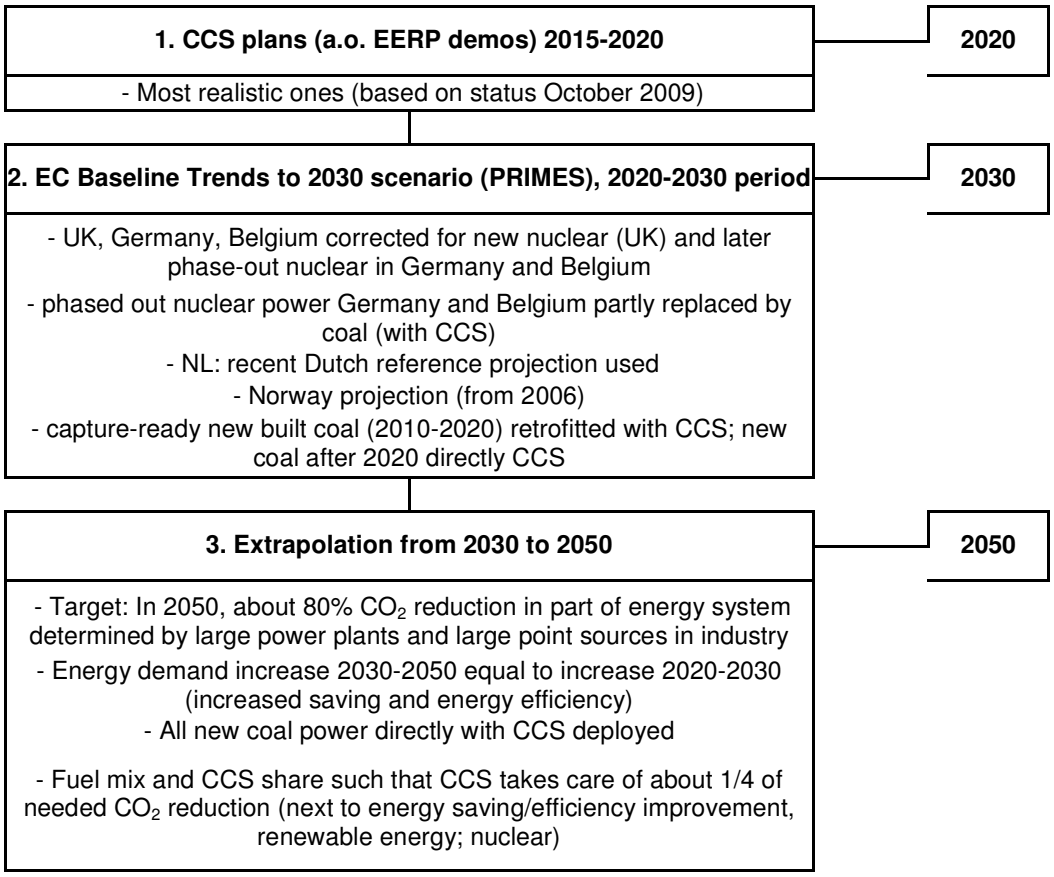

Figure 2.1 Overview methodology emission sources and CO_2 captured.

2.2 Current and future CCS policy and relevant developments

EU CCS

The European Union (EU) has formulated ambitious targets to curb greenhouse gas emissions by 2020, to increase the share of renewable energy, and to speed up the pace of energy saving and efficiency improvement. The broad package of EU measures was adopted by the European Parliament in December 2008. These included a proposal to share the burden of climate mitigation among the 27 Member States, a directive for the geological storage of CO_2, a directive on the promotion of renewable energy and a review of the EU Emissions Trading Scheme (EU ETS). Recently, the European Commission has set aside an amount of €1.05 billion to subsidize six large demonstration programmes planned in EU Member States in the European Energy Plan for Recovery (EEPR). Each of the awarded plans will receive a subsidy of € 180 million. As of December 2009, six of these plans have been selected. The national governments will provide subsidy in addition to the EEPR grant, but the size of these additional national subsidies is not clear yet.

Relevant short term developments and uncertainties

The electricity markets in Northwest Europe (NWEU) will undergo structural changes in the near future. The power sector is the main contributor to CO_2 point sources. Besides expected demand growth and increasing fossil fuel and CO_2 prices, new investments in power generation capacity (including wind energy) are foreseen as well as decommissioning of old power plants. Within the EU Emission Trading System (ETS), CO_2 prices are anticipated to increase in the longer term with more stringent climate policies in place. CCS is considered to be an important technology in the transition portfolio to a long-term sustainable energy supply. The recent economic recession makes future cost estimates rather uncertain. This can make investment in innovative CCS technology a financial risk in the short to medium term. In addition, it is not possible to make assumptions on the cost of commercial CCS based on the costs of CCS demonstration projects.

A Member State example: the Netherlands

The Netherlands has a large potential for CCS due to its high density of CO_2 point sources and its geographical advantage as regards nearby storage locations for CO_2 (e.g., Vosbeek et al., 2007; Vangkilde-Pedersen et al., 2009). Currently, small-scale pilot CO_2 capture projects and small storage demonstration projects have been executed or planned in the near future in the Netherlands. The current pilots for CO_2 capture (TNO/E.ON at existing coal-fired power plant Maasvlakte; Nuon, at the Buggenum site, an existing IGCC power plant) are planned to be followed by larger demonstration projects around 2015. In particular, in the Rotterdam area the ambitions regarding CCS are high. Energy-intensive industry (e.g. a large petrochemical industry) and a high concentration of fossil fuelled power plants are located in this area. The Rotterdam area is also an attractive location for new power plants. The Rotterdam Climate Initiative has formulated a target of 50% reduction in 2025 compared to 1990. Half of these reductions should come from CCS (RCI, 2009). The Dutch Government considers CCS as an essential option in the transition towards a sustainable energy system (EZ, 2009).

2.3 Source clusters

It is generally thought that large-scale CCS will occur through the linking of source clusters with sink clusters by trunk line (backbone), in combination with satellite pipelines to link the individual sources and sinks within the cluster to the trunk line. This way the CO_2 demand and supply can be matched in a flexible way. For this reason clustering of sources has been performed.

Data from emission points with an emission more than 100 kt/yr in each country was collected in the EU FP6 Geocapacity project (Vangkilde-Pedersen et al., 2009). Based on this data, a bottom-up approach was used to determine which large point sources cluster together. Point sources were clustered on national scale, with each cluster contributing a significant fraction to the total national CO_2 emission. Because the Geocapacity data was administrated for the year 2005, it can be compared to results of the same year in the PRIMES results. The total point source emissions as used in the regional clusters, is on average about 90% of the total amount of emissions calculated by the PRIMES model. Figure 2.2 shows the geographic distribution of these clusters.

For an estimate of the sources that could be used for CCS, only point sources with an output of at least 250 kt/yr were considered. As an approximation of the total point source emissions from industry the sector emissions were considered from the iron & steel, non-ferrous metals, chemicals, non-metallic minerals, paper industry and the energy sector.

2.4 CCS plans 2015-2020

The number of plans for demonstration of CO_2 capture and storage has increased considerably since 2005, and more so since the European Commission has made funds available for CCS demonstrations in EEPR and from the New Entrants Reserve under the revised ETS. Most of these demonstrations are planned to be operational by 2015. Table 2-1 provides an overview of the currently available plans for CO_2 capture demonstrations in nine European countries. It also shows which of these demonstration plans has received an EEPR fund. In addition to these 6 projects, the Compostilla project in Spain and the Porto Tolle project in Italy have received funding support.

Only a few of the demonstration projects shown in Table 2-1 are close to realisation i.e. planned to operate at the end of 2015. The EEPR requires the demos to be started in 2015 in order to receive the subsidies. A selection was made on the following grounds.

- A preference was given to projects that were on the shortlist for receiving financial support under the EEPR.
- Some CCS projects are in a more advanced phase compared to others, i.e. some projects are well committed in terms of budget and personnel while other announced projects have the status of feasibility study.
- Information is scarce for some demonstration projects. This makes these projects more uncertain as to their realisation by 2015.

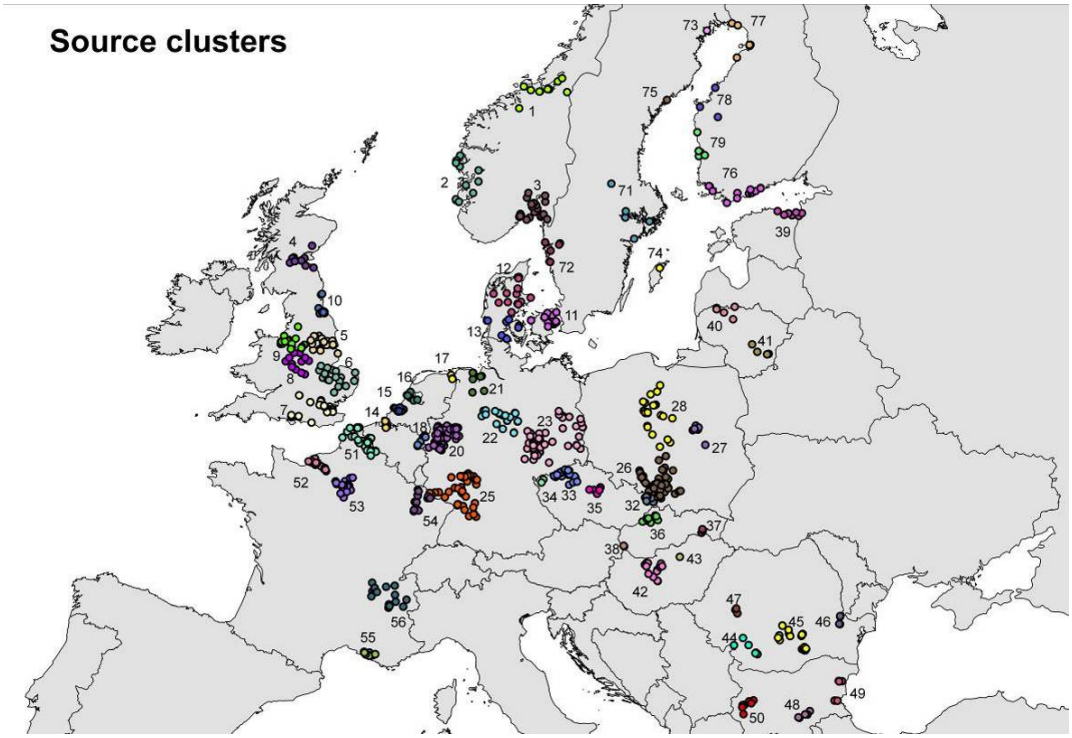

Figure 2.2 CO_2 point source clusters in North-west Europe, created from the Geocapacity database. Colours indicate emission points belonging to the same cluster. In following sections in this report, clusters are represented by a single point. The numbers represent cluster identifiers, used in Appendix A.

The projects in Table 2-1 in bold have been taken into account in this assessment as CCS potential for 2020.

2.5 Emission scenarios 2030-2050

2.5.1 PRIMES 'Trends to 2030' scenario

Several publicly available sources have published data for point source emissions of CO_2 in North-West Europe, including the International Energy Association databases GHG and Statistics [Internet REF 1)]. These databases include historical information on sector level, but do not provide a projection to the future. For the CO_2 emission projections a study for the European Commission Directorate-General for Energy and Transport was used (EC, 2008). The publication of the emission projections in this report was prepared by the Institute of Communication and Computer Systems of the National Technical University of Athens. For all member countries of the EU this study presents scenarios under several policy assumptions, calculated by the integrated energy-economic-environment PRIMES model. This model can compute energy balances, energy production, fuel use and CO_2 emissions up to 2030, for each EU Member State and the EU-27 as a whole. As the emission projection calculations are based on the same model and methodology, a consistent set of country projections is obtained. Apart from the Netherlands and Norway, where other studies were available,

projections into the future in this report are based on the outcome of the scenario calculations with the PRIMES model. The study *Et klimavennlig Norge* [Departementenes servicesenter Informasjonsforvaltning, 2006] was used for Norway, as it is not covered by the PRIMES model.

The PRIMES results were used to produce an estimate for the CCS potential until 2030. Projections for 2050 were obtained by extrapolation, taking into account the assumptions of the policy scenario (next section).

2.5.2 CCS Policy Scenario

Assumptions

Several assumptions were made in order to define the CO_2 capture potential for the timeline 2020 – 2050.

1. The first CCS demonstrations (Total about 45 Mt) will be deployed during 2010-2020. For these power plants, CCS is fully applied from 2020 onwards. They comprise large power plants (solid fuel, i.e. hard coal, lignite and some with co-firing of biomass) and some industry sources (e.g., pure CO_2 streams).
2. All coal-fired power plants built after 2010 will be equipped with CO_2 capture installations. Plants built after 2010 will still be running in 2050 (40 years lifetime assumed).
3. For 2030 and 2050 the current PRIMES scenario assumes future CO_2 sources to replace old ones in the same region. This leads to a conservative estimate of CO_2 sources near shore or rivers. In several countries, new steel plants, power plants, and refineries are planned near the coast or near rivers for logistic reasons, where currently no or only few point sources are located.
4. CCS is applied on a large scale from 2025 onwards. From 2025 onwards, it will be mandatory for any new coal-fired power plant. Coal-fired power plants are also to co-fire biomass, which may result in negative CO_2 emissions. E.g., a coal-fired power plant with 20% biomass and a CO_2 capture rate of 90% results in a negative CO_2 emission of -111 g/kWh net electricity produced. Data on CO_2 capture rates and emission factors used for coal-fired power plants are shown in Table 2-2.
5. Only the large and centralised part of the power generation was included in the assessment (units larger than 200 MW_e).
6. There will be no CCS retrofit on coal-fired generation capacity built before 2010. In 2050, there will be no coal-fired power generation without CCS.
7. No CCS will be installed on gas-fired power plants as they are not necessary in order to arrive at sufficient CO_2 reductions in 2050 for the EU. CCS on gas-fired power plants is only assumed feasible for Norway.
8. Large industrial point sources will deploy CCS to reduce CO_2 emissions.
9. Source clusters with demonstration projects included in the 2020 capture scenario will generally develop to be the most important carbon capture centres, unless indicated otherwise by country specific scenarios.
10. Projections for the years 2030 – 2050 are based on an extrapolation of the energy demand in electricity in 2020 and 2030. The annual rate of change in the total CO_2 emissions was separated into CO_2 emission from the power sector and several industrial sectors.

Table 2-1 CO_2 capture demonstrations until 2020. Captured volumes in italics represent estimates/corrections by ECN (original list of projects based but adapted from CSLF, 2009). Bold faced projects have been assumed to be deployed in 2020 (see also Table 2-4). The totals have been place between brackets for each country.

Developer(s)	Location	EEPR (€million)	Technology	Start	Capacity [MWe]	Volume CO_2 captured [Mt/yr]*
United Kingdom (total 20.6)						
Progressive Energy	Teesside		IGCC [3]	2012	800	4.2
RWE	Blyth		PC [4]	2014	2400	3
RWE	Aberthaw		PC	2015	25	Small
Scottish Power	**Longannet**	**?**	**PC**	**2014**	**300**	**2**
Scottish Power	Cockenzie		PC	2014	300	2
Eon	Killinghome		IGCC	2013	450	2.5
SSE	Ferrybridge		PC	2015	500	1.7
RWE	**Tilbury**		**PC**	**2016**	**1600**	***10.6***
Powerfuel	**Hatfield**	**180**	**IGCC**	**2010**	**900**	**6**
Eon	**Kingsnorth**		**PC**	**2016**	**300**	**2**
Progressive Energy	Onllwyn (Drym)		IGCC	2015	450	2.4
Norway (total 6)						
Haugesund Haugalandkraft	Haugesund		PC	2014	400-800	2
Government	**Kårstø**		**NGCC [5]**	**2012**	**400**	**1.1**
Tinfos AS. Sor-Norge Aluminium AS. Eramet Norway AS. Sargas AS	**Sargas Hunes**		**PC**	**unknown**	**420**	**2.6**
StatoilHydro / gov	**Snøhvit**		**Natural Gas Processing**	**2008**	**-**	**0.7**
StatoilHydro	**Sleipner**		**Natural Gas Processing**	**1996**	**-**	**1**
StatoilHydro / Gassnova	**Mongstad**		**CHP [6]**	**2014**	**280MWe/ 380MWh**	**1.3**
StatoilHydro / Gassnova	**Mongstad**		**Natural Gas Processing**	**unknown**		**1.2**
Eramet. Sargas. Sør Norge Aluminum. Tinfos	Hordaland		Coal	unknown	380	*2.4*
Skagerak Kraft	Grenland		Gas	unknown	1000	1.6
Industrikraft Møre	Elnesvågen		Gas	unknown	450	1.2
Finland (total 0)						
Fortum/TVO	Meri Pori		IGCC	2015	565	2.5
Poland (total 1.8)						
ZAK. PSA.Shell. GE	Kędzierzyn-Koźle		Coal / biomass	2014	250	2.4
Alstom/PGE	**Belchatov**	**180**	**PC**	**2015**	**858**	**1.8**
Vattenfall	Siekierki		PC	2015	480	*3.2*

[3] IGCC = Integrated Gasification Combined Cycle, a type of coal-fired power plant
[4] PC = Pulverised Coal, an other type of coal-fired power plant
[5] NGCC = Natural Gas Combined Cycle, a type of gas-fired power plant
[6] CHP = Combined Heat and Power, a power planrt producing both electricity and (useful) heat.

Developer(s)	Location	EEPR (€million)	Technology	Start	Capacity [MWe]	Volume CO_2 captured [Mt/yr]*
Germany (total 5.3)						
Dong Energy	Greifswald		PC	2015	1500	*9.9*
ArcelorMittal	Eisenhüttenstadt		steel; coal / petroleum coke	2015	-	2
RWE	**Huerth**		**IGCC (lignite)**	**2015**	**450**	**2.6**
Vattenfall	Schwarze Pumpe		Oxyfuel	2008	30	0.1
Vattenfall	**Jänschwalde**	**180**	**Oxy fuel + post combustion**	**2015**	**375**	**2.7**
Eon. Fluor	Wilhelmshafen		PC	2015	100	0.6
Eon	Grosskrotzenburg		PC	2015	512	*3.4*
Denmark (total 0)						
Dong	Esbjerg		PC	2015	400	*2.7*
Dong	Kalundborg		PC	2015	600	4
Vattenfall	Aalborg		PC	2020[7]	310	1.8
The Netherlands (total 7.6)						
DSM/GTI	**Geleen**		**NH3. coal seams**	**2015**	**-**	**0.2**
Shell. Abengoa et al	**Barendrecht**		**H2 + biofuel. pure CO2**	**2011**	**-**	**0.4**
Nuon	**Buggenum**		**PC**	**2012**		**Small**
Eon	**Rotterdam**	**180**	**PC**	**2015**	**1070**	**1.1**
Electrabel	**Rotterdam**		**PC**	**2013**	**800**	**Together with Eon**
Essent	Rotterdam		IGCC	2016	1000	2
CGEN NV	**Rotterdam**		**IGCC + hydrogen production**	**2014**	**450**	**2**
Nuon	**Eemsmond**	**180**	**IGCC**	**2013**	**1200**	**2.5**
RWE	**Eemsmond**		**PC**	**2015**	**40**	**0.2**
SEQ ZEP	**IJmuiden**		**oxyfuel**	**2015**	**200**	**0.7**
Czech Republic (total 0)						
CEZ	Hodonin		PC + retrofit	2015	105	0.3
CEZ	Ledvice		PC + retrofit	2015	660	0.9
Northern France (total 1.5)						
ArcelorMittal	**Florange**		**Steel Production Facility**	**-**		**1.5**
Veolia	Claye Souilly		Waste incineration	2013		0.2

[7] The CCS project at Nordjyllandvaerket is no longer a Demo project. This power plant is a candidate for a commercial project in 2010. Storage site development is ongoing. (Vattenfall, project partner, personal communication, March 2010).

Table 2-2 CO_2 capture rate and emission factor for several types of coal-fired power plants.

Net efficiency Coal-fired power plant	CO_2 capture rate	Biomass co-firing percentage (energy basis	CO_2 emission factor [g/kWh] [8]
46%	0%	0%	741
With biomass			
45%	0%	20%	606
With CCS			
37%	75%	0%	230 [9]
35%	90%	0%	97
With CCS and Biomass			
35%	75%	20%	78
35%	90%	20%	-111

Table 2-3 Country specific scenario studies with CCS.

Member State	Study	Time horizon	Description
The Netherlands	Groenenberg et al. 2009 and Van den Broek et al., 2009	2050	Based on one long-term scenario: a modified strong European scenario, with an average GDP growth of about 2%/year and CO_2 prices up to 80 €/ton. CCS is applied from 2020 onwards.
	Seebregts and Groenenberg (2009)	2030	Based on one long-term study: global economy scenario, average GDP increase of almost 3%/year, CO_2 price of 50 €/ton year. CCS applied from 2020 on. Power generation only (coal & gas).
	ECN/PBL, 2010	2030	New Dutch reference projections will be published in 2010. Preliminary results used by ECN for NL emissions and CCS potential.
Norway	Et klimavennlig Norge; Departementenes servicesenter Informasjonsforvaltning, 2006	2050	Scenario provided by Gassco.

Country-specific emission and CCS scenario studies used

Long-term country-specific scenario studies were used to the extent available. Table 2-3 provides an overview of such studies. Except for the Netherlands and Norway, the PRIMES scenarios have been used as a basis, with some corrections for recent developments (e.g., postponement of nuclear phase-out in Germany and Belgium).

[8] Based on a standard CO_2 emission factor of 94.7 kg/GJ for bituminous coal (LHV of 24.5 MJ/kg) for The Netherlands. Other emission factors apply for coal or lignite used in other countries.
[9] Based on (Seebregts & Scheepers, 2007).

Corrections were made based on new Dutch reference projections which also include neighbouring countries, because of the Northwest European electricity market context (see also Seebregts & Groenenberg, 2009).

Table 2-4 Results of national captured CO_2 emissions.

Country	Total captured CO_2 [Mt/year]		
	2020	**2030**	**2050**
Norway	6	8	9
UK	20.6	36	112
Denmark	1.8	6	22
The Nether1ands	7.6	22	49
Germany	5.3	73	379
Poland	1.8	89	133
Czech Republic	0	32	80
Slovakia	0	5	17
Estonia	0	6	10
Lithuania	0	1	3
Hungary	0	9	25
Romania	0	36	72
Bulgaria	0	13	39
France	1.5	6	94
Belgium	0	10	66
Sweden	0	2	41
Finland	0	7	70
Total (Mt/yr)	**45**	**358**	**1222**

2.6 Capture results

Table 2-4 shows the volumes of captured CO_2 that were derived with the assumptions outlined above. As can be seen from Table 2-4, the largest potential for CCS is in Germany and Poland. In a series of future reports from the CO2Europipe project, dealing with detailed case studies in Germany, The Netherlands, Norway and Poland – Czech Republic, the capture potential of Table 2-5 will be compared with the most recent national projections.

The larger part of the CO_2 captured in 2050 originates from biomass, as it was assumed that after 2030 only few new coal-fired power plants will be built. Instead, biomass-fired power plants or multi-fuel coal/biomass power plants using (solid) biomass as fuel are the preferred option for new technologies and investments in the transition towards a sustainable energy supply in the period 2030-2050. This development enables a CO_2 reduction of 80% or more in the year 2050 compared to 1990 levels. This development between 2030 and 2050 is an assumption following the trend from the used PRIMES scenario with increasing levels of renewables, including biomass. This assumption of the development from 2030 to 2050 will be compared and verified with new scenarios

expected to be published in 2010. Among these scenarios will be the new EU Baseline scenario (2030).

New coal-fired (hard coal and lignite) power plants built and coming into operation in the period 2010-2030 will still be operational in 2050, as a 40-year lifetime was assumed for these modern coal-fired power plants. The source/sink matching part as described in Section 4 will outline the regional level of detail that has been used.

2.7 Uncertainty in capture volumes and comparison with other scenarios and studies

The development in the captured volumes presented here is from about 45 Mt/yr by 2020 to more than 1.2 Gt/yr by 2050. These figures represent an order of magnitude. The uncertainty in estimates from energy scenarios is large and increase over time. Consequently, the uncertainty in the CO_2 captured is large and increase over time. The order of magnitude development as presented in Table 2.4 is in agreement with projections given by the IEA [2009] for Europe, considering these uncertainties. Focusing on only the countries part of the North Sea Basin Task Force (NSBTF), the CO2Europipe captured volumes in 2030 are about in the middle of the low and high 'One North Sea' scenarios (One North Sea, 2010). Compared to the most recent EC Baseline 'Energy Trends to 2030' (EC, 2010), the CO2Europipe capture scenario is somewhat higher. The number of capture installations required to reach such volumes is likely to be more than 300, in all of Europe. This rapid growth of CCS in Europe, and also in other parts of the world, is also foreseen in other road maps published recently, and is the direct result of the ambitious CO_2 emission reduction targets for 2030 and 2050. Table 2-5 compares the captured volumes in the period 2020 – 2050 from various recent studies with those presented here.

Table 2-5 Volumes CO_2 Captured in Mton/year, other studies in comparison with CO2Europipe, for the NSBTF countries or the EU Member States (EU27).

Region	2020	2030	2050
EU-27 or OECD Europe			
CO2Europipe, this report	45	358	1222
IEA CCS Roadmap 2009, OECD Europe	37	300	1000
EC Baseline (EC, 2010), EU-27 Total	36	272	
NSBTF countries	**2020**	**2030**	
- CO2Europipe, this report	41	145	
One North Sea, High		273	
One North Sea, Low		46	

3 DISTRIBUTION AND TIMING OF STORAGE CAPACITY

In order to match the captured streams with storage capacity, an assessment was performed of the geographical distribution and timing of available storage capacity. For this purpose, data from the Geocapacity database[10], which is currently the most up to date database, served as a basis. Data available on the sinks, e.g. type, location, storage capacity and discovery year, was used to determine the distribution in space and time of the available storage capacity.

3.1 Uncertainties and assumptions

Uncertainties regarding storage capacity exist in the storage capacity itself, due to incomplete knowledge of subsurface structures, as well as in the timing of availability of reservoirs. This project considers clusters of storage locations, rather than specific sites. This section discusses the available data and the approach to handle the uncertainties in the data.

3.1.1 Capacity levels

The storage capacities recorded in the Geocapacity database give an estimate of the maximum amount of CO_2 that can be stored, based on reservoir parameters and physical limits to be detailed below. According to the storage capacity classification scheme (Figure 3.1) of the Carbon Sequestration Leadership Forum (CSLF, 2007; Bachu et al., 2007), most of this capacity is theoretical capacity, due to uncertainty in many aspects of the storage locations. Detailed feasibility studies, considering factors like size and permeability limits, location, availability, political and legal considerations and many more, will exclude a number of potential sinks and result in a more realistic storage capacity estimate (van de Velde et al., 2008). Detailed studies can only be expected as part of the development of actual CCS projects, and therefore, the Geocapacity database only include results from feasibility studies for few of the included storage sites. While almost all of the saline aquifer storage capacity in the database should be considered 'theoretical', the database is considered to contain 'effective capacity' estimates for hydrocarbon fields, for which the storage capacity estimate is based on production data and, perhaps more importantly, which have proven to store hydrocarbons for millions of years.

For the northern part of Germany qualitative data on aquifer storage capacity was supplied by project partners. Due to confidentiality issues, exact coordinates were not given. These specific aquifers were located in North Germany, near the border with Denmark.

[10] The CO2Europipe consortium was granted access to the Geocapacity database by the individual countries considered in this study, but only at the level of aggregated emission levels or storage capacities for source or storage clusters.

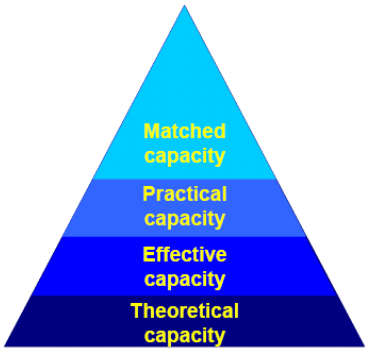

Figure 3.1 Storage capacity classification scheme (after CSLF, 2007).

3.1.2 Storage capacity cut-off

A lower size limit can readily be applied to the sink database. However, the economic viability of storing CO_2 in a specific site depends on local conditions and a generally applicable cut-off can not be defined. Different studies (e.g. van de Velde et al., 2008 and BERR, 2007) apply different cut-offs, ranging from 2.5 Mt for depleted gas fields to 100 Mt for deep saline formations. In this study the effects were investigated of different cut-offs on the total available storage capacity. Cut-offs of 2.5, 10 and 20 Mt were applied to oil and gas fields and 50 Mt to saline aquifers. The lower limits for oil and gas fields are comparable to other studies. The lower limit for aquifers is higher, as it is expected that developing storage in deep saline formations is more expensive than converting a hydrocarbon field for CO_2 storage. The impact of the size cut-off on storage capacity is shown below.

3.1.3 Commercial availability of sinks

The commercial availability of oil and gas fields for CCS is uncertain and highly dependent on several factors, e.g. oil and gas prices and technical developments. In this study, no attempt was made to predict these factors. Fields were assumed to be available for CCS 50 years after discovery of the field.

Saline aquifer availability is subject to an even larger uncertainty, since the lead time for site development for CO_2 storage is longer and more uncertain. For instance, saline aquifers have not generally received the same detailed scientific attention as hydrocarbon reservoirs.
Currently, the feasibility of storing CO_2 in deep saline formations is being evaluated in a number of demonstration projects, such as the Utsira formation (Sleipner since 1996), the In-Salah project in Algeria and the Ketzin project in Germany. In this study, large-scale availability of saline aquifers was assumed to evolve between 2025 and 2050 unless national CCS plans or assumptions give more detailed timing (Appendix C). Only for Norway and Denmark is it known which specific saline aquifer fields are currently being used or investigated (see Appendix C for further details).

Table 3-1 Time to fill for hydrocarbon fields and deep saline aquifers.

Hydrocarbon fields		Deep saline aquifers	
Capacity [Mt]	**Time to fill [yr]**	**Capacity [Mt]**	**Time to fill [yr]**
<10	10	50-100	15
>10	25	100-1000	25
		>1000	40

3.1.4 Injection rate

The feasibility of storing CO_2 in a reservoir depends on both total storage capacity and injection rates that can be reached at safe injection pressure levels (albeit ignoring other factors, such as economic and societal issues). The injection rate depends, apart from the supply (capture) side, on reservoir permeability and reservoir thickness. For aquifers, a permeability higher than 200 mD is considered to be required for significant injection rates, of the order of 1 Mt/yr [van der Meer, 1993; Dynamis, 2007]. For gas fields, permeability requirements are probably less stringent than for aquifers. In a recent study [Van der Velde et al., 2008] on the feasibility of CO_2 storage in the Dutch offshore, a lower limit for the product of permeability and thickness of 0.25 Dm (Darcy meter) is considered, which corresponds to, for example a permeability of 2.5 mD for a formation thickness of 100 m.

Whereas reservoir thickness is available in the database, permeability, unfortunately, is generally not. No threshold for permeability can be set on the Geocapacity database. Without permeability data, or production data (for hydrocarbon reservoirs), the injection rate must be estimated. Based on a feasibility study for the Southern North Sea by DTI (DTI, 2007), the time taken for a reservoir to fill was defined to vary between 10 and 40 years, see Table 3-1.

3.2 Methods

Based on cluster sizes of previous studies regarding source-sink matching (e.g. Wildenborg et al., 2008ab), hydrocarbon field clusters and deep saline aquifer clusters were created with the Geocapacity database. Clusters can include sinks of different countries. For each cluster the total capacities were determined for the timeline 2020 - 2050. This was also done using capacity thresholds of 2.5, 10 and 20 Mt for hydrocarbon fields and 50 Mt for saline aquifers. Furthermore, the injection rates were computed per cluster for these timelines, based on total capacity (no cut-off) and the assumptions explained in section 3.1.4. Subsequently, for each cluster the available capacity (in Mt) was visualised, showing the effect of the different cut-offs, and injection rate (in Mt/yr).

When, for a certain region in the area of research, a feasibility study was available, the data from the database was replaced by more realistic capacities and knowledge, based on these studies. This was the case for offshore gas fields in the Netherlands (Van der Velde et al., 2008), Southern North Sea (UK fields) (DTI, 2007), East Irish Sea (Kirk et al., 2006) and Scotland offshore (University of Edinburgh, 2009). No storage capacity cut-off has been applied to the results from the regional studies.

3.3 Timing issues and hardware re-use

3.3.1 Availability of reservoirs

Most of the currently known gas and oil fields in the area of research are producing gas and oil at this time, or will be producing in the near future. Hydrocarbon fields are assumed to become available for CO_2 storage as soon as oil or gas production is not economically viable anymore. The end of production is highly dependent on factors like future oil and gas prices and developments in enhanced hydrocarbon production. For the objective of this study it is sufficient to roughly estimate the availability of reservoirs. For hydrocarbon fields the availability was assessed to be 50 years after discovery of the field, based on experience from fields that are already depleted.

Saline formations availability is more difficult to predict. Theoretically, all saline aquifers are available at this moment, since they do not contain hydrocarbons that need to be produced. However, data on aquifers is sparse since usually only limited information is available. Extensive feasibility studies are required for each specific saline reservoir in order to prove their potential to retain CO_2. Since hydrocarbon fields will most probably be the first reservoirs used for CO_2 storage, availability of saline formations was assessed to evolve gradually between 2025 and 2050, unless national scenarios assume otherwise.

3.3.2 Infrastructure

Another important aspect in the timing of oil and gas fields is the re-use of infrastructure. Currently, an extensive network of pipelines, transporting mainly natural gas, is present onshore as well as offshore. Pipelines that will not be used for transportation of gas in the future could be used to transport CO_2. The quality of each specific pipeline would need to be investigated to determine whether they can transport the required amounts of CO_2. While that is outside the scope of this study, the existing pipeline network has been used to estimate the length of new CO_2 trunk lines, by assuming that new CO_2 lines will preferentially be located along existing pipeline corridors.

More important than pipelines are the wells currently present in hydrocarbon fields for hydrocarbon production and platforms at offshore sites. When hydrocarbon production stops and CO_2 injection commences, wells and platforms can be re-used. Abandonment regulations for hydrocarbon fields, however, force operations to abandon their fields within two years after production ends. Furthermore, maintenance of the platform is costly (van de Velde et al., 2008). Abandonment of hydrocarbon fields implies breakdown of platforms and plugging of wells. When an abandoned field is to be re-opened for CO_2 storage, new platforms have to be built and wells drilled. Re-use of the infrastructure would, however, significantly decrease the costs for CO_2 storage. Platforms would need some adaptation and the possibility for re-use of both platforms and wells would have to be investigated on a case-to-case basis (BERR, 2007). The construction of new infrastructure could render CO_2 storage economically unfeasible. This implies that CO_2 storage in a hydrocarbon field needs to be commenced as soon as possible after the end of production. Since it is difficult to predict when production will

end (as explained above), re-use of infrastructure requires a great deal of flexibility in the organisation of large-scale CCS as well as co-operation of the operators.

3.4 Hydrocarbon fields

The maps established for gas and oil fields are shown in Appendix B, Figure B.1 and Figure B.2 respectively. For each cluster the availability of storage capacity as a function of time (on the left axis) and cut-off (see legend) is shown in the diagrams as well as injection rate as a function of time (on the right axis). Table B-1 and Table B-2 list the values for each cluster.

3.4.1 Timing of storage capacity

Gas fields

The total storage capacity in depleted gas fields is about 19 Gt. Note that this capacity is a combination of data from the Geocapacity database for the main part of the clusters, and more detailed feasibility studies for the Netherlands offshore, Southern North Sea, East Irish Sea and offshore Scotland. The capacities are particularly high for clusters in Norway, the UK and Germany. For Norway and the UK, the gas fields do not become available before 2020, most fields not even before 2030, except for Scotland and the Southern North Sea. The feasibility studies for Scotland and the Southern North Sea have shown that gas fields become available for storage well before 50 years after discovery of the field. This is also true for the Netherlands offshore and could therefore also be true for the clusters where feasibility studies have not yet been performed. Also in Germany, Denmark, Poland and the Netherlands some of the gas field capacity becomes available earlier in the timeline.

The best injection rates are found offshore in Norway and the UK sector (cluster NO: 90 Mt/yr, NO_UK: 200 Mt/yr and Southern North Sea: 90 Mt/yr in 2050) and onshore in the Netherlands and Germany (85 and 93 Mt/yr respectively in 2050). The total injection rate in 2050 is about 800 Mt/yr, assuming that all capacity is still available. Injectivity decreases as soon as storage fields become filled, which is included in the results presented below.

Oil fields

The storage capacity in oil fields is smaller than the capacity in gas fields; the total capacity is about 5.6 Gt. In none of the clusters does capacity become available before 2015. After 2015, the capacity becomes available slowly. The largest part of the capacity is located offshore of Norway and UK. The total injection rate in oil fields is about 250 Mt/yr in 2050, with the highest injection rates in cluster NO_UK, almost 140 Mt/yr (54% of the total maximum theoretical injection rate in 2050).

3.4.2 Cut-off dependency

Gas fields

The reservoir storage capacity thresholds applied to the clusters are visible as different colours in the diagrams. The diagrams show that even the most severe threshold used (20 Mt, in light blue) has only little effect on the capacity for most clusters. For the Netherlands cluster 2 (NL_2 in Appendix A) and Poland cluster 1 (Pl in Appendix B),

however, no capacity remains when thresholds of 20 or 2.5 Mt are applied. The total storage capacity for a threshold of 20 Mt is about 17 Gt, compared to a total capacity of about 19 Gt.

Oil fields
Application of a storage capacity threshold has a larger effect on oil field storage capacity. For the clusters NO_UK_4 and NO_UK_DK a cut-off of 10 Mt lowers the total capacity with over 30%. A cut-off of 20 Mt further lowers the capacity with 20-30%, with roughly 30-50% of the total capacity remaining. France possesses few, small oil fields, leaving no capacity at a cut-off of 2.5 Mt. Poland only possesses a few oil fields <10 Mt and Germany <20 Mt. Application of a size threshold of 20 Mt reduces the total storage capacity in oil fields from about 5.3 to about 4.5 Gt.

3.5 Aquifers

3.5.1 Timing of storage capacity

The map established for aquifer fields is shown in Appendix B, Figure B.3. The corresponding table is given in Table B-3. The storage capacity in aquifers, as recorded in the Geocapacity database, is large, but remains uncertain. The three aquifer clusters of Norway have total capacities of 120, 30 and 26 Gt. Clusters UK and DK_GE have capacities of 14 and 34 Gt, respectively. The total capacities of the other clusters are lower, but still significant compared to those of the oil and gas field clusters. The total amount of CO_2 that theoretically can be stored in aquifers is about 290 Gt.

3.5.2 Cut-off dependency

For aquifers a storage capacity threshold of 50 Mt was applied. For most clusters it does not have a (large) effect on the storage capacity, except for the Netherlands where the cut-off reduces the capacity from 425 to 75 Mt and for Lithuania which does not have aquifers larger than 50 Mt. The total capacity of aquifers is reduced slightly, from about 290 to 286 Gt.

3.6 Enhanced Oil Recovery

3.6.1 Method

CO_2 can be injected in declining oil fields to further enhance oil recovery. This process is called Enhanced Oil Recovery (EOR). Secondary oil production is performed by injection of water to maintain sufficient pressure for oil production. CO_2-EOR is known as tertiary production. The CO_2 storage capacity determined for oil fields in the Geocapacity database takes water injection during secondary production into account.

EOR with CO_2 is standard practice in several regions of the United States (e.g., West Texas, Wyoming, Mississippi and Oklahoma), where CO_2 is available at low cost. An overview of all EOR projects in the North Sea, including currently planned projects is given by Awan et al. (2008). CO_2 injection has been attempted mainly for research goals. A recent study performed by the Norwegian Petroleum Directorate has shown

that EOR using CO_2 in the Norwegian part of the North Sea will need 12 – 16 Mt/yr for a period of 25 years (Midttun, 2003). An analysis of Norwegian and British oil fields in the North Sea suggested a storage potential of the order of 2.2 Gt (Holt et al., 2009). It should be noted that before CO_2 – EOR will be deployed on this scale, the security of supply of CO_2 in sufficient quantities must be guaranteed. Holt et al. (2009) also points out that the volume of CO_2 injected into EOR fields decreases from a maximum demand at the start of each CO_2-EOR project due to the utilisation of recycled CO_2. Additional storage capacity is required to store the CO_2 not used in the oil fields.

3.6.2 Financial issues

The re-use of existing platforms is complicated for EOR because of the requirement of uninterrupted hydrocarbon production. Extensive top-side adaptation would be envisaged for the injection of CO_2, and in many circumstances it is probably more economical to install a new injection platform (BERR, 2007). It has been suggested that EOR should be driven by the oil production and not CO_2 storage. Several studies have shown that high oil prices, of the order of over US $100 per barrel are required for EOR to be economically attractive (e.g. BERR, 2007; University of Edinburgh, 2009). Currently, the oil price is below this level. It is considered most likely that CO_2-EOR will develop only if CO_2 transport lines to North Sea storage locations already exist and can be used to divert some of the CO_2 to oil fields.

3.6.3 Significance of EOR

Application of EOR can enhance the development of infrastructure required for large-scale CCS, but as mentioned above, it is unlikely that large-scale infrastructure for CO_2 will evolve on the basis of CO_2-EOR alone. The volumes of CO_2 stored, of the order of about 55 Mt/yr over a time span of 40 years (Holt et al., 2009), is insignificant compared to the volumes stored in hydrocarbon (gas) fields and saline aquifers, as shown in the next section.

4 FUTURE CO_2 REGIONAL TRANSPORT

4.1 Introduction

A view on future, large-scale CO_2 transport infrastructure can be obtained by matching the source (capture) side to the storage side, for the period 2020 - 2050. The source – sink matching process was started using CCS scenarios on a national scale for the countries considered; these scenarios describe the development of CCS, for capture and storage, in the short term. The transport infrastructure for the medium and long term was obtained by extending the short-term networks. The assumption is that the infrastructure constructed by early projects can be used in later projects.

The reference scenario is based on the current national CCS plans for 2020, from which the infrastructure has been further developed in 2030 and 2050, based on national assumptions (Appendix C). Two alternative scenarios have been evaluated. The first is an 'offshore-only' scenario, in which it is assumed that onshore storage will not be possible up to 2050 due to stringent permitting issues. The second alternative scenario also includes the development of EOR: the 'EOR scenario'. It too assumes that onshore storage is not possible.

The infrastructure maps can be found in Appendix D. Figure D.1 through Figure D.3 show the transport corridors and corresponding names for the reference, offshore-only and EOR scenario, respectively. Figure D.4 through Figure D.12 show the annual transported volumes for 2020, 2030 and 2050 for the reference, offshore-only and EOR scenarios. Table E-1 through Table E-3 list the transport routes and their flow rates.

4.2 Reference scenario

The infrastructure development of the reference scenario for the periods 2020, 2030 and 2050 is described in the following three sections. Detailed country-specific descriptions of the assumptions taken into account can be found in Appendix C.

4.2.1 2010 - 2020

In the reference scenario, the infrastructure remains very limited up to 2020. Only a few small-scale CCS projects are implemented, resulting in a limited number of national pipelines. This is due to the fact that the underlying PRIMES scenario assumes that emission reduction targets for 2020 are met, without the need for CCS. Therefore, the only active CCS projects in 2020 are those that arise from demonstration projects. The UK needs to construct the larger part of pipelines required.

4.2.2 2020 - 2030

By 2030, all source clusters defined in this study will capture CO_2, in varying amounts. This implies that infrastructure is required for every source cluster to connect to sink clusters. Norway and the UK will store all CO_2 captured in reservoir clusters in the North Sea. Sweden, Finland and the Baltic States lack national storage capacity and

transport towards the Norwegian aquifers in the North Sea is therefore expected. For Belgium, Netherlands and Denmark part of the CO_2 is stored in the North Sea, while the remaining part is stored onshore. No cross-border transport and storage is necessary between Norway, the UK, Denmark and the Netherlands. The CO_2 captured in Belgium needs to be partially transported to the Dutch offshore. Poland, Hungary, and Romania do not have (sufficient) national storage capacity. Hungary and Romania can store in the Slovak aquifers which have sufficient capacity. Poland needs to transport and store part of their CO_2 in the Northern aquifers in Germany (cluster DE_1, Appendix B, Figure B.3). Bulgaria has national storage options. Transport flows are limited to maximum values of 47 Mt/yr from the Ruhr area and eastern Germany to the northern German gas fields and aquifers.

4.2.3 2030 - 2050

The infrastructure changes slightly around 2030. In the UK a new pipeline towards the gas fields in the East Irish Sea is required, where storage capacity becomes available. A pipeline from the Rotterdam area to the onshore gas fields in the northern part of the country (gas field cluster NL) is necessary since the offshore fields do not have sufficient capacity for the increased amounts of CO_2 captured in the Netherlands and Belgium. Poland now has sufficient storage capacity due to the increasing availability of onshore aquifers. Also Estonia and Lithuania do not need cross border transport at this stage.

Most of the pipelines required in 2030 will still be in use. They will have to be able to transport larger volumes of CO_2. In most countries CO_2 flows are smaller than 100 Mt/yr. The largest amount of CO_2 to be transported is estimated to be 246 Mt/yr from the German Ruhr area to the gas fields in Northern Germany.

4.3 Offshore-only scenario

An offshore-only scenario alternative was outlined to study the needed change in infrastructure and the possible bottle-necks that would be the result, if a Europe-wide decision should be taken not to store in onshore locations.

4.3.1 2020

Compared to the reference scenario, several needs for changes are evident in the transport routes. Every current onshore storage demo-project would have to find an offshore alternative. From north-eastern France, transport to the coastal area, to the Rotterdam area in the Netherlands and further to the North Sea gas fields of the Netherlands is the closest option. Due to lack of sufficient Dutch offshore storage capacity a small part requires further transport to the gas fields of the Southern North Sea.

In Germany pipelines transport CO_2 from the Ruhr area and the eastern source cluster (Brandenburg area) to the offshore German aquifers. CO_2 from Poland is also stored there, requiring a pipeline from the source cluster in southern Poland to the German Brandenburg area, while Denmark can store its captured CO_2 in the offshore gas fields.

4.3.2 2020 - 2030

Between 2020 and 2030 the infrastructure needs to be extended considerably. For the UK, Norway, Sweden, Finland and the Baltic states there are no differences with the reference scenario since storage already occurred offshore. For the remaining countries, all pipelines are part of a network which transports CO_2 towards the North Sea.
France and Belgium can transport their captured amounts to the Rotterdam area of the Netherlands, and further to the Netherlands offshore.
From Bulgaria, Romania, Hungary, Slovakia, Czech Republic and Poland, pipelines arrive at the German Brandenburg area from where CO_2 is further transported towards North Germany and the North Sea. This results in very large amounts of CO_2 to be transported by the pipelines. The amount leaving from the coastal area of Germany towards the North Sea is approximately 256 Mt/yr. The German aquifer field offshore does not have a sufficiently high (cumulative) injection rate and further transport to the gas fields and aquifer clusters to the North all the way to the Norwegian aquifer cluster NO_2 is required.

4.3.3 2030 - 2050

In 2050 the transport routes will be the same as in 2030, except for the additional pipeline in the UK towards the gas fields in the East Irish Sea. The volumes to be transported, however, increase considerably. The transport corridor from the northern German source cluster to the offshore aquifer cluster and further North to the offshore gas fields of Denmark and the southern Norwegian aquifer cluster, transports an amount of CO_2 in the order of 750 Mt/yr. Due to the very high theoretical storage potential foreseen mainly in the aquifers in the North Sea, all CO_2 captured can be stored offshore.

The result of excluding onshore storage locations is a more extensive transport network, already in 2020, in comparison to the reference scenario.

4.4 EOR scenario

This scenario is based on the offshore-only scenario, with the addition of CO_2 demand from oil fields in CO_2-EOR activities. EOR might be an economically attractive option for CCS in the case of higher oil prices.

4.4.1 2020

CO_2–EOR requires an extended transport network from the Netherlands and Germany towards the Norwegian oil fields. Norway and Denmark can use the oil fields which are located closest to the source cluster from which capture takes place. For onshore transport in France, the Netherlands, Poland and Germany no further changes have been made with respect to the offshore-only scenario.

4.4.2 2030

In Norway, all CO_2 captured can be stored by means of EOR, based on current estimates of storage potential of the oil fields.
Each source cluster in the UK will be connected to the oil field cluster NO_UK_3 where most of the CO_2 captured can be stored. This requires a transport network from the

southern source clusters towards source cluster 10 (Teesside) and from there to the oil field cluster. The remaining part of the CO_2 will go to the gas fields of the Southern North Sea.
The onshore transport network in the mainland will be the same as for the offshore-only scenario. Also the offshore network, from northern Germany all the way to the Norwegian oil fields and aquifers is very similar to the offshore-only scenario due to the location of the oil fields close to the gas fields and aquifers in the North Sea. From the Netherlands offshore a connecting pipeline to the German offshore network is required.

4.4.3 2050

The transport network is equal to that established by 2030. The routes need to be able to transport much higher CO_2 volumes, similar to the volumes in the offshore-only scenario. Approximately 27% of the total amount of CO_2 captured can theoretically be stored by means of EOR.

4.4.4 Remaining storage capacity

Table 4-1 shows the percentages of the storage capacity filled for the three different scenarios. The total cumulative amounts are given in Table 4-2. In the reference scenario the larger part of the onshore gas fields is filled. For the offshore-only and the EOR scenario some of the offshore gas fields clusters are filled to capacity. The average percentage of gas field capacity filled by 2050 is 25%, 18% and 13% for the three scenarios, respectively. In the EOR scenario, the offshore oil fields have been filled as much as possible; 85% of the capacity has been used by 2050. It is noted that this is probably an optimistic view on CO_2 demand by oil fields, as a recent study indicates that a total demand of about 2 Gt (instead of 5.0 Gt in this study) is a more realistic value (Holt et al., 2009).

Due to the vast capacities of the aquifers and their (assumed) late availability, only low percentages have been used for storage; 5%, 5% and 4% for the reference, offshore-only and EOR scenarios, respectively.

Table 4-1 Percentage of storage clusters filled for the three different scenarios.

	Reference scenario			Offshore-only scenario			EOR scenario		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Gas field clusters	0	4	25	0	4	18	0	2	13
Oil field clusters	0	0	2	0	0	0	1	17	85
Aquifer clusters	0	0	5	0	0	5	0	0	4

Table 4-2 Total volume [Mt] stored per cluster type for the three different scenarios.

	Reference scenario			Offshore-only scenario			EOR scenario		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Gas field clusters	70	800	4800	82	850	3500	50	500	2600
Oil field clusters	0	0	130	0	0	0	45	1000	5000
Aquifer clusters	40	1400	14000	30	1300	15000	16	675	11000

Table 4-3 Percentage of total amount of CO_2 stored per cluster type for the three different scenarios.

	Reference scenario			Offshore-only scenario			EOR scenario		
	2020	2030	2050	2020	2030	2050	2020	2030	2050
Gas field clusters	63	37	26	74	39	19	46	23	14
Oil field clusters	0	0	1	0	0	0	40	46	27
Aquifer clusters	37	63	73	26	61	81	13	31	59

Overall, large storage capacity remains available after 2050. In Appendix F , Table F-1 through Table F-3, the capacity filled for the three scenarios are shown for gas field, oil field and aquifer clusters, respectively. Table F-4 through Table F-6 give the remaining capacity in 2050 and the corresponding percentage of the total capacity.

Table 4-3 shows the contribution of total CO_2 storage by the different storage types. For each scenario gas fields take care of the largest part of CO_2 storage in 2020. This share decreases in time. This is the other way around for aquifers, which contribution increases between 2020 and 2050. This is due to the assumed increased availability of storage capacity in time. Generally, aquifers have a large share in the storage of CO_2. This share is largest in the offshore scenario, where 81% of all CO_2 captured up to 2050 is stored in aquifers. Oil fields only contribute in the EOR scenario, where they have a share of 27% in 2050.

5 PIPELINE VERSUS SHIP TRANSPORT

5.1 Introduction

The transport network presented in the previous section is likely to be implemented with a network of pipelines for the larger part. For some of the transport corridors ship transportation can be an alternative option, either during the start-up of CCS, or in a more permanent fashion. This section describes the requirements for ship transport.

5.2 General considerations

Shipping can play an important role at the start-up of CCS, deployed during the planning and construction of pipeline projects and infrastructures. Once the pipeline(s) become(s) available, the ship(s) can either be redeployed into another trade, complement the pipeline to mitigate network downtime risks, and/or seize opportunities in developing CO_2 storage in easily accessible smaller capacity fields. For the purpose of this document it is assumed that upon pipeline network completion (i.e., the network being operational) ship transport will not be necessary to complement pipeline transport. However, in practice one may expect ships to continue operating, serving smaller cost efficient storage fields.

Shipping can play a role in two types of projects; (i) early development stage CCS projects concerning sink clusters of which the trunk line is still used for oil or gas production or is under construction and (ii) 'shipping-only' projects in which shipping is the most cost-effective solution.

Although CO_2 ships can be used in an economical fashion with capacities ranging from 1,000 up to 80,000 cubic meters (cbm), it will be assumed in this document that only ships with a volume of 30,000 cbm will be used. The ships' economic lifespan is set at 25 years. When developing shipping scenarios, ships that participate in short-term CO_2 transport projects will switch at the end of one project to another to ensure full utilisation of the ship.

5.3 Source requirements and desirables

CO_2 is liquefied (low temperature -50 °C, relatively low pressure 8 bar) to allow efficient shipping. The liquefaction can be performed at the CO_2 capture facility or at the ship loading facility, via connection with a (short) pipeline. After liquefaction, intermediate CO_2 storage is needed, given the batch loading nature of shipping. Suitable CO_2 sources are evaluated by the following properties which can be divided in requirements and desirables.

- **Location:** Sources preferably have one or more of the following properties.
  - **Near the coast**: The CO_2 can be immediately liquefied prior to being stored and loaded into the ships.

- **Close to other CO_2 sources**: This will allow for collection of CO_2 by a ship at different (coastal) sources, increasing CO_2 supply capacity and decreasing the risk of ships being idle.
- **Near an important inland waterway**: CO_2 from inland sources near the waterway can be collected with ships or barges and brought to the primary loading facility before being transported to a sink.

- **Volume related step-up**: CO_2 sources with a relatively low, but increasing start-up CO_2 capturing rate are suited for CO_2 ship transport, as shipping can adequately cope with fluctuating transport volumes.

5.4 Sink requirements and desirables

Sinks and sink clusters are evaluated by the following properties.

- **Sink type:** Certain sink types are preferred above others. The following sinks are listed in descending order of preference:
  1. **Oil fields**: Because CO_2 injection in oil fields enables EOR, the transportation of CO_2 adds value to the transport chain; therefore EOR suitable oil fields are highly preferable as sinks. Holt et al. (2009) show that the oil field CO_2 demand decreases from the start of CO_2-EOR, when the injection rate is largest. Such variable demand is easily accommodated by ships. In addition EOR project lifetimes are typically limited and the investment for a CO_2 pipeline infrastructure may not be justified.
  2. **Gas field**: Storing CO_2 can enable Enhanced Gas Recovery (EGR), although this technology has not been proven to be commercially viable for the gas fields in the North Sea. Gas field storage of CO_2 currently is regarded upon as storage only.
  3. **Aquifer**: This type of storage promises to have the highest storage capacity of the three types. However, unlike EOR or EGR amenable fields, aquifers do not add value to the trade. Furthermore, the injection technology for discharging CO_2 in aquifers is still under development and it can be assumed that viable aquifer injection technology needs a decade of further research, development and testing.
- **Availability of trunk pipeline:** In an early phase of the development of a sink cluster for CCS, a trunk line may be still in use for oil or gas production or it may be under construction. In this phase, ship transport can be deployed for CO_2 transport enhancing the flexibility of the source-sink cluster matching.
- **Starting date of injection:** Ship transport is an option for sinks that are available for CO_2 storage before a pipeline connection or network is available.
- **Injection rate:** The maximum injection rate into a field depends on the allowed injection rates/flows at the well head; ship installations generally do not present limitations. Fields with relatively low injection rates cause extended round trip durations which will decrease the feasibility of the trade by ship. As maximum injection rates generally decrease over time, due to the reservoir filling up, transport by ship is expected to be more viable early in a sink lifetime.

- **Field size:** Relatively small fields which are remotely located, for which a connection to the pipeline network is not feasible, are assumed to be candidates for ship transport. The fields need to have sufficient storage capacity to support a shipping project for a minimum lifetime justifying the investments on the subsea infrastructure enabling the ship to discharge at the fields.

5.5 Source and sink matching requirements

With the above considerations on sources and sinks, combinations where ship transportation is possible can be identified.

Preferably the source(s) capture rates and sink(s) injection rates develop in a similar way, although with multiple sinks a match is more easily obtained. When comparing the unit cost of CO_2 transport between ships and pipelines, pipelines are the most cost-effective solution when sources and sinks are located close to each other. With increasing distance, the cost of pipelines (especially capital expenses) gradually increases, making shipping an economically more competitive solution. For the development of CO_2 projects, it can be assumed that trades with the shorter distance between source and sink are developed first and implemented with a pipeline network.

With the above considerations, requirements for feasible CO_2 shipping routes become apparent. CO_2 ship transport can play a significant role as an enabler of CCS projects given the flexible nature as a transport modality. This applies not only in the early stages of CCS, when ships can play a role during the construction of parts of the transport network, but also at any time during the deployment of CCS by implementing transport to sinks that are remote or available before completion of a pipeline connection. Furthermore the ship can serve several different storage locations, and eventually, when a pipeline becomes available, they can service small opportunity fields or other new storage locations or CCS routes. CO_2 shipping cases will be considered in further detail in future reports.

6 TRANSPORT REQUIREMENTS

The transport corridors presented in the previous section provide a view on the transport infrastructure for CO_2 that would be required if CCS develops on a large scale between 2020 and 2050. If CCS is to contribute in reducing CO_2 emission, as assumed in the previous sections, the maps can be used to define its impact on various levels.

6.1 Infrastructure development

The length of the transport connections required has been estimated, assuming that they will be implemented with pipeline connections located alongside existing oil and gas pipelines. For this purpose, the Geocapacity database for existing pipelines has been used. In case a straightforward existing pipeline route is not present, the direct route length has been estimated. The estimated transport distances should be interpreted as first-order indications.

Table 6-1 gives the total pipeline length for the three scenarios. In 2020, the differences between the scenarios are large. The required pipeline length increases significantly between 2020 and 2030, by which time almost all connections need to be in place. The increase in total length between 2030 and 2050 is due to the large CO_2 volumes captured, which require parallel pipelines to be built. The effort in terms of transport network development is a continuous one between 2020 and 2050: between 2020 and 2030 because of addition of pipeline routes, between 2030 and 2050 because of addition of parallel pipelines. In a recent similar study of large-scale CCS infrastructure in the USA, a similar network size was obtained, with network (pipeline) lengths ranging from 15000 to 45000 km (ICF, 2009).

Figure 6.1 shows the length of pipelines by country required for 2020, 2030 and 2050 for the reference scenario. The graphs for the reference, offshore-only and EOR scenario and corresponding tables can (also) be found in Appendix G, Figure G.1 through Figure G.3, and Table G-1 through Table G-3. Note that the lengths reported in the tables represent the transport backbone or trunk lines that connect source clusters to sink clusters. Additional pipelines will be required at the collection (source) and distribution (sink) ends, resulting in significant increase in the total length of pipeline to be constructed. The graphs and tables show that the effort in pipeline construction required by the countries is unevenly distributed. Especially Norway, Germany and Poland will have to build a significant high amount of pipeline. Finland, Lithuania and

Table 6-1 Total pipeline length for the three scenarios.

	Total pipeline length [km]		
	Reference scenario	**Offshore-only scenario**	**EOR scenario**
2020	2.300	4.200	5.300
2030	15.000	20.000	21.000
2050	22.000	33.000	33.000

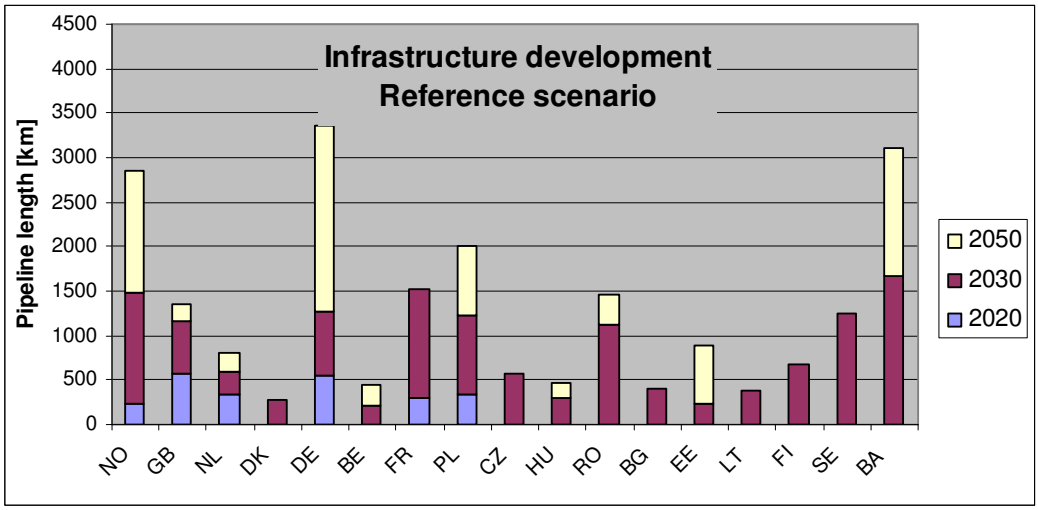

Figure 6.1 National infrastructure development for the reference scenario.

Estonia will share the construction of the pipeline from Southern Finland all the way to the offshore aquifers in Norway (BA pipelines). In the alternative scenarios co-operation is required in the construction of pipelines from Germany and the Netherlands to the storage aquifers in the North Sea (EU pipelines), which will have to transport CO_2 captured in several countries.

Figure 6.2 shows the lengths of pipeline with a specific diameter required for the reference scenario. In Appendix G, Figure G.4 through Figure G.6, the graphs are shown also for the offshore-only and EOR scenario. The assumptions used to estimate pipeline diameters are the following:

- Design pressure of 150 bar (onshore), or 200 bar (offshore);
- Use standard pipeline diameters;
- Pressure drop over distance taken into account;
- Pumps and compressors not taken into account
- Pipeline diameters were computed for the transported volumes in 2020, 2030 or 2050, without looking ahead to future CO_2 flows to be realized.

In Figure 6.3 the average transportation distance of CO_2 is shown for the different scenarios. In the reference scenario the average transportation distance increases from about 200 km in 2020 to about 600 km in 2030 and 2050. For the offshore-only and EOR scenario the transport distances are much larger. For both scenarios the distance is at its maximum in 2030 and is about 1350 km.

For comparison, the average transport distances in the USA are about 500 km and 1500 km for oil and gas, respectively (ICF, 2009).

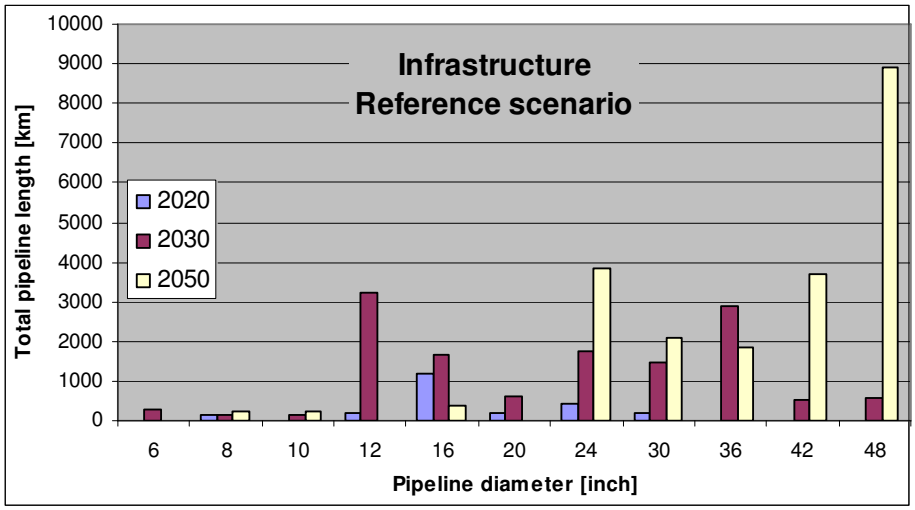

Figure 6.2 Required pipeline length per diameter for the reference scenario.

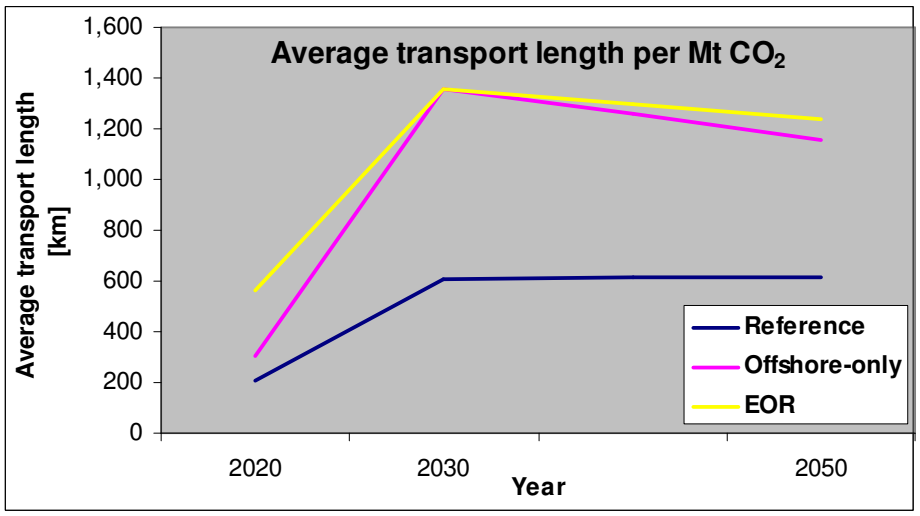

Figure 6.3 Average transport length of one Mt of CO_2.

6.2 Cross-border transport

Cross-border transport is an indication of the level of international cooperation required in the development of CCS infrastructure. Table *6-2* shows the total amount of net cross border transport for the three scenarios. In the reference scenario, cross border transport starts between 2020 and 2030. All current plans for early CCS projects are national projects. In the two alternative scenarios storage abroad is required already in 2020 since the current, onshore CCS plans would need to be changed to use offshore storage sites. France and Poland do not have offshore storage capacity and need to transport their CO_2 abroad. The Netherlands and Germany have sufficient offshore capacity to

change their onshore storage plans to offshore sites. In the EOR scenario, CO_2 storage in oil fields is economically attractive. In 2030 and 2050, the larger part (about 70%) of the captured CO_2 in the alternative scenarios is transported across the border.

Table 6-2 Cross-border transport for the three scenarios.

	Cross border transport					
	Reference Scenario (Mt/yr)	% of total	Offshore-only scenario (Mt/yr)	% of total	EOR Scenario (Mt/yr)	% of total
2020	-	-	3	7	9	19
2030	89	25	249	70	254	71
2050	215	18	861	70	857	70

Appendix H, Table H-1 through Table H-3 show the amount of CO_2 transported from one country to another and the corresponding percentage of the total national amount captured. In the reference scenario, for some countries, all of the CO_2 captured needs to be transported across the border due to zero national storage capacity. In the offshore-only and EOR scenario, several countries are added to this list, due to the absence of national offshore storage capacity.

6.3 Cost of infrastructure

To put the results presented here in perspective, the efforts involved can be expressed in terms of financial implications. Specifically, they can be compared to current investments in the energy sector in the countries involved.

Assuming that the larger part of the transport infrastructure will be implemented by pipeline connections, the construction effort in the period 2020 – 2050, as apparent from Table 6-1, is of the order of 1200 km/yr, in the region considered. This effort is large, but not beyond the current European pipeline construction capacity. For comparison, the Nordstream pipeline is constructed at a similar pace.

The total pipeline length in the two alternative scenarios, which is ~150% of the total length in the reference scenario, would impose a significant cost increase on the government and companies.

As the infrastructure is to be constructed within a short time span and over the entire region considered, cooperation among the countries is required, starting at the earliest construction efforts. Bottlenecks are expected to arise due to permitting issues. Indeed, pipeline construction has to deal with increasing public awareness of construction efforts, which will lead to increasing lead times.

6.4 Capture

The largest cost factor in CCS is the capture installation. Table 2-4 shows the national capture levels used as a basis in this study. The scenario used here leads to a captured

volume of CO_2 of the order of 1200 Mt/yr by 2050. This number can be put in perspective by considering the number of capture installations required.

A typical unit capture plant used here is a 1000 MW coal-fired power plant, with a post-combustion capture installation. The typical CO_2 production is about 5 Mt/yr. The investment costs for fitting a capture installation to such a plant (new built) is of the order of one billion Euros.

A capture rate of 1200 Mt/yr by 2050 can then be interpreted as requiring 240 coal-fired CCS power plants. The required rate at which these are to be built, between 2020 and 2050, is about 10 each year. For the area considered, this results in about one such power plant per country every two years, for a period of 30 years. This is an interpretation in terms of power plants; in terms of captured volume the required rate of increase in capture capacity is about 5 Mt/yr every two years. This is certainly a strong requirement, as it needs to be kept up for several decades. The associated investments are of the order of €0.5 billion/yr on average for each country.

In a later report these numbers will be compared with current investment budgets spent in the energy sector, for a more accurate perspective on the impact of investments for CCS on a both a European and national scale.

7 DISCUSSION AND RECOMMENDATIONS

7.1 Discussion

Transport network development

For all scenarios considered here, an extensive CO_2 transport infrastructure network will be required if CCS is to play a significant role in achieving the European CO_2 reduction aims. In the reference scenario more than 25.000 km of transport needs to be realized. This is to be developed by a continued effort in the period 2020 – 2050 and the larger contribution will probably be by pipeline transportation. This investigated transport infrastructure includes trunk lines only, as no individual sources or sinks have been connected in this assessment. In both alternative scenarios a trunk pipeline from the continent into the North Sea, providing access to the larger part of the Danish, British and Norwegian storage fields, is required in 2030 to transport large amounts of CO_2 that cannot be stored nationally. In these scenarios, annual flow rates of the order of 700 Mt/yr could require up to ten parallel pipelines.

In the CASTOR project a similar large-scale source and sink matching has been performed up to 2030 assuming the possibility of onshore CO_2 storage (Wildenborg et al., 2008b). That project included Spain, Portugal, Italy, Austria, Slovenia and Greece. Based on older sink data, the capture scenarios show captured and transported volumes of the same order of magnitude. The CASTOR project focussed on the matching, rather than on the transport and, aiming for perfect matching, the results for Western Europe show connections between source and sink cluster which are less evident.

The figures for the transport networks presented in this report, such as total pipeline length and potential volumes of CO_2 to be transported, compare well with those reported by other studies. A similar study for the United States reported transport distances and network sizes of the same order of magnitude [INGAA, 2009]. The IEA, in the recent Technology Roadmap, presented network size of the order of 1200 – 1600 km by 2020, growing to 20.000 – 35.000 km by 2050 for Europe [IEA, 2009].

Several reports emphasize that CO_2 transport by pipeline is daily business, with several thousands of kilometres of pipeline transporting tens of megatonnes of CO_2 [IEA, 2009; ZEP, 2010]. Most of these pipelines are located in the USA and Canada. It is not expected that major technological developments are needed to enable large-scale networks, such as those presented here [INGAA, 2009; ZEP, 2010]. The efforts involved in the construction of the CO_2 transport infrastructure, in terms of construction and cost, are significant, but within the range of current pipeline construction in the region considered. However, due to the higher population density in many European regions it is likely that more efforts are needed to take into account its impact on logistics and safety than in typical North American oil and gas field areas.

Transport network layout
In the UK many feasibility and infrastructure studies have been performed for the North Sea region. In the BERR report (2007) a one-to-one matching approach has been used between sources and sinks for the UK and Norway, where similar, but fewer source clusters have been selected for CO_2 capture. The study considered storing CO_2 from sources in the UK and Norway and the resulting infrastructure was limited to these countries.

Haszeldine (2009), in his study of CCS development in the North Sea, shows infrastructure comparable to that presented here, for the offshore-only and EOR scenarios. He includes a pipeline connection between the Ruhr area in Germany and the Rotterdam area in the Netherlands. In the present study, the Ruhr area was connected to northern Germany on the assumption that cross-border transport is avoided during the early phases of CCS. Furthermore, the Danish source clusters have been connected to the German offshore aquifer fields. In the present study, sources in Denmark were connected to sinks in Denmark, since the Germany aquifers need to be used for CO_2 captured in Germany and Poland (which was assumed to require storage capacity in Germany before 2030 and to develop sufficient saline aquifer storage after 2030).

In a report focusing on CCS developing in the countries bordering the North Sea, the required CO_2 transport infrastructure was investigated for several levels of capture efforts [One North Sea, 2010]. The results presented compare well with those presented here, taking into account that the current study includes a larger number of countries. The two studies foresee similar transport requirements and cross-border transport.

Capture effort
The development in the captured volumes presented here is from about 45 Mt/yr by 2020 to more than 1.2 Gt/yr by 2050. These figures represent an order of magnitude. The uncertainty in estimates from energy scenarios is large and increases over time. Consequently, the uncertainty in the CO_2 captured is large and increase over time. The order of magnitude development as presented here is in agreement with earlier projections given by the IEA [2009] for Europe. Focusing on only the countries part of the North Sea Basin Task Force (NSBTF), the CO2Europipe captured volumes in 2030 are about in the middle of the low and high 'One North Sea' scenarios (One North Sea, 2010). Compared to the most recent EC Baseline 'Energy Trends to 2030' (EC, 2010), the CO2Europipe capture scenario is somewhat higher. The number of capture installations required to reach such volumes is likely to be more than 300, in all of Europe. This rapid growth of CCS in Europe, and also in other parts of the world, is also foreseen in other road maps published recently, and is the direct result of the ambitious CO_2 emission reduction targets for 2030 and 2050.

Storage locations
The storage capacity does not limit CCS development, especially in the later stage when it is assumed that sufficient work has been undertaken to fully utilise the saline aquifer storage potential. This means that, in theory, storage capacity and injectivity can meet the requirements of the captured streams. In 2050, only a small part of the total capacity

has been used for storage, in spite of the large amounts of CO_2 captured. Unfortunately, the geographical distribution of the storage capacity that is known by screening studies so far is not even. The main part of the capacity is located in the North Sea. In East Europe, lack of sufficient storage capacity could be a bottle-neck since the extensive infrastructure network required to store CO_2 abroad is challenging (in Poland and Germany for the reference scenario and in the North Sea for the alternative scenarios).

The main challenge, as far as storage capacity is concerned, lies in the development of saline aquifer capacity. This capacity is likely to be large, but its size is uncertain. Saline aquifer storage is assumed here to become available on a large scale after 2020, which is in agreement with assumptions made in the ZEP R&D report [ZEP, 2010]. This requires that a project related characterisation of deep formations throughout Europe starts now and continues until 2050, to make the 300 CCS projects storage ready, with storage capacity needs up to 18 Gt by 2050.

International cooperation

The results in this report suggest that CCS infrastructure development should start from the commercial introduction of CCS by 2020 and continue until at least 2050. Almost from the start of EU-wide CCS project developments, international cooperation is required due to significant cross-border transport. This requires EU-wide cooperation to ensure matching technical solutions being adopted throughout Europe[11]. Presently, the EU flagship projects are being promoted and these will produce the first elements of the future infrastructure. To optimise the contribution of these early projects to the future infrastructure, these projects should employ the same technical solution. Knowledge of future transport requirements may lead to changing (oversizing) the technical solutions used. The need for a regional, long-term infrastructure plan has been recognised [IEA, 2009], not only with the aim of optimising the development of CO_2 transport infrastructure, but also to avoid conflicts of interest [ZEP, 2010]. These apply to land use at the surface, as well as to applications of the subsurface, where CO_2 storage is but one of several possible uses of the subsurface pore volume.

Challenges

While the technology required is available today, challenges remain for large-scale CO_2 transport to be reality; several are mentioned above. Significant cost reductions can be obtained by clustering CCS projects, i.e., clustering sources and sinks, but the business models and management of a complex network, handling CO_2 with different quality from different sources must be demonstrated [IEA, 2009; CSLF, 2009; ZEP, 2010]. The international aspect of CCS will play a central role in Europe and a good cooperation between European countries will be decisive in reaching cost-effective solutions.

Current EU objectives and emission reduction targets do not require CCS to be implemented before 2020. However, the financial crisis has made financing of renewables more difficult than the less capital intensive CCS, requiring CCS to play a

[11] A knowledge sharing network, led by DNV, has been put in place in 2010; see http://ccsnetwork.eu.

role on the short term. The source – sink matching described here would fit in the EU-ETS system, rather than resulting from current national emission reduction targets.

The results presented here will be used in future reports from the CO2Europipe project, that will analyse the development of large-scale future CCS infrastructure in Europe from a number of angles, such as technical, organisational, societal and financial.

7.2 Recommendations

Based on the discussion in the previous section, the following recommendations can be formulated:

1. CO_2 storage capacity is not a limiting factor in the development of large scale CCS infrastructure. However, validating the storage capacity that is reported in the most recent databases is a huge effort, which must precede the development of transport infrastructure. It is recommended that this effort is started as soon as possible, on a large scale. As available storage capacity is, however, not evenly distributed over the area considered, with the larger part located in the North Sea, some centralised planning and support is required.
2. It is essential that storing CO_2 onshore storage is possible, if CCS is to be feasible throughout Europe. The political climate is currently not favouring onshore storage. It is recommended to demonstrate safe and secure storage at offshore locations as soon as possible and to combine this with a strong and clear political message regarding the necessity of CCS as one of the means of reducing CO_2 emissions. The demonstration projects currently planned throughout Europe can be used to this end.
3. Transport infrastructure construction efforts will be considerable, but lowest when onshore storage is possible. A governmental authority, at European level, is needed to 'future-proof' any additions to the transport infrastructure. Studies such as CO2Europipe can provide the insight necessary to assess future demand for CO_2 transport capacity.
4. International cooperation and alignment of infrastructure developments is required for an efficient CCS transport infrastructure in Europe. As soon as planning and design starts for elements of a European transport infrastructure, the different projects and regions must make sure that their elements can, in the long term, be connected without undue redesign costs.

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APPENDIX A. SOURCE CLUSTERS

Table A-1 Total CO_2 captured and net cross border transport [%] per country for the reference scenario.

					Cumulative captured emissions [CO2 Mton]			Captured emissions per year [CO2 Mton/yr]		
Cluster	Country	CO2 emissions	Total emissions	%	2020	2030	2050	2020	2030	2050
1	Norway	5.967		46%	0.0	1.1	7.3	0	0.2	0.4
2		3.296		25%	30.0	93.3	231.5	6	6.7	7.2
3		3.73	12.993	29%	0.0	4.0	26.2	0	0.8	1.4
4	UK	17.91		7%	10.0	40.8	212.8	2	4.2	13.1
5		80.1		33%	30.0	95.0	343.9	6	7.0	17.9
6		17.44		7%	63.0	194.5	752.2	12.6	13.7	42.1
7		35.37		15%	0.0	15.5	160.9	0	3.1	11.4
8		23.37		10%	0.0	13.0	127.1	0	2.6	8.8
9		44.69		18%	0.0	14.5	141.9	0	2.9	9.8
10		22.94	241.82	9%	0.0	12.5	130.1	0	2.5	9.3
11	Denmark	10.194		38%	0.0	11.6	118.8	0	2.3	8.4
12		9.254		34%	9.0	26.4	112.7	1.8	1.7	6.9
13		7.587	27.035	28%	0.0	9.2	91.8	0	1.8	6.4
14	Netherlands	12.509		18%	0.0	16.6	136.8	0	3.3	8.7
15		23.16		33%	25.0	80.8	297.9	5	6.2	15.6
16		19.507		27%	5.0	43.2	246.6	1	6.6	13.7
17		7.005		10%	6.8	27.9	103.8	1.35	2.9	4.7
18		9.046	71.227	13%	1.0	14.8	102.1	0.2	2.6	6.2
20	Germany	208.49		52%	13.0	218.2	2611.1	2.6	38.4	200.9
21		12.743		3%	0.0	11.8	155.9	0	2.4	12.0
22		26.608		7%	0.0	24.3	327.4	0	4.9	25.4
23		100.523		25%	13.5	121.5	1264.8	2.7	18.9	95.4
25		48.866	397.23	12%	0.0	43.7	585.8	0	8.7	45.5
26	Poland	87.963		65%	9.0	307.2	1752.5	1.8	58.0	86.7
27		15.732		12%	0.0	56.6	328.2	0	10.6	15.8
28		31.524	135.219	23%	0.0	99.4	603.4	0	20.4	30.5
32	Czech Rep	16.941		25%	0.0	19.2	161.6	0	3.8	10.4
33		37.765		56%	0.0	118.4	949.4	0	23.7	59.4
34		5.981		9%	0.0	10.8	84.8	0	2.2	5.3
35		6.66	67.347	10%	0.0	10.4	82.8	0	2.1	5.2

36	Slovakia	3.645		22%	0.0	12.0	123.4	0	2.4	8.8
37		9.997		61%	0.0	9.3	83.4	0	1.9	5.6
38		2.754	16.396	17%	0.0	4.3	41.4	0	0.9	2.9
39	Estonia	11.521	11.521	100%		30.30	109.33	0	6.06	9.75
40	Lithuania	3.595		67%	0.0	1.9	29.0	0	0.4	2.3
41		1.749	5.344	33%	0.0	0.8	13.2	0	0.2	1.1
42	Hungary	10.783		64%	0.0	24.5	213.6	0	4.9	14.0
43		6.11	16.893	36%	0.0	18.5	160.9	0	3.7	10.5
44	Romania	21.713		40%	0.0	102.4	693.9	0	20.5	38.7
45		12.932		24%	0.0	30.2	221.1	0	6.0	13.0
46		14.493		26%	0.0	22.5	184.4	0	4.5	11.7
47		5.713	54.851	10%	0.0	22.6	154.7	0	4.5	8.7
48	Bulgaria	20.09		44%	0.0	30.8	285.5	0	6.2	19.3
49		15.55		34%	0.0	19.6	179.6	0	3.9	12.1
50		10.33	45.97	22%	0.0	13.0	119.4	0	2.6	8.0
51	France	30.833		34%	0.0	11.0	299.5	0	2.2	26.6
52		13.734		15%	0.0	5.4	114.7	0	1.1	9.9
53		12.943		14%	0.0	1.9	197.4	0	0.4	19.2
54		13.852		15%	7.5	18.9	185.1	1.5	0.8	15.9
55		11.115		12%	0.0	3.1	134.3	0	0.6	12.5
56		8.639	91.116	9%	0.0	2.2	107.8	0	0.4	10.1
57	Belgium	6.1384		12%	0.0	5.5	86.1	0	1.1	7.0
58		7.5414		15%	0.0	9.4	170.2	0	1.9	14.2
59		4.6966		10%	0.0	5.7	102.7	0	1.1	8.6
60		5.2407		11%	0.0	6.7	121.3	0	1.3	10.1
61		25.7703	49.3874	52%	0.0	22.3	327.7	0	4.5	26.1
71	Sweden				0.0	2.4	198.9	0	0.5	19.2
72					0.0	2.9	25.7	0	0.6	1.7
73					0.0	1.1	190.1	0	0.2	18.7
74					0.0	1.2	11.2	0	0.2	0.7
75					0.0	1.6	14.4	0	0.3	1.0
76	Finland				0.0	15.5	385.9	0	3.1	33.9
77					0.0	5.6	87.3	0	1.1	7.1
78					0.0	4.5	124.8	0	0.9	11.1
79					0.0	7.4	201.7	0	1.5	17.9

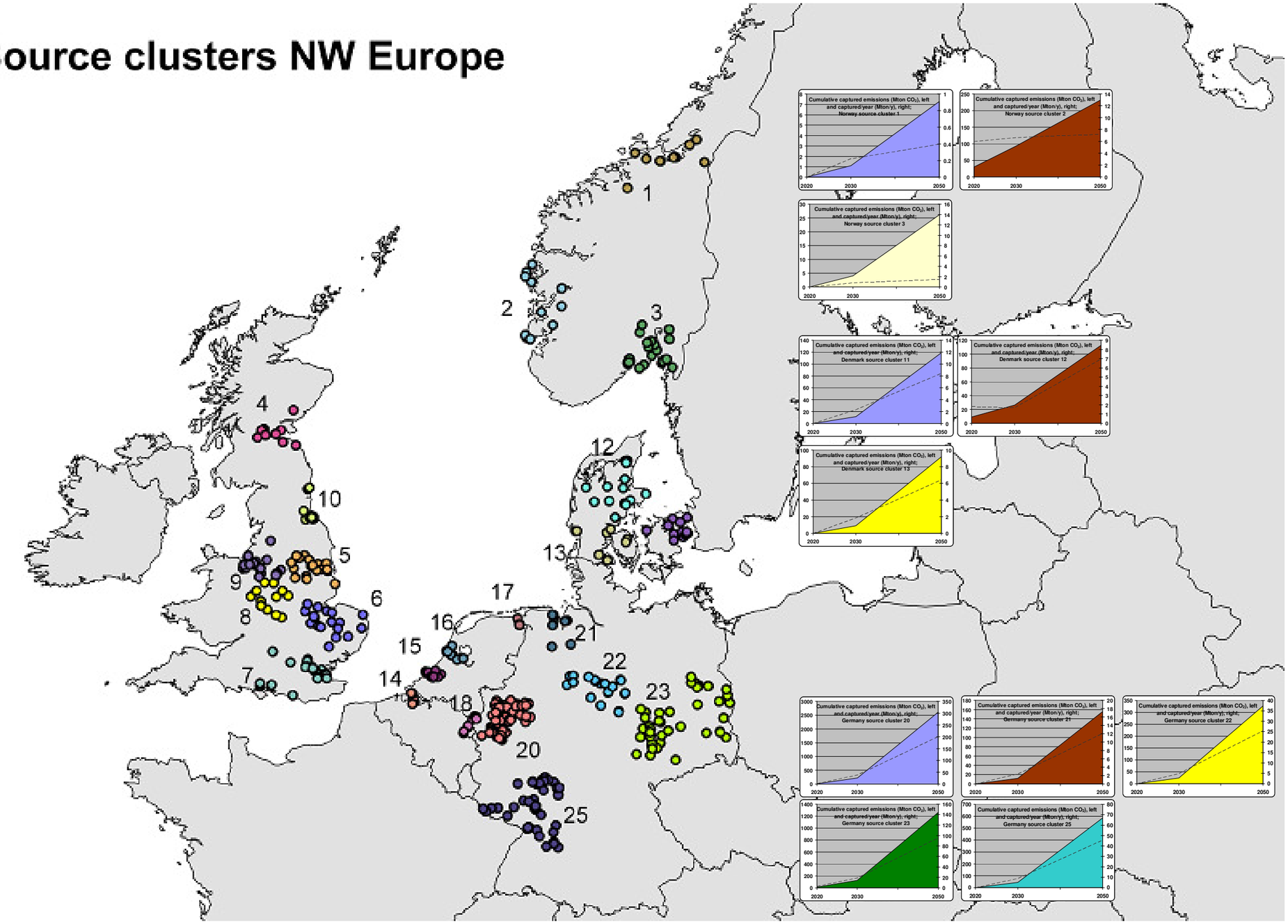

Figure A.0.1 Source clusters and corresponding captured flows.

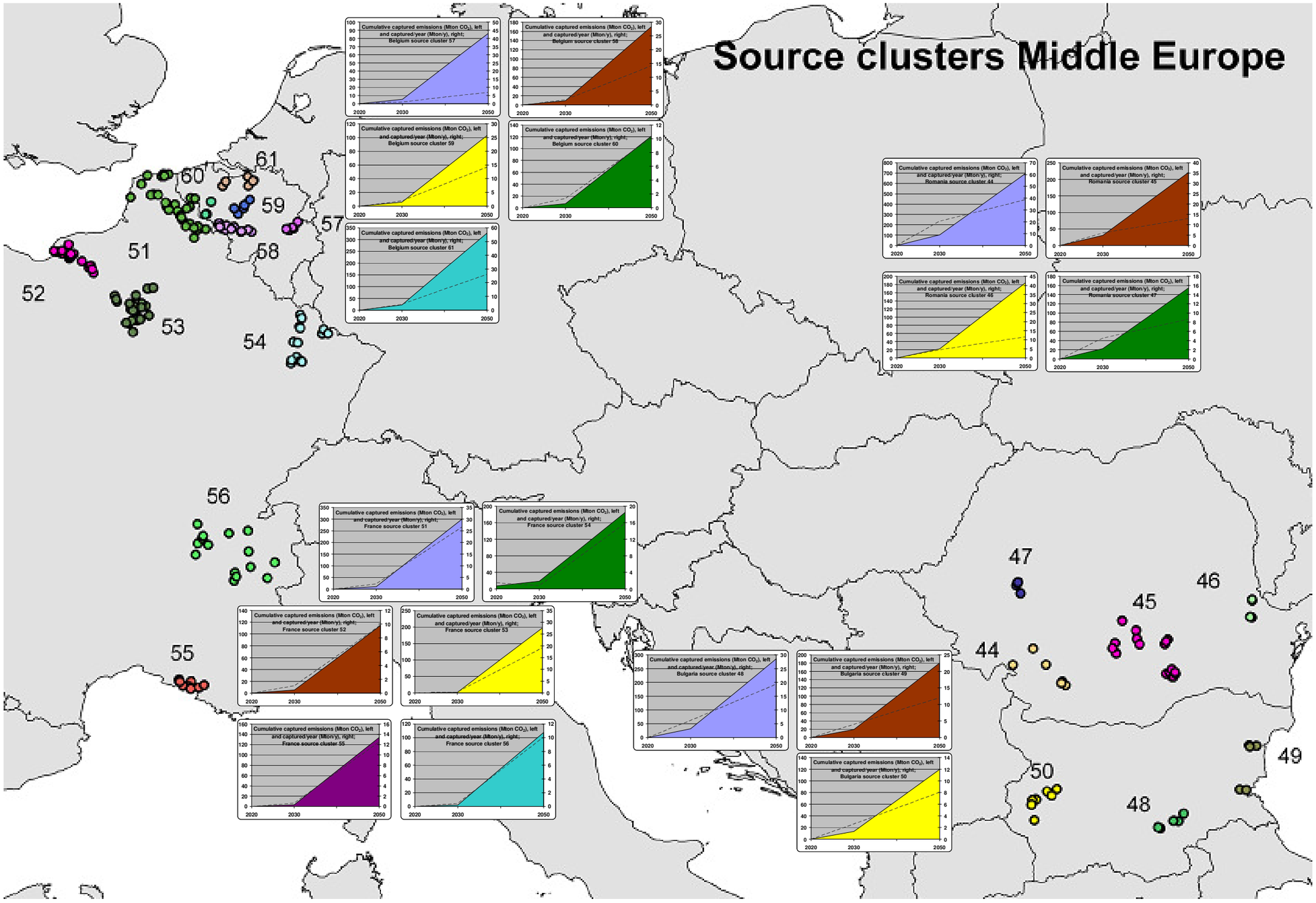

Figure A.0.2 Source clusters and corresponding captured flows.

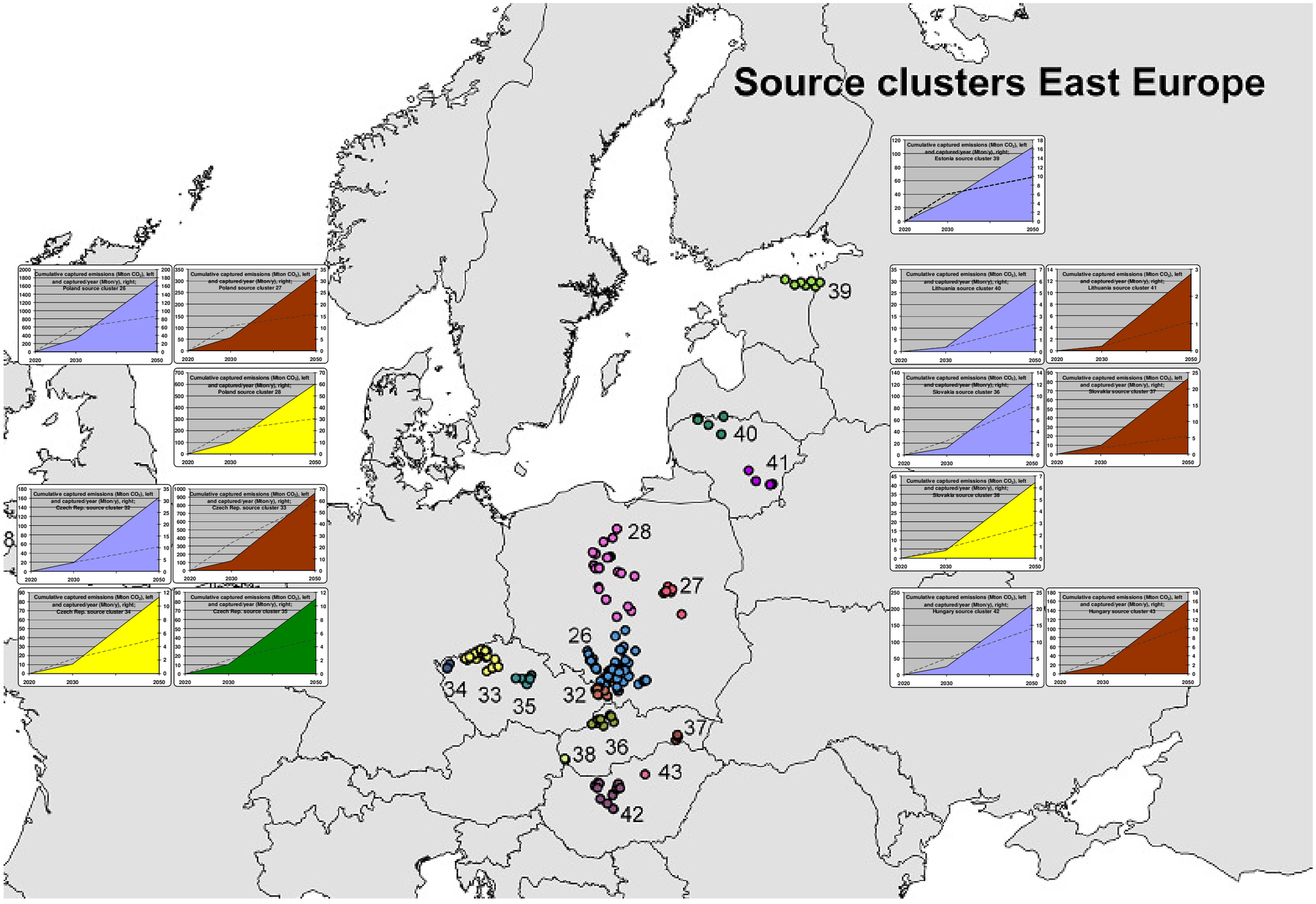

Figure A.0.3 Source clusters and corresponding captured flows.

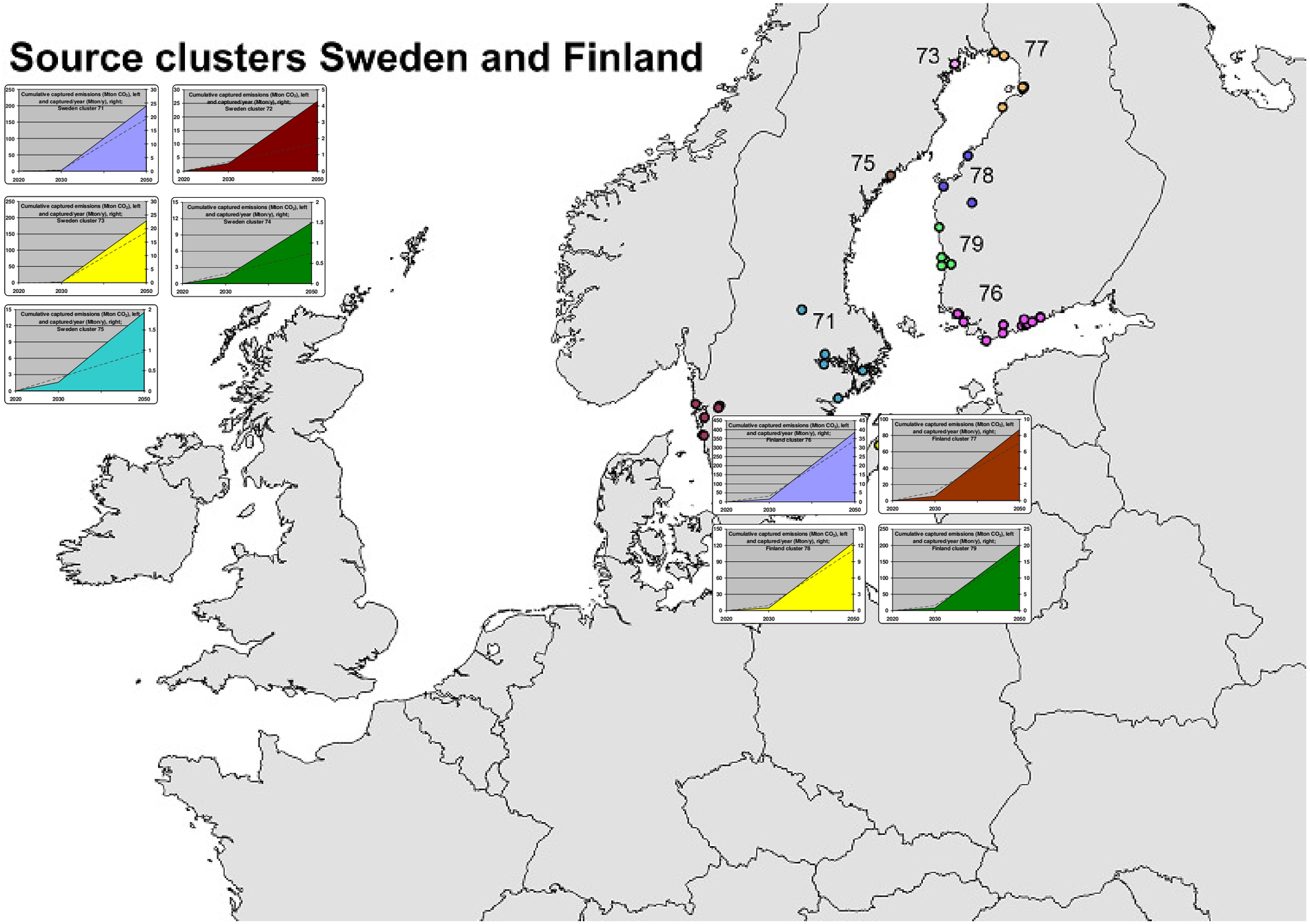

Figure A.0.4 Source clusters and corresponding captured flows.

APPENDIX B. STORAGE CLUSTERS

Total cumulative capacity without cut off [Mt] and corresponding injectivity [Mt/yr] of the storage clusters. The clusters in blue represent offshore fields. The storage fields of Hungary, the gas fields of NL_2 and CZ and the oil fields of PL_2 and UK_1 have not been taken into account due to the limited capacity and/or remote location.

Table B-1 Gas field clusters.

Gas fields

	Cumulative capacity [Mt]			Injectivity [Mt/yr]		
Sink cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO			2259			90
NO_UK_1		4519	5066		182	205
NO_UK_2		1060	1113		43	47
NO_UK_4	15	120	479	0.6	5	20
Scotland	601	712	712	21	28	28
Eastern Irish Sea	36	36	1046	1.4	1.4	42
Southern North Sea	1533	1963	1963	70	89	89
DK	286	424	424	12	17	17
NL offshore	200	800	800	8	32	32
NL	1306	1639	1943	53	68	85
NL_2	18	18	63	1.8	1.8	5
DE	1587	1862	2262	65	77	93
PL_2	71	296	296	4	15	15
PL_3	382	401	418	16	17	19
CZ	5	5	5	0.5	0.5	0.5
HU			55			3
SK	22	44	47	1.4	2.5	3
SK_2	9	29	49	0.9	2.0	3
RO			165			7
RO_2			50			2.0
Total	**6071**	**13928**	**19215**	**255**	**581**	**805**

Table B-2 Oil field clusters.

Oil fields

	Cumulative capacity [Mt]			Injectivity [Mt/yr]		
Sink cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO			81			3
NO_UK_1		3052	3302		124	136
NO_UK_2	29	31	230	1.1	1.4	11
NO_UK_3	273	578	996	11	26	46
NO_UK_4	19	51	187	0.8	2.0	11
UK_1			126			5
NO_UK_DK	53	74	126	2.1	4	8
DK	68	246	246	3	11	11
PL_2		2.0	7		0.2	0.7
HU			15			1.5
RO_1			15			1.5
RO_2			216			10
RO_3			15			1.5
DE	41	56	56	3	4	4
Total	**483**	**4090**	**5618**	**21**	**172**	**250**

Table B-3 Aquifer clusters. The orange numbers in the DE aquifer cluster represent aquifers that need early development in the offshore-only scenario.

Aquifers

	Cumulative capacity (Mt)			Injectivity (Mt/yr)		
Sink cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO		5301	26507		136	678
NO_2	43476	68576	125498	1087	1717	3153
NO_3		6042	30210		155	774
GB		2861	14304		88	440
GB_2		131	655		5	26
DK	162	3496	16672	6	100	466
DE	13	1272	6361	5	38	190
DE_1	3000	7001	20003	75	176	507
DE_2		326	1630		12	58
DE_3		425	2126		10	51
NL	63	188	438	0.6	1.7	4
BE		278	1392		10	51
FR	3079	9238	21555	75	226	527
PL	112	817	3522	4	35	154
CZ		223	1113		9	42
CZ_2	241	722	1684	10	29	67
LV		85	423		3	13
LT		8	42		0	0
SK		2742	13708		70	349
BU		531	2657		23	114
Total	**50146**	**110262**	**290500**	**1264**	**2843**	**7663**

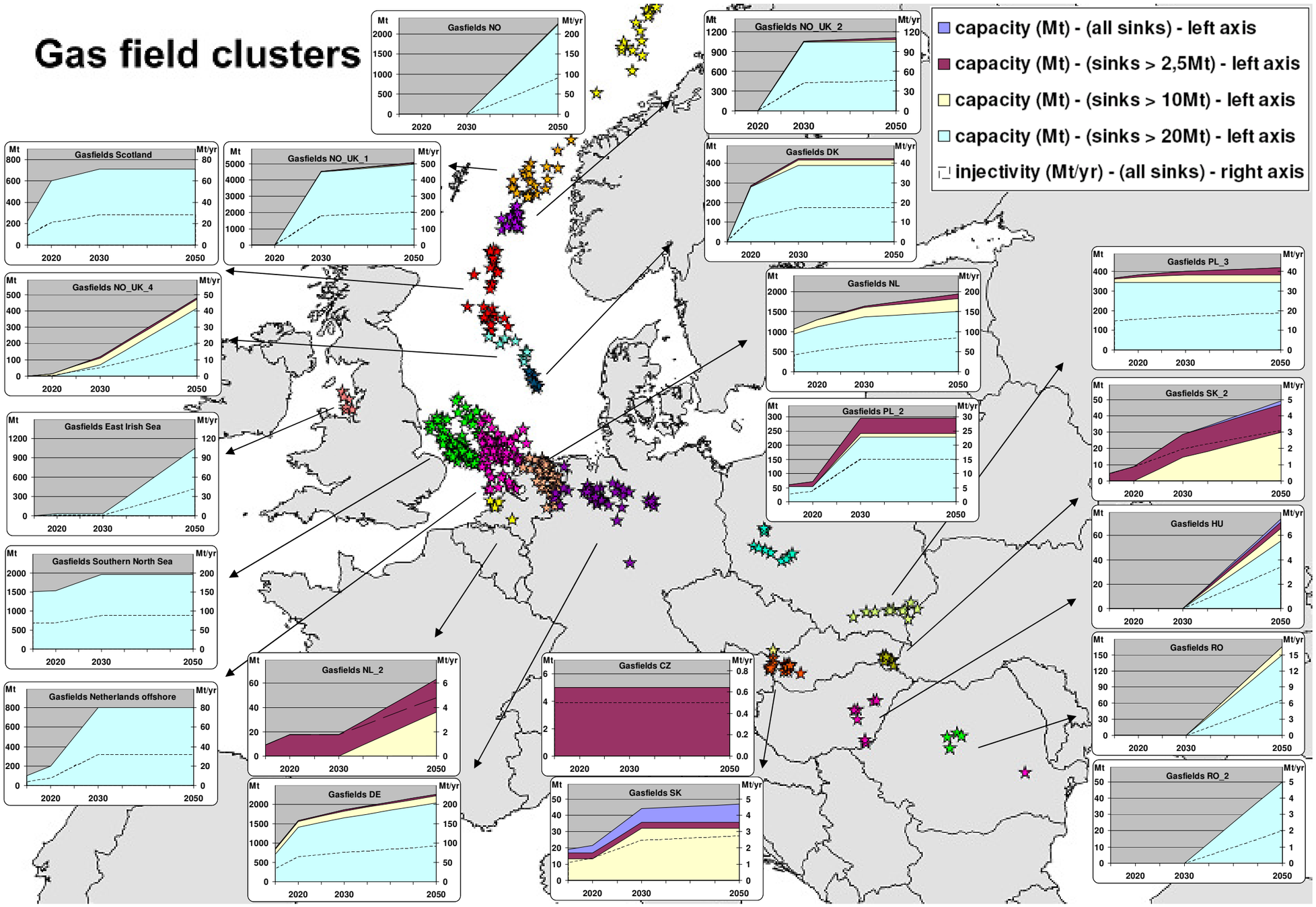

Figure B.1 Gas field clusters, with capacity [Mt] and injectivity [Mt/yr].

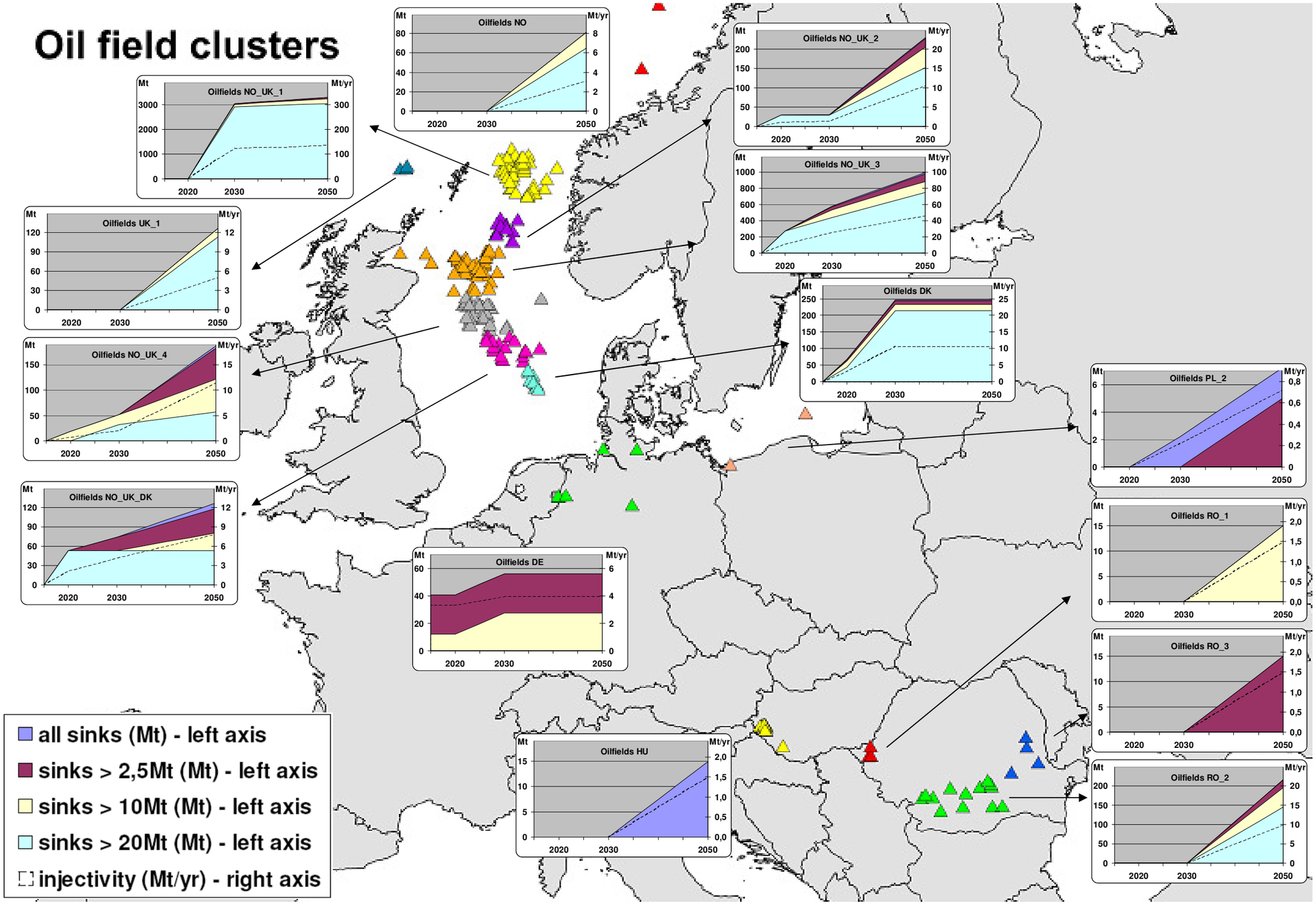

Figure B.2 Oil field clusters, with capacity [Mt] and injectivity [Mt/yr].

Aquifer clusters

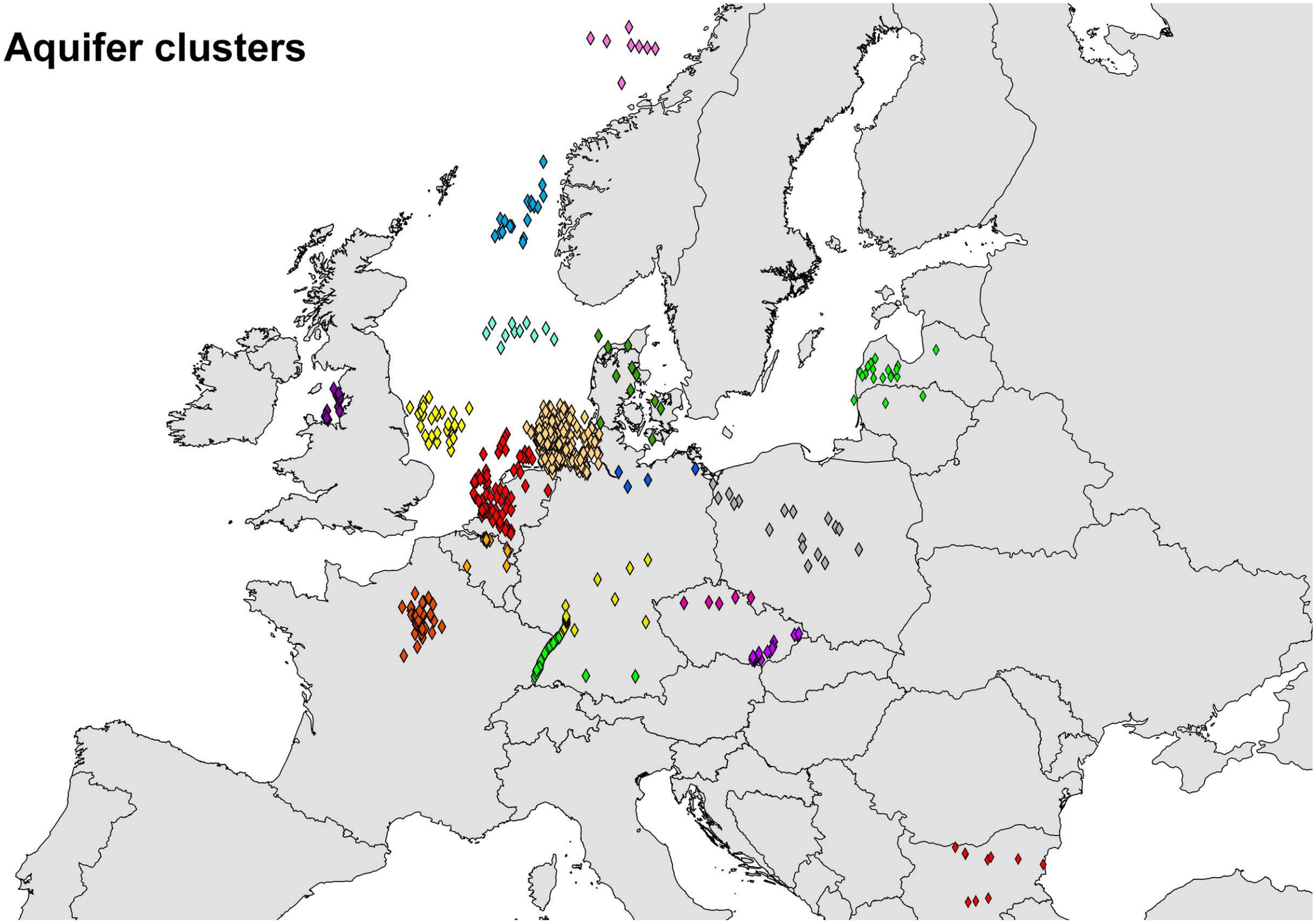

Figure B.3 Aquifer clusters, with capacity [Mt] and injectivity [Mt/yr]. The location of Slovak aquifers is unknown.

APPENDIX C. NATIONAL ASSUMPTIONS

For the countries involved in the CO_2Europipe project, national assumptions have been defined on source cluster development, initial storage options, and subsequently availability of aquifers. The assumptions are partially based on national CCS plans and partially on experience and personal insight from the partners. For the source cluster development, the relative timing and importance of the source clusters is essential. The clusters in which CCS projects will start will be ahead in the production of captured CO_2. Furthermore they will attract new CCS projects due to the presence of infrastructure. For each country the type of storage (gas fields, aquifers and/or EOR) which has most potential for the short term has been defined. It has also been defined whether onshore storage would be an option. If aquifers are assigned for storage in current CCS plans, research on aquifer storage capacity and seal potential will need to start earlier than when oil or gas fields are investigated for storage.

Norway

Norway has a huge offshore storage potential in oil and gas fields, as well as in aquifers. Onshore sinks have not been identified. The main focus for storage locations in Norway are the offshore aquifer formations, for the short term particularly the Utsira and Johansen formation of sink cluster NO_2 (see Appendix B). The Utsira aquifer is already in use for CO_2 storage and the Johansen aquifer formation has been assigned for future activities. These aquifers are therefore assumed to be available from the beginning of the timeline used in this project (2015). The remaining aquifers are assumed to become available from 2020 onwards. EOR is considered as an (expensive) option. Currently, there are no specific EOR plans present and it is therefore not considered as an initial storage option.

UK

In the short term, storage is likely to initiate in offshore depleted oil and gas fields. Offshore aquifers and, if necessary, international fields are foreseen for the medium to long term. There is potential for EOR development in the North-Sea in the short to medium term.

The Netherlands

In the Netherlands, many gas fields and aquifers are present, but most of them are relatively small compared to (other) regions in the North Sea. In the western offshore part of the Netherlands the gas fields of the K en L blocks (van de Velde at al., 2008) have been screened for near future CCS projects. Sources in the clusters of the Rotterdam and Amsterdam area will therefore initially focus on storage in this area (the onshore gas fields near Barendrecht (Rotterdam area) were investigated for a pilot project with CO_2 captured at the hydrogen gasification plant from Shell in Pernis, which is located in the Rotterdam source cluster; this pilot project was cancelled in 2010). The Eemsmond region (cluster 17) focuses on the onshore gas fields and aquifers in the

northern part of the Netherlands[12]. For this reason, the aquifers in the Netherlands will start to become available from 2015, so that capacity is available in 2020. Clusters 14 and 18 will probably be connected to the Rotterdam area from where the CO_2 will be transported to the gas fields offshore.

Denmark
Denmark contains mostly onshore aquifers and offshore oil and gas fields. Current CCS plans are still in a very early stage. Offshore storage in gas fields is an option, but also onshore storage in aquifers is considered. De Vedsted aquifer is currently investigated. This aquifer is assumed to be available from 2020, the remaining aquifers will develop from 2030 onwards.

Germany
EOR will not be important in the near future nor later, as reservoir oils in Germany are mainly quite heavy (low API). CO_2 injection would probably precipitate asphalthenes and block the oil reservoirs. Also, many potential CCS-EOR reservoirs are located shallower than 800m, which is not deep enough for CO_2 to be in a dense phase. Realistic storage options in Germany are Enhance Gas Recovery (EGR) and deep saline formation onshore as well as offshore. Two aquifers near Schwerin and Norderstedt (cluster DE_1) are being investigated. These two are therefore assumed to be available in 2020. The remaining aquifers are assumed to develop between 2020 and 2050.

France
In France, only limited storage potential is available. The storage capacity in the aquifers of the Paris basin is still uncertain. However, initially, storage is most likely to develop in these aquifers. Their availability is considered to evolve from 2015 so that capacity is available from the beginning of the timeline used in this project (2020). Some oil fields are present in the same area. However, their storage capacity is small. EOR might only be applicable on a small scale and is, for this reason, not considered in this assessment.

Czech Republic
In the Czech Republic, only aquifers and one small gas field are present. The gas field is too small to be used and is therefore not taken into account in this assessment. The aquifers are divided into two clusters. Of these only the northern cluster (CZ_2 in Appendix B) contains sufficiently large reservoirs for early storage. The capacity of the cluster is considered to evolve from 2015 so that capacity is available from the

[12] Early 2011, onshore storage in depleted gas fields in the North of The Netherlands was canceled by the national government. It is assumed here that national policies onshore storage is possible after the first demonstration projects.

beginning of the timeline used in this project (2020). Cluster CZ might develop after 2030 when higher captured volumes need to be stored.

APPENDIX D. CCS INFRASTRUCTURE MAPS

Figure D.1 to D.3 show all transportation routes required for the reference, offshore-only and EOR scenario respectively. Figure D.4 tot D.6 show the annual transported volumes for 2020, 2030 and 2050 for the reference scenario, figure D.7 to D.9 those for the offshore-only scenario and figure D.10 to D.12 for the EOR scenario.

Note: for practical reasons, unused storage clusters have been omitted from the maps when needed.

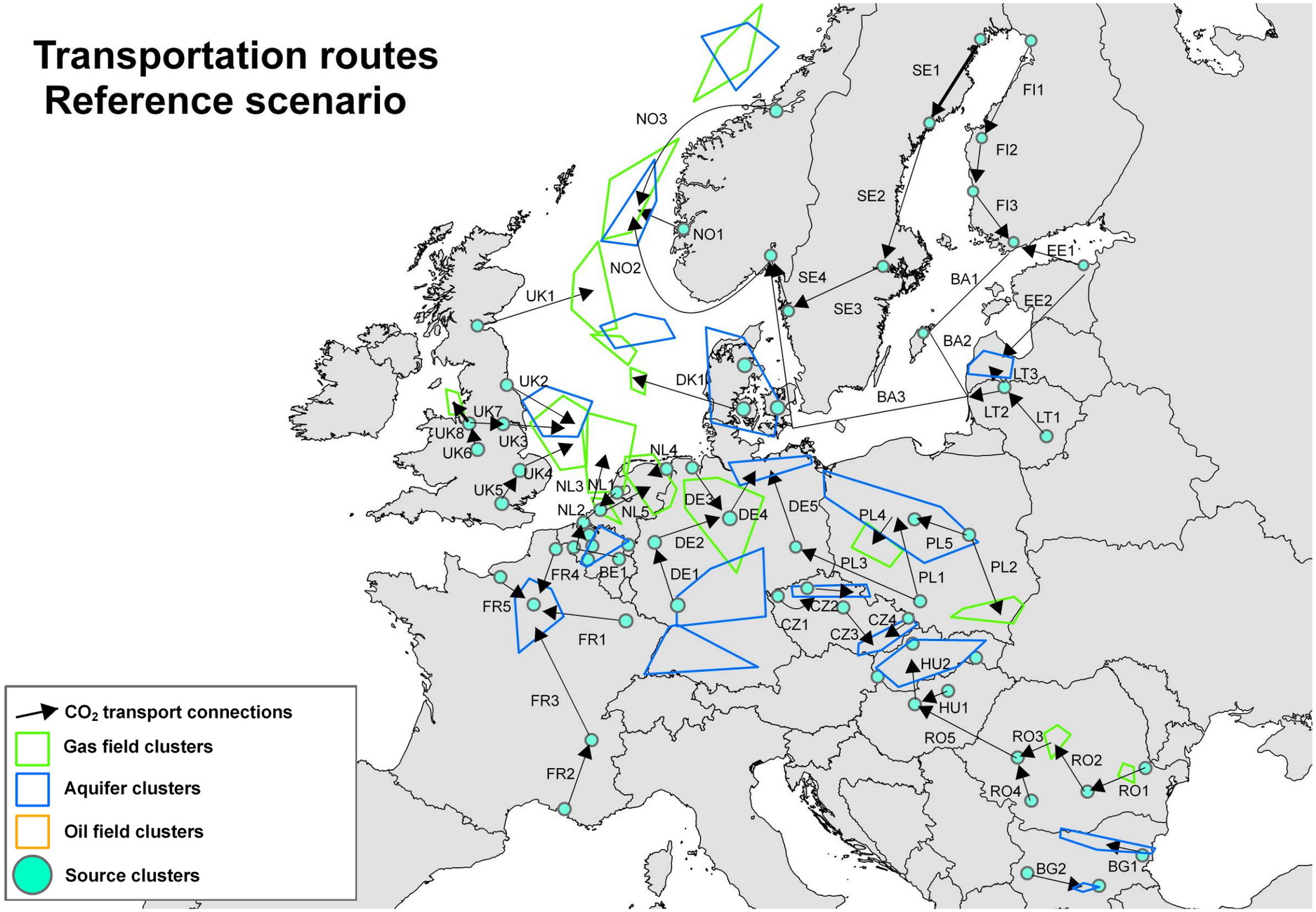

Figure D.1 Transport routes and corresponding names for the reference scenario.

Transportation routes
Offshore-only scenario

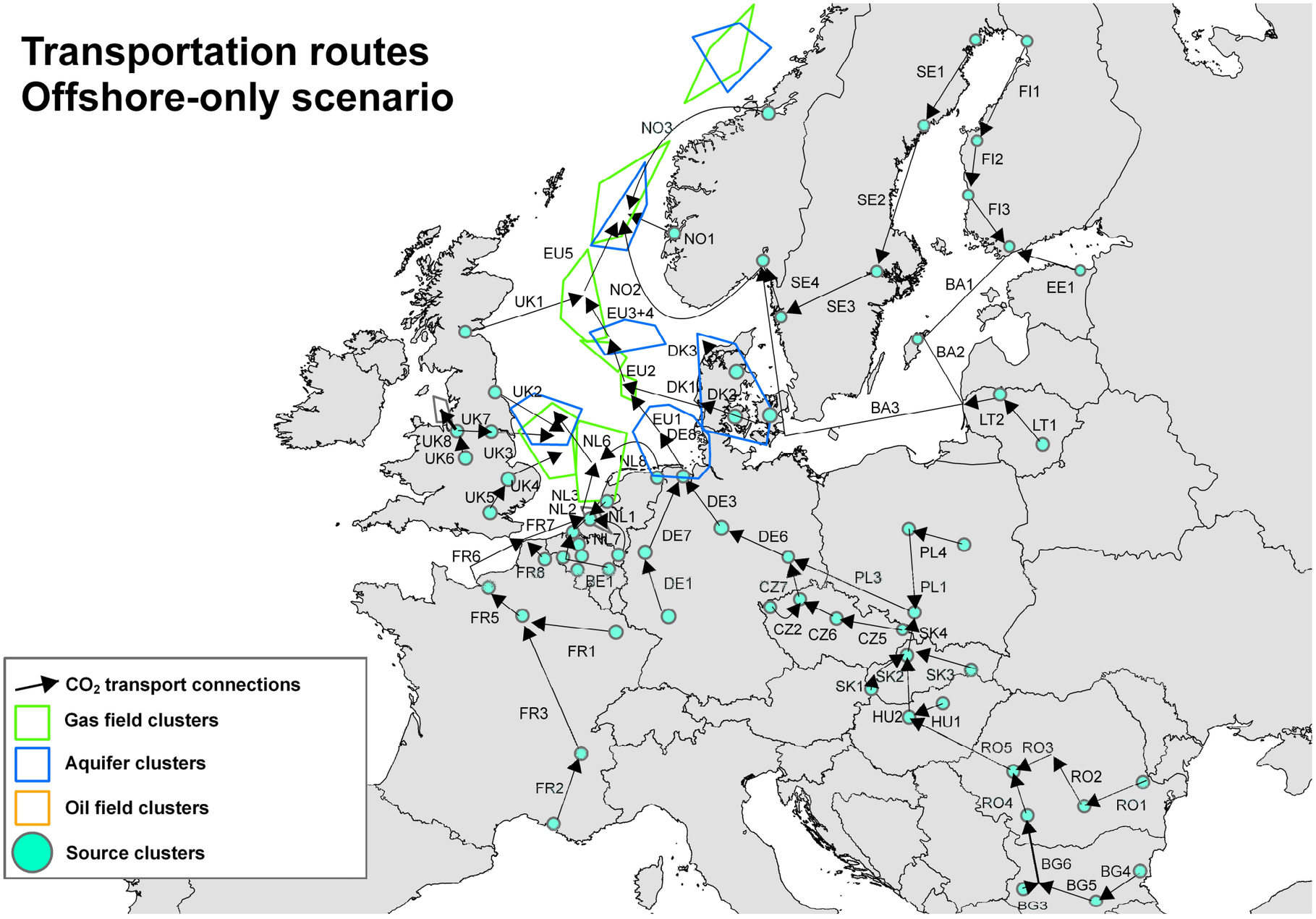

Figure D.2 Transport routes and corresponding names for the 'offshore-only' scenario.

Transportation routes EOR scenario

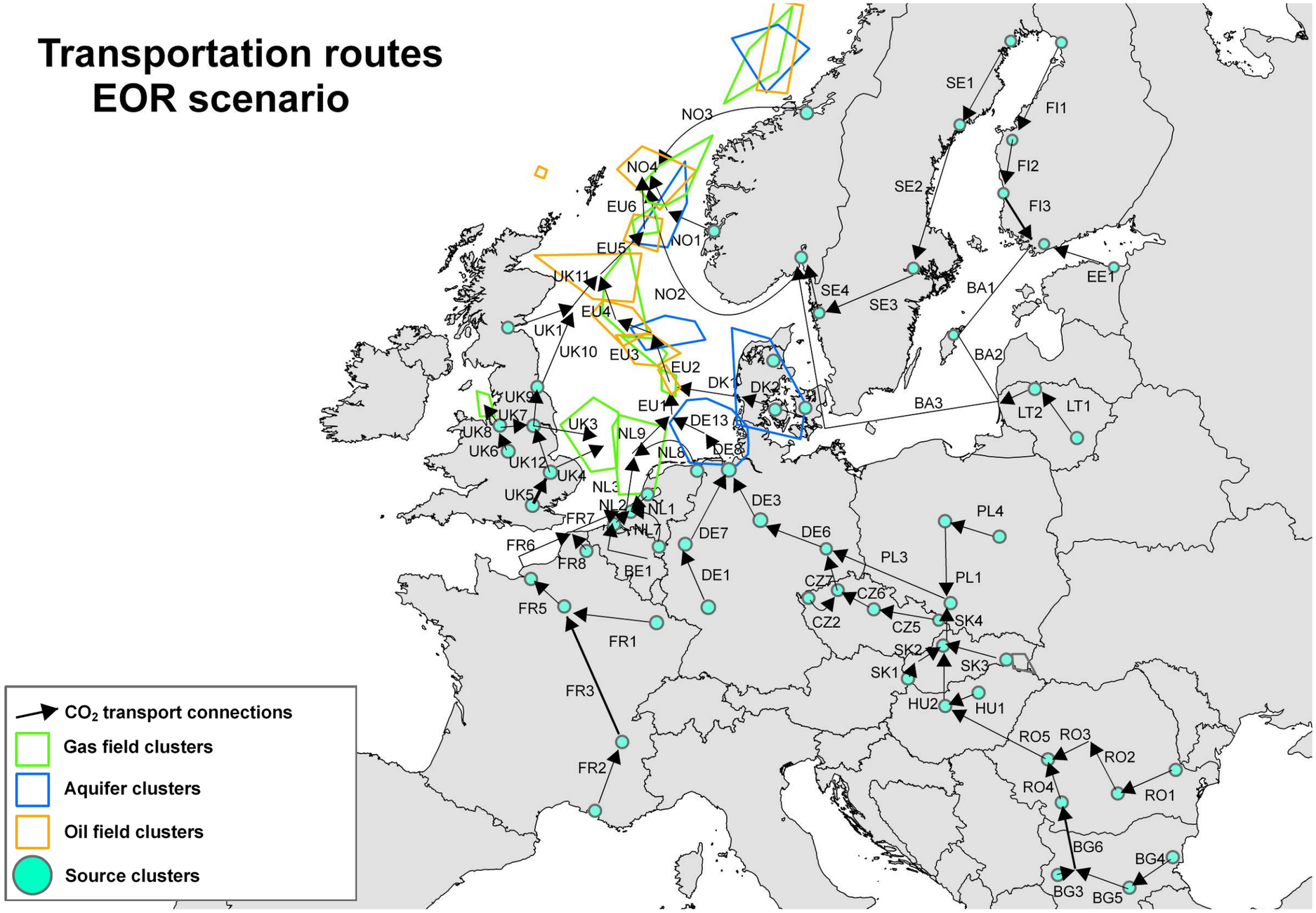

Figure D.3 Transport routes and corresponding names for the EOR scenario.

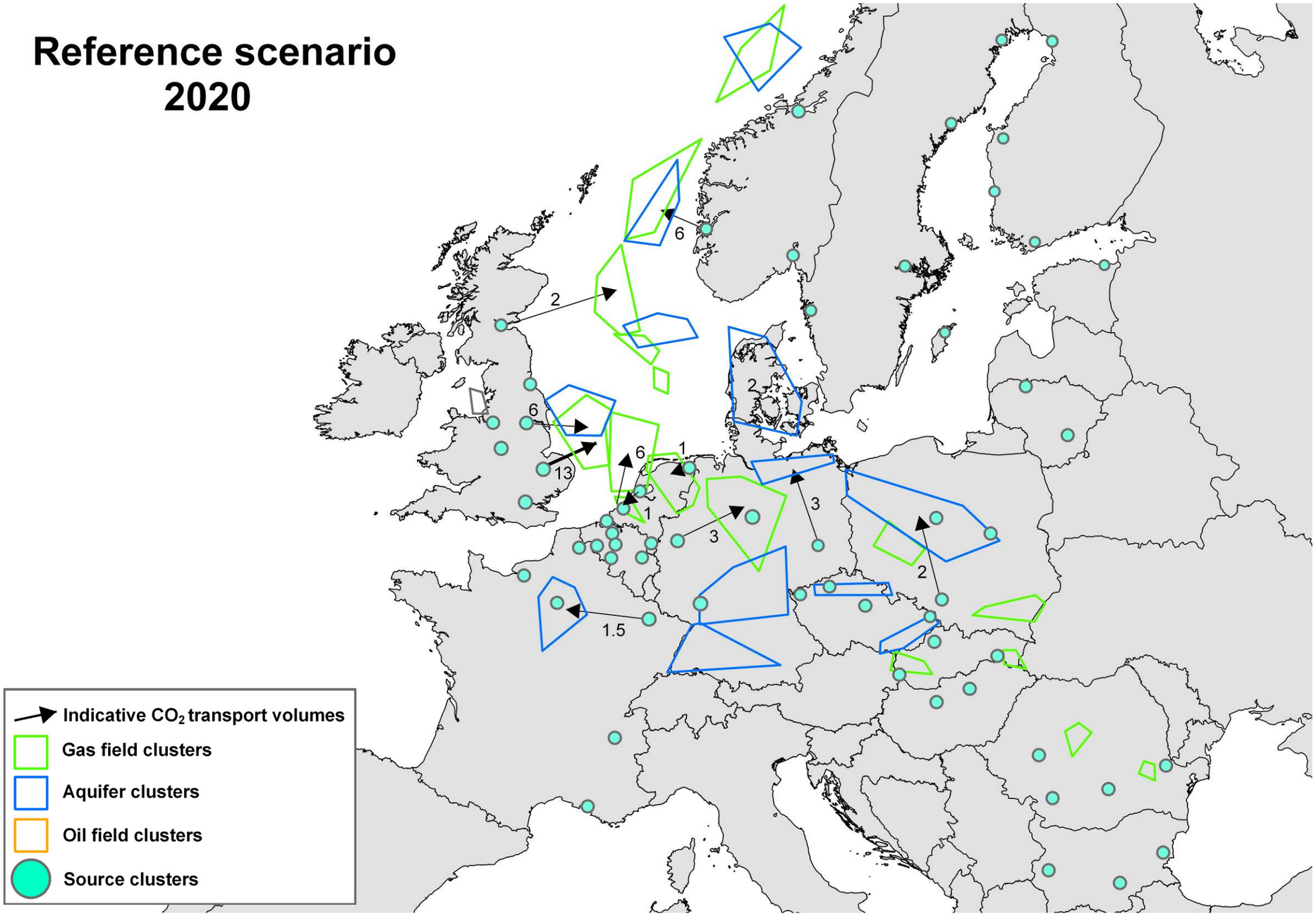

Figure D.4 Flow rates for the reference scenario in 2020.

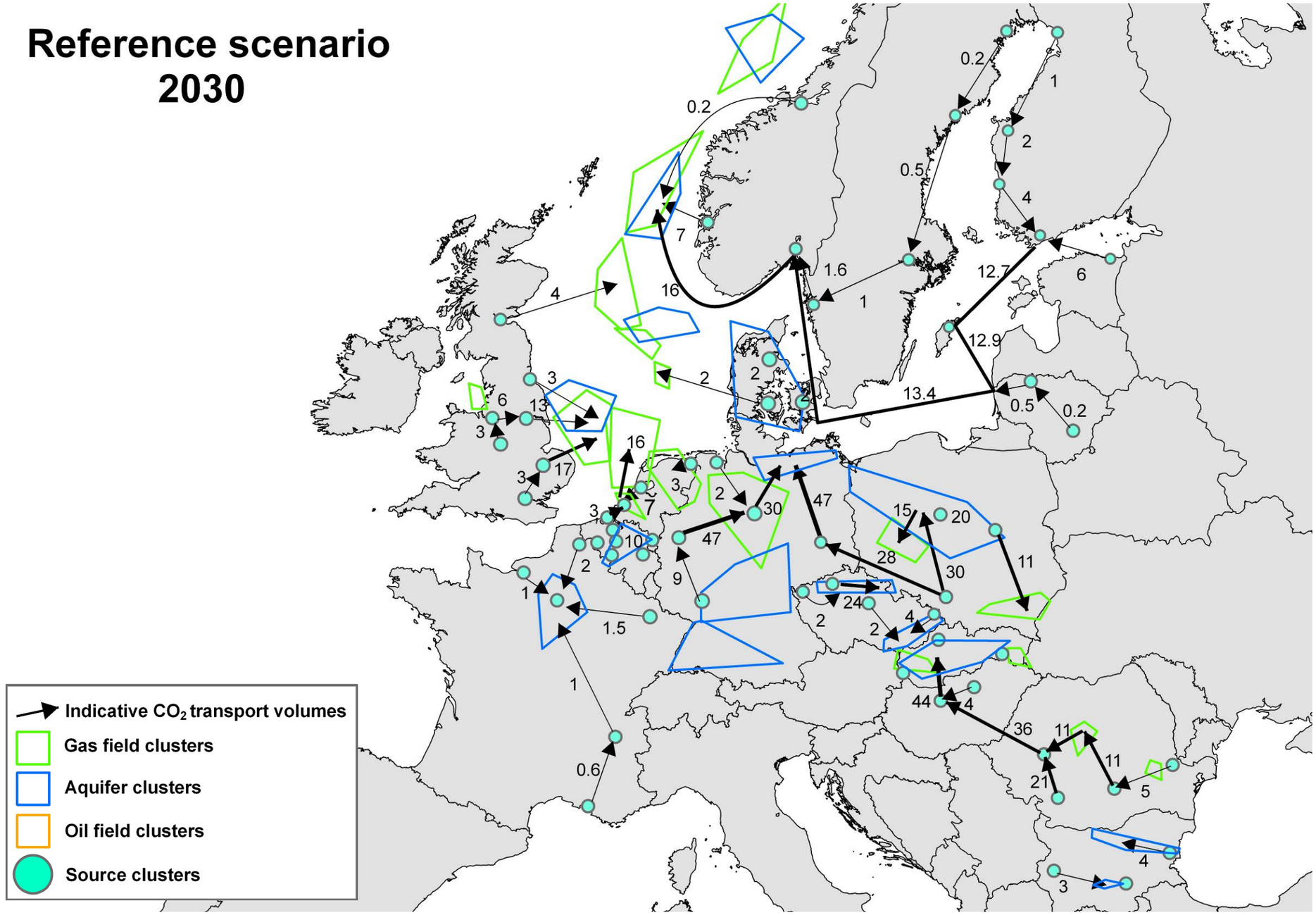

Figure D.5 Flow rates for the reference scenario in 2030.

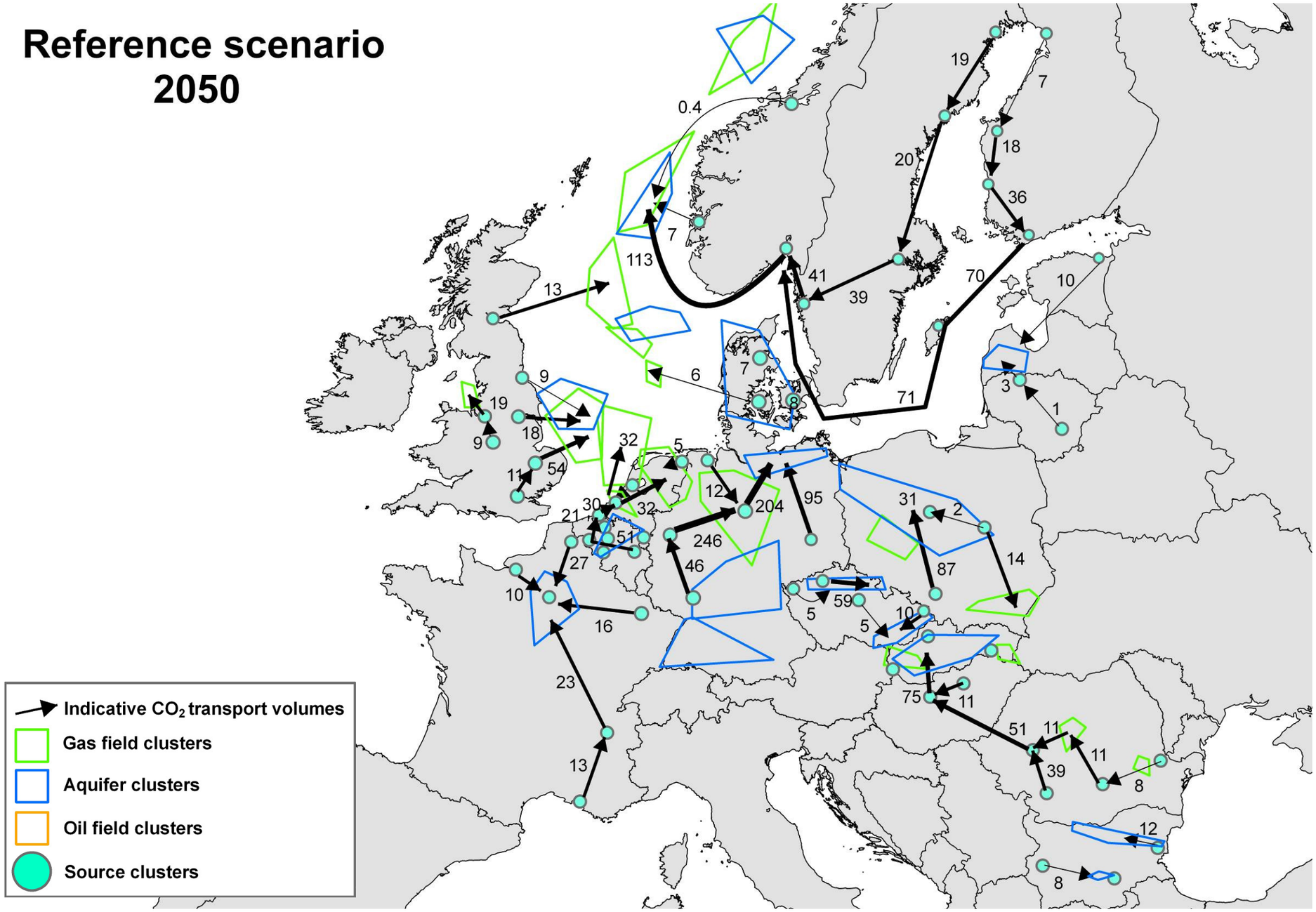

Figure D.6 Flow rates for the reference scenario in 2050.

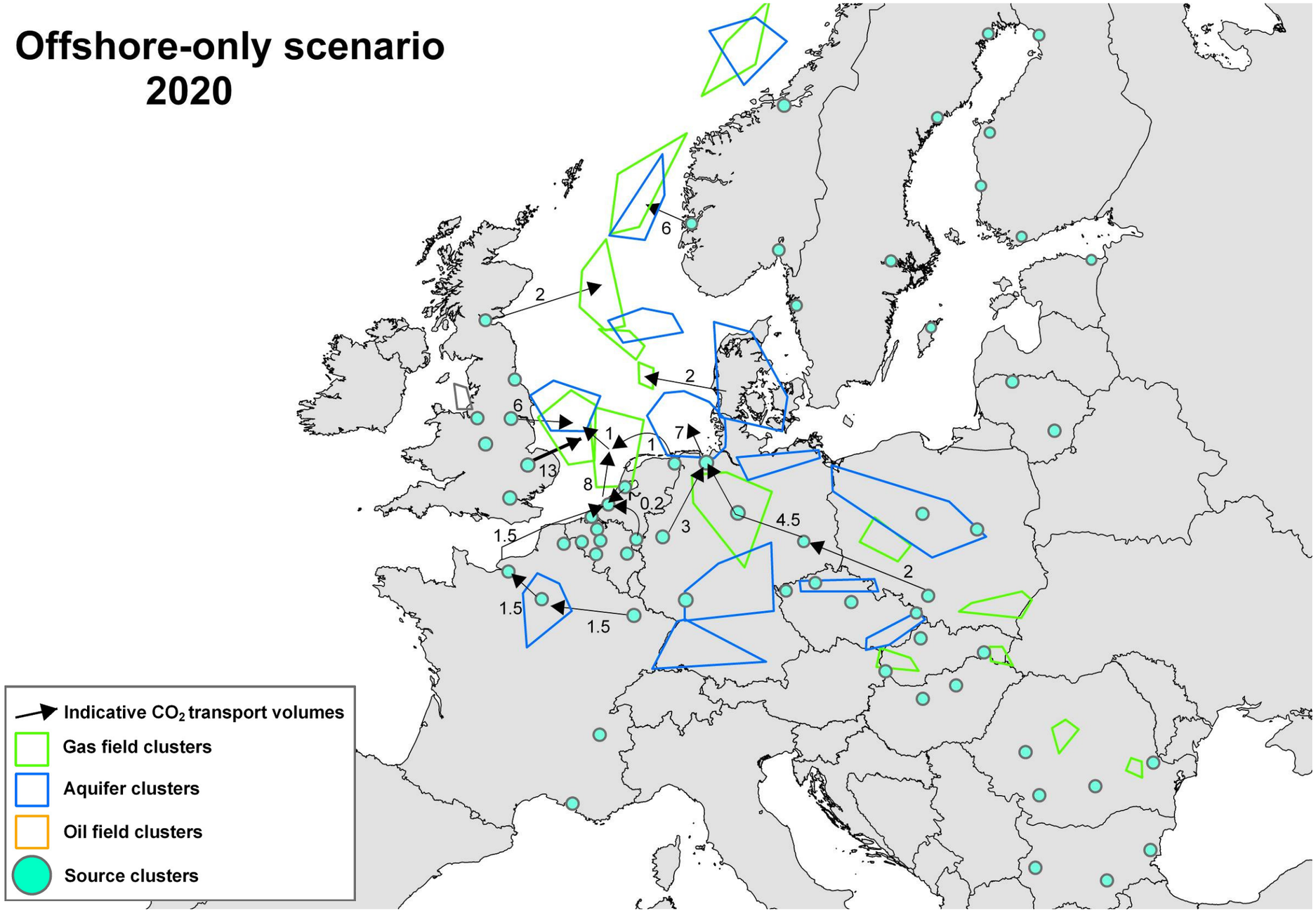

Figure D.7 Flow rates for the offshore-only scenario in 2020.

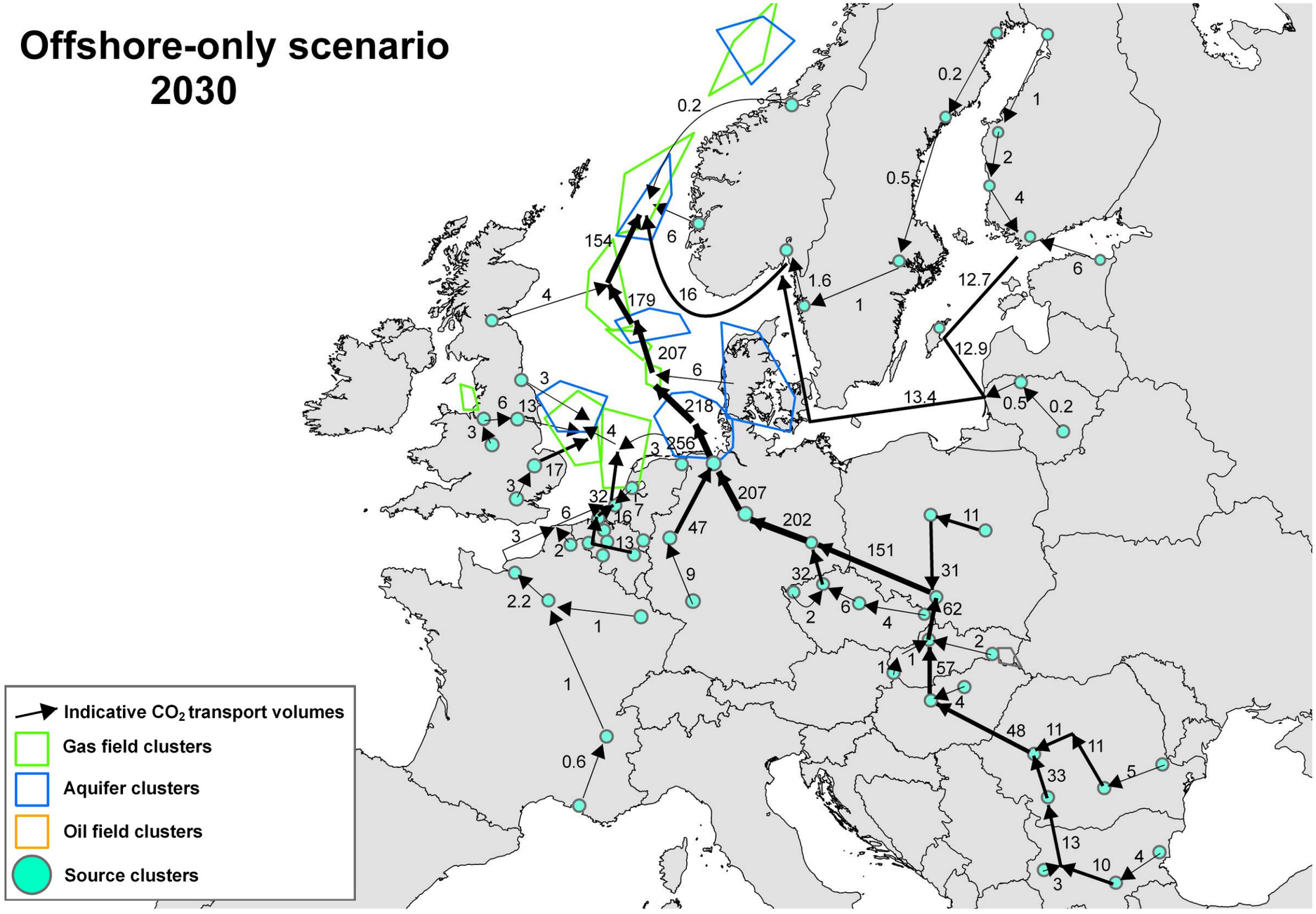

Figure D.8 Flow rates for the offshore-only scenario in 2030.

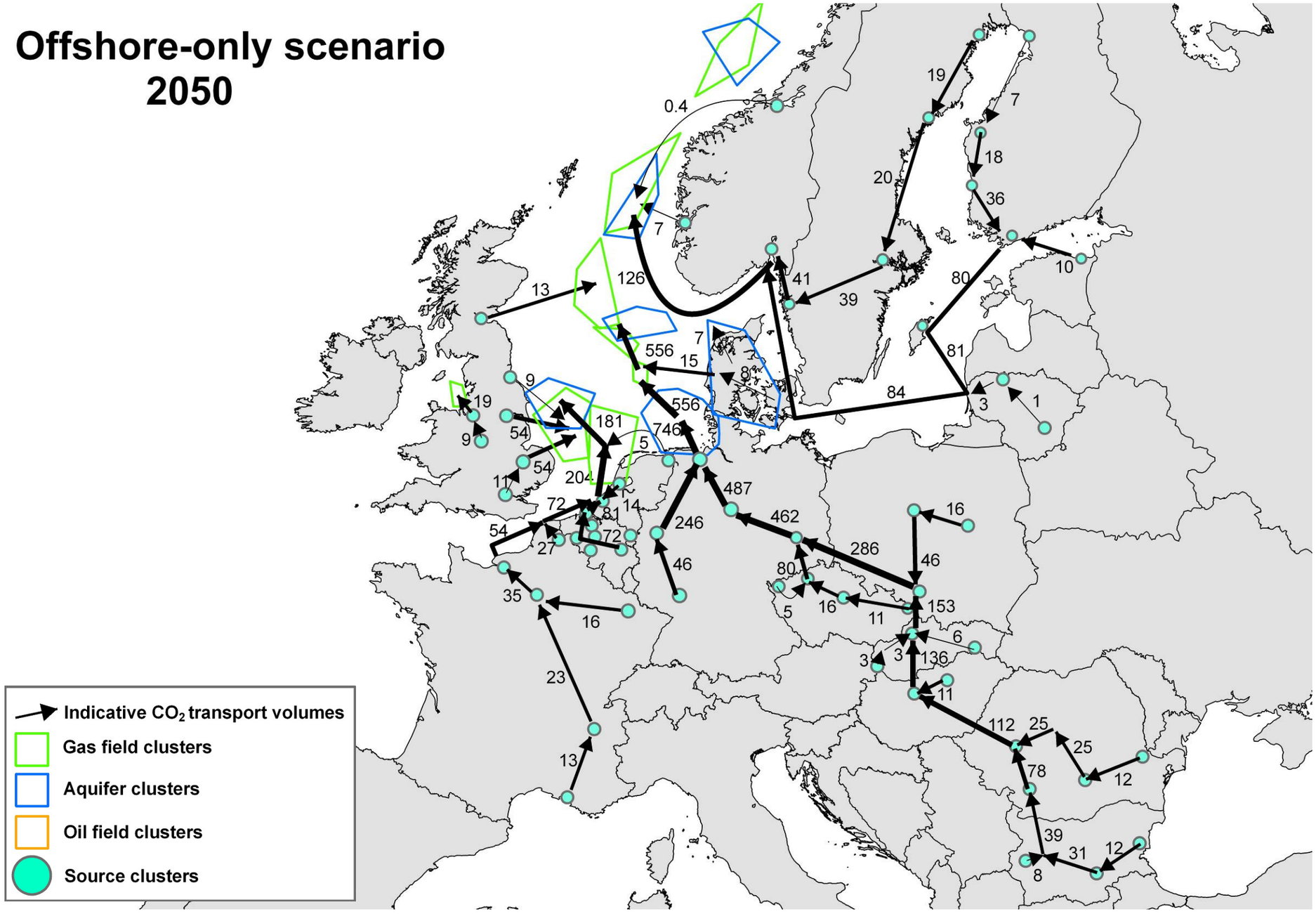

Figure D.9 Flow rates for the offshore-only scenario in 2050.

EOR scenario 2020

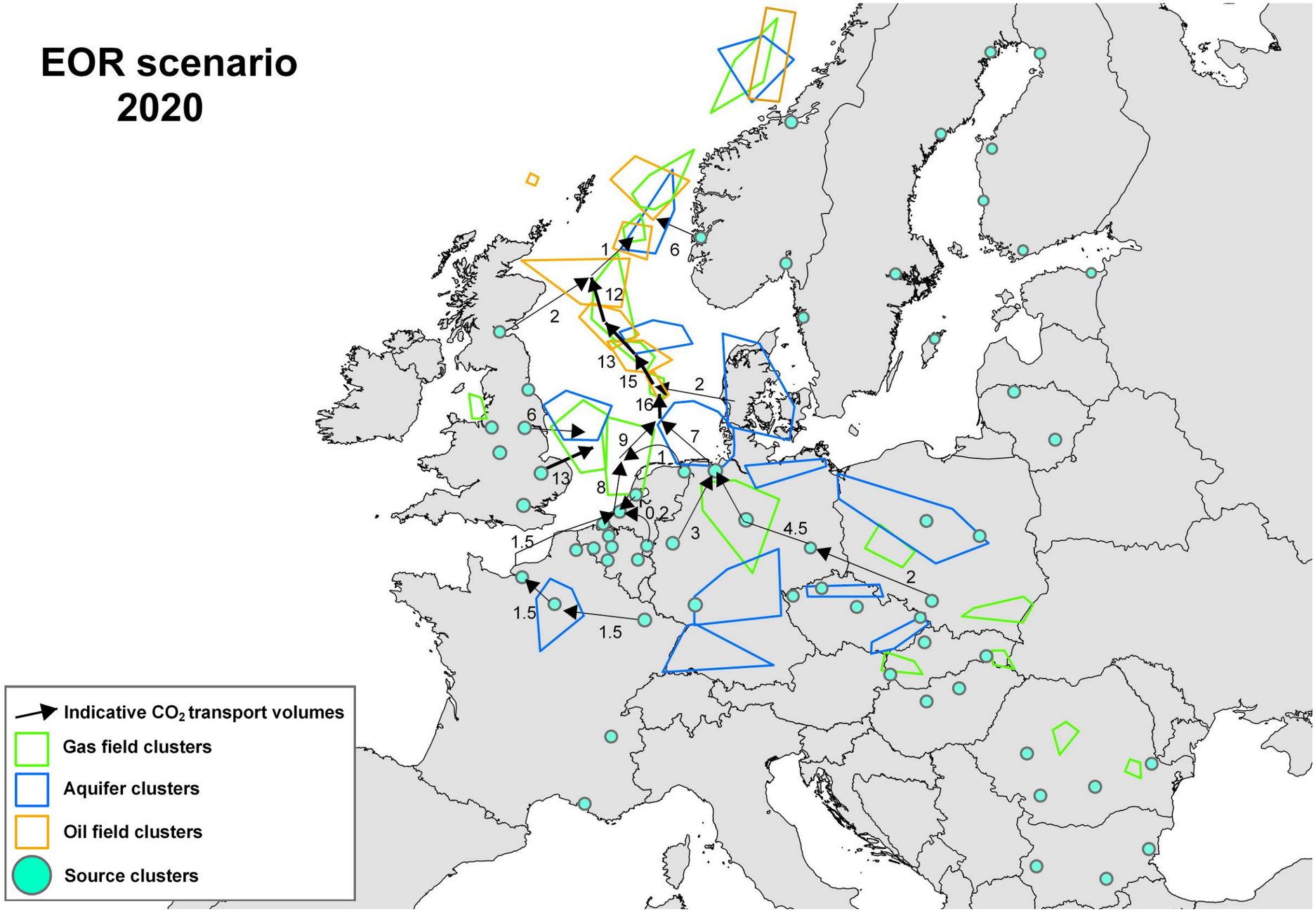

Figure D.10 Flow rates for the EOR scenario in 2020.

EOR scenario 2030

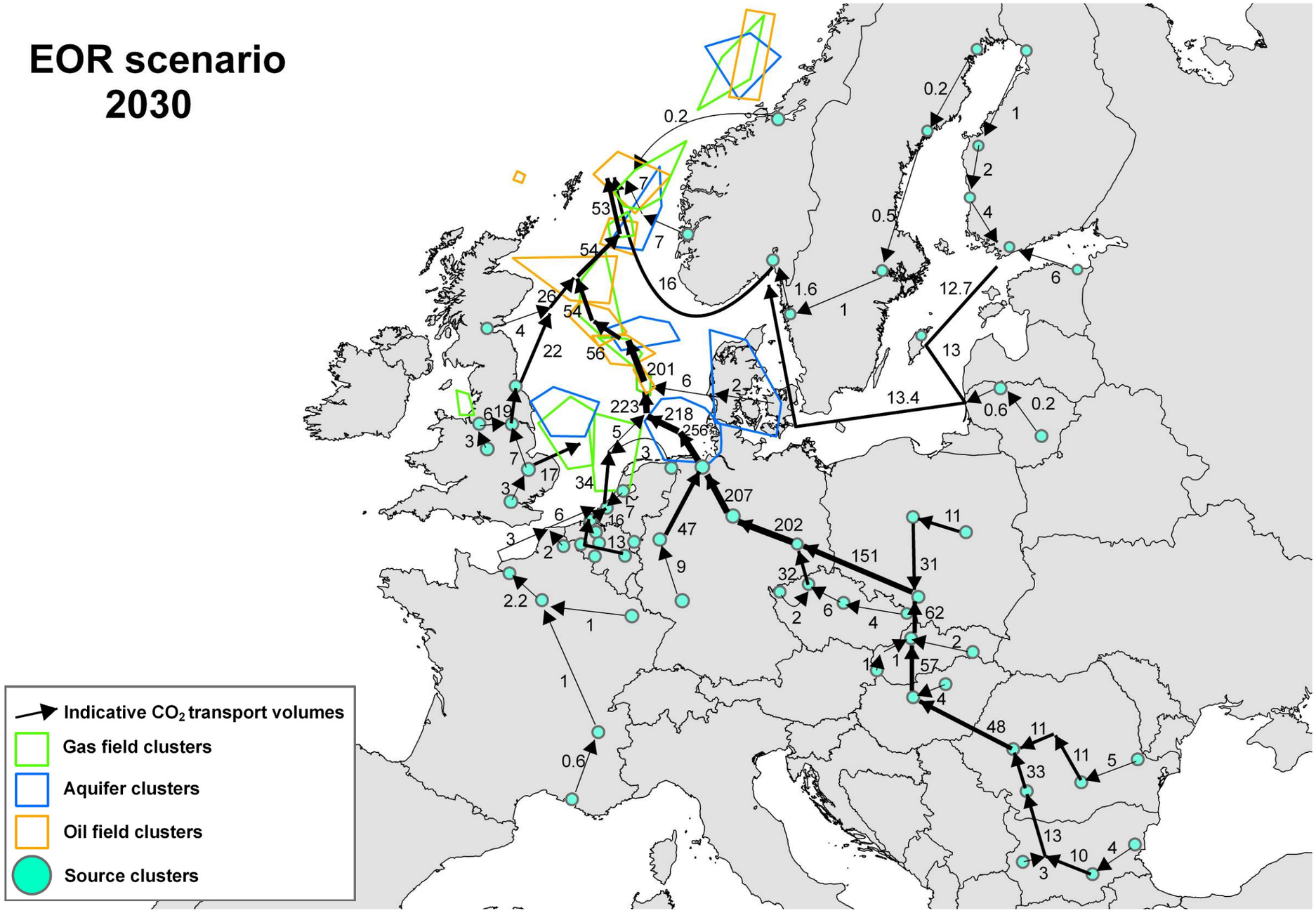

Figure D.11 Flow rates for the EOR scenario in 2030.

EOR scenario 2050

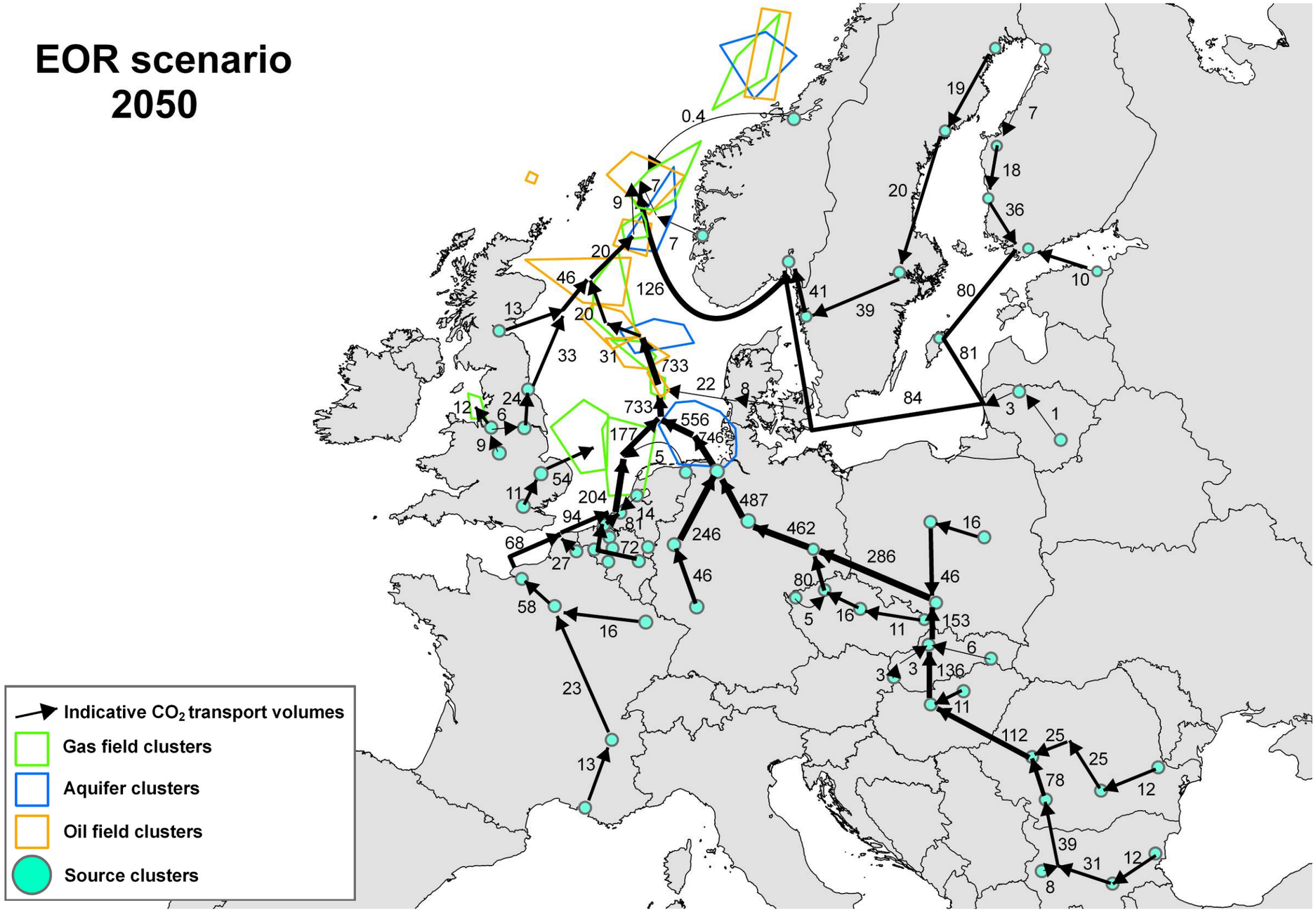

Figure D.12 Flow rates for the EOR scenario in 2050.

APPENDIX E. TRANSPORT ROUTES AND FLOW RATES

Table E-1 Transport routes, lengths and CO_2 flow rates for the reference scenario.

route	length [km]	CO2 flow [Mt/yr] 2020	2030	2050	route	length [km]	CO2 flow [Mt/yr] 2020	2030	2050
NW1	230	6	7	7	**PL3**	465	-	28	-
NW2	680	-	16	113	**PL4**	110	-	15	7
NW3	575	-	0.2	0.4	**CZ1**	145	-	2	5
UK1	200	2	4	13	**CZ2**	155	-	24	59
UK2	265	-	3	9	**CZ3**	165	-	2	5
UK3	190	6	13	18	**CZ4**	95	-	4	10
UK4	180	13	17	54	**HU1**	110	-	4	11
UK5	145	-	3	11	**HU2**	180	-	44	75
UK6	80	-	3	9	**RO1**	220	-	5	8
UK7	110	-	6	-	**RO2**	230	-	11	11
UK8	190	-	-	19	**RO3**	130	-	11	11
NL1	80	1	7	14	**RO4**	180	-	21	39
NL2	255	-	3	30	**RO5**	350	-	36	51
NL3	190	6	16	32	**BG1**	190	-	4	12
NL4	75	1	3	5	**BG2**	210	-	3	8
NL5	210	-	-	32	**EE1**	225	-	6	-
DK1	280	-	2	6	**EE2**	660		-	10
DE1	240	-	9	46	**LT1**	250	-	0	1
DE2	280	3	47	246	**LT2**	135	-	1	-
DE3	240	-	2	12	**LT3**	80	-	-	3
DE4	230	-	30	204	**FI1**	330	-	1	7
DE5	277	3	47	95	**FI2**	160	-	2	18
BE1	220	-	-	21	**FI3**	195	-	4	36
FR1	300	2	2	16	**SE1**	300	-	0	19
FR2	275	-	1	13	**SE2**	450	-	1	20
FR3	615	-	1	23	**SE3**	320	-	1	39
FR4	200	-	2	27	**SE4**	175	-	2	41
FR5	140	-	1	10	**BA1**	390	-	13	70
PL1	330	2	30	87	**BA2**	228	-	13	71
PL2	310	-	11	16	**BA3**	1050	-	13	71

Table E-2 Transport routes, lengths and CO_2 flow rates for the offshore-only scenario.

Route	Length [km]	CO_2 flow [Mt/yr]			Route	Length [km]	CO_2 flow [Mt/yr]		
		2020	2030	2050			2020	2030	2050
NO1	230	6	6	7	**PL1**	330	-	31	46
NO2	680	-	16	126	**PL3**	465	2	151	286
NO3	575	-	0.2	0.4	**PL4**	215	-	11	16
UK1	200	2	4	13	**CZ2**	155	-	2	5
UK2	265	-	3	9	**CZ5**	240	-	4	10
UK3	190	6	13	54	**CZ6**	125	-	6	16
UK4	180	13	13	54	**CZ7**	190	-	32	80
UK5	145	-	3	11	**SK2**	110	-	1	3
UK7	110	-	6	-	**SK3**	55	-	1	3
UK8	190	-	-	19	**SK5**	255	-	2	6
NL1	80	1	7	14	**SK6**	135	-	62	153
NL2	255	-	13	81	**HU1**	110	-	4	11
NL3	190	8	32	204	**HU2**	180	-	57	136
NL6	240	1	4	181	**RO1**	220	-	5	12
NL7	195	0.2	-	-	**RO2**	230	-	11	25
NL8	195	1	3	5	**RO3**	130	-	11	25
DK1	280	2	6	15	**RO4**	180	-	33	78
DK2	200	-	2	8	**RO5**	350	-	48	112
DK3	130	-	-	7	**BG3**	200	-	4	12
DE1	240	-	9	46	**BG4**	230	-	10	31
DE3	240	4.5	207	487	**BG5**	35	-	3	8
DE6	160	4.5	202	462	**BG6**	210	-	13	39
DE7	290	3	47	246	**LT1**	250	-	0.2	1
DE8	150	7	256	746	**LT2**	135	-	0.5	3
EU1	180	-	218	556	**EE1**	225	-	6	10
EU2	210	-	207	556	**SE1**	300	-	0.2	19
EU 3 + 4	200	-	179	-	**SE2**	450	-	0.5	20
EU5	210	-	154	-	**SE3**	320	-	1	39
BE1	220	-	10	72	**SE4**	175	-	1.6	41
FR1	300	1.5	1	16	**FI1**	330	-	1	7
FR2	275	-	0.6	13	**FI2**	160	-	2	18
FR3	615	-	1	23	**FI3**	195	-	4	36
FR5	140	1.5	2	58	**BA1**	390	-	13	80
FR6	315	1.5	3	68	**BA2**	228	-	13	81
FR7	160	1.5	6	94	**BA3**	1050	-	13	84
FR8	85	-	2	27					

Table E-3 Transport routes, lengths and CO_2 flow rates for the EOR scenario.

Route	Length [km]	CO2 flow [Mt/yr]			Route	Length [km]	CO2 flow [Mt/yr]		
		2020	2030	2050			2020	2030	2050
NO1	230	6	6	7	**FR6**	315	1.5	3	68
NO2	680	-	16	126	**FR7**	160	1.5	6	94
NO3	575	-	0.2	0.4	**FR8**	85	-	2	27
NO4	125	-	6	7	**PL1**	330	-	31	46
UK1	200	2	4	13	**PL3**	465	2	151	286
UK3	190	6	-	-	**PL4**	215	-	11	16
UK4	180	13	17	54	**CZ2**	155	-	2	5
UK5	145	-	3	11	**CZ5**	240	-	4	10
UK6	80	-	3	9	**CZ6**	125	-	6	16
UK7	110	-	6	6	**CZ7**	190	-	32	80
UK8	190	-	-	12	**SK2**	110	-	1	3
UK9	240	-	19	24	**SK3**	55	-	1	3
UK10	435	-	22	33	**SK5**	255	-	2	6
UK11	145	1	26	46	**SK6**	135	-	62	153
UK12	155	-	7	-	**HU1**	110	-	4	11
NL1	80	1	7	14	**HU2**	180	-	57	136
NL2	255	-	16	81	**RO1**	220	-	5	12
NL3	190	8	27	189	**RO2**	230	-	11	25
NL7	195	0.2	-	-	**RO3**	130	-	11	25
NL8	195	1	3	5	**RO4**	180	-	33	78
NL9	235	9	5	177	**RO5**	350	-	48	112
DK1	280	2	6	22	**BG3**	200	-	4	12
DK2	200	-	2	8	**BG4**	230	-	10	31
DE1	240	-	9	46	**BG5**	35	-	3	8
DE3	240	4.5	207	487	**BG6**	210	-	13	39
DE6	160	4.5	202	462	**LT1**	250	-	0.2	1
DE7	290	3	47	246	**LT2**	135	-	0.5	3
DE8	150	7	256	746	**EE1**	225	-	6	10
DE13	120	7	218	556	**SE1**	300	-	0.2	19
BE1	220	-	13	72	**SE2**	450	-	0.5	20
EU1	110	16	223	733	**SE3**	320	-	1	39
EU2	210	15	201	733	**SE4**	175	-	1.6	41
EU3	115	13	56	31	**FI1**	330	-	1	7
EU4	170	12	54	19	**FI2**	160	-	2	18
EU5	210	1	54	19	**FI3**	195	-	4	36
FR1	300	1.5	1	16	**BA1**	390	-	13	80
FR2	275	-	0.6	13	**BA2**	228	-	13	81
FR3	615	-	1	23	**BA3**	1050	-	13	84
FR5	140	1.5	2	58					

APPENDIX F. STORAGE CAPACITY

Table F-1 Gas field capacity used for the three scenarios

	Capacity filled								
	Reference scenario			Offshore-only scenario			EOR offshore-only scenario		
Gas field cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO	0	0	0	0	0	0	0	0	0
NO_GB_1	0	0	0	0	0	0	0	0	0
NO_GB_2	0	0	0	0	0	0	0	0	85
NO_GB_4	0	0	0	0	0	0	0	27	277
Scotland	5	36	209	5	158	574	5	15	15
Eastern Irish Sea	0	0	187	0	0	187	0	0	124
Southern North Sea	47	299	1424	49	329	1498	47	191	767
DK	0	9	91	5	101	423	0	87	419
NL offshore	15	175	755	20	210	790	0	160	800
NL	4	25	881	0	0	0	0	0	0
NL_2	0	0	0	0	0	0	0	0	0
DE	0	124	1172	0	0	0	0	0	0
PL_2	0	75	295	0	0	0	0	0	0
PL_3	0	53	294	0	0	0	0	0	0
CZ	0	0	0	0	0	0	0	0	0
HU	0	0	0	0	0	0	0	0	0
SK	0	13	47	0	0	0	0	0	0
SK_2	0	10	49	0	0	0	0	0	0
RO	0	0	66	0	0	0	0	0	0
RO_2	0	0	20	0	0	0	0	0	0
Total	**70**	**818**	**5489**	**79**	**797**	**3471**	**52**	**480**	**2487**

Table F-2 Oil field capacity used for the three scenarios

	Capacity filled								
	Reference scenario			Offshore-only scenario			EOR offshore-only scenario		
Oil field cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO	0	0	0	0	0	0	0	0	0
NO_GB_1	0	0	0	0	0	0	0	622	3200
NO_GB_2	0	0	0	0	0	0	3	15	135
NO_GB_3	0	0	0	0	0	0	27	210	932
NO_GB_4	0	0	0	0	0	0	2	16	150
GB_1	0	0	0	0	0	0	0	0	0
NO_GB_DK	0	0	0	0	0	0	5	37	124
DK	0	0	0	0	0	0	8	77	244
PL_2	0	0	0	0	0	0	0	0	0
HU	0	0	0	0	0	0	0	0	0
RO_1	0	0	15	0	0	0	0	0	0
RO_2	0	0	99	0	0	0	0	0	0
RO_3	0	0	15	0	0	0	0	0	0
DE	0	0	0	0	0	0	0	0	0
Total	**0**	**0**	**129**	**0**	**0**	**0**	**45**	**977**	**4785**

Table F-3 Aquifer capacity used for the three scenarios

	Capacity filled								
	Reference scenario			Offshore-only scenario			EOR offshore-only scenario		
Aquifer cluster	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
NO	0	0	0	0	678	8364	0	432	8076
NO_2	15	159	1589	15	365	2340	15	45	45
NO_3	0	0	0	0	0	0	0	0	0
GB	0	0	0	0	0	1809	0	0	0
GB_2	0	0	0	0	0	0	0	0	0
DK	5	34	227	0	0	70	0	0	0
DE	0	0	0	13	230	2510	0	190	2470
DE_1	13	423	4182	0	0	0	0	0	0
DE_2	0	0	0	0	0	0	0	0	0
DE_3	0	0	0	0	0	0	0	0	0
NL	0	0	0	0	0	0	0	0	0
BE	0	50	659	0	0	0	0	0	0
FR	4	39	1036	0	0	0	0	0	0
PL	5	191	1740	0	0	0	0	0	0
CZ	0	43	548	0	0	0	0	0	0
CZ_2	0	129	1034	0	0	0	0	0	0
LV	0	0	125	0	0	0	0	0	0
LT	0	0	0	0	0	0	0	0	0
SK	0	246	1661	0	0	0	0	0	0
BU	0	64	585	0	0	0	0	0	0
Total	**41**	**1375**	**13383**	**28**	**1272**	**15092**	**15**	**667**	**10591**

Table F-4 Remaining capacity and percentage filled of gas field clusters in 2050 for the three different scenarios.

	Reference scenario		Offshore-only scenario		EOR scenario	
Gas field cluster	Capacity left [Mt]	% filled	Capacity left [Mt]	% filled	Capacity left [Mt]	% filled
NO	2259	0	2259	0	2259	0
NO_UK_1	5066	0	5066	0	5066	0
NO_UK_2	1113	0	1113	0	1028	8
NO_UK_4	479	0	479	0	203	58
Scotland	503	29	139	81	697	2
Eastern Irish Sea	859	18	859	18	922	12
Southern North Sea	540	73	465	76	1196	39
DK	333	21	2	100	5	99
NL offshore	45	94	10	99	0	100
NL	1062	45	1943	0	1943	0
DE	1090	52	2262	0	2262	0
PL_2	1	100	296	0	296	0
PL_3	124	70	418	0	418	0
SK	1	99	47	0	47	0
SK_2	1	99	49	0	49	0
RO	99	40	165	0	165	0
RO_2	30	40	50	0	50	0
Total	**13727**	**29**	**15745**	**18**	**16729**	**13**

Table F-5 Remaining capacity and percentage filled for oil field clusters in 2050 for the three different scenarios.

	Capacity overview in 2050					
	Reference scenario		Offshore-only scenario		EOR scenario	
Oil field cluster	Capacity left [Mt]	% filled	Capacity left [Mt]	% filled	Capacity left [Mt]	% filled
NO	81	0	81	0	81	0
NO_UK_1	3302	0	3302	0	103	97
NO_UK_2	230	0	230	0	95	59
NO_UK_3	996	0	996	0	64	94
NO_UK_4	187	0	187	0	37	80
UK_1	126	0	126	0	126	0
NO_UK_DK	126	0	126	0	2	98
DK	246	0	246	0	2	99
PL_2	7	0	7	0	7	0
HU	15	0	15	0	15	0
RO_1	0	100	15	0	15	0
RO_2	117	46	216	0	216	0
RO_3	0	100	15	0	15	0
DE	56	0	56	0	56	0
Total	**5489**	**2**	**5618**	**0**	**834**	**85**

Table F-6 Remaining capacity and percentage filled of aquifer clusters in 2050 for the three different scenarios.

	Capacity in 2050					
	Reference scenario		Offshore-only scenario		EOR scenario	
Aquifer cluster	Capacity left [Mt]	Percentage filled	Capacity left [Mt]	Percentage filled	Capacity left [Mt]	Percentage filled
NO	26507	0	18144	32	18431	30
NO_2	123778	1	123158	2	125453	0
NO_3	30210	0	30210	0	30210	0
GB	14304	0	12495	13	14304	0
GB_2	655	0	655	0	655	0
DK	16445	1	16602	0.4	16671.94	0
DE	6361	0	3851	39	3891	39
DE_1	14387	21	20003	0	20003	0
DE_2	1630	0	1630	0	1630	0
DE_3	2126	0	2126	0	2126	0
NL	438	0	438	0	438	0
BE	1392	47	1392	0	1392	0
FR	20519	5	21555	0	21555	0
PL	1438	49	3522	0	3522	0
CZ	566	49	1113	0	1113	0
CZ_2	650	61	1684	0	1684	0
LV	298	30	423	0	423	0
LT	41.5	0	42	0	42	0
SK	12047	12	13708	0	13708	0
BU	2072	22	2657	0	2657	0
Total	**277117**	5	**275407**	5	**279909**	4

APPENDIX G. INFRASTRUCTURE DEVELOPMENT

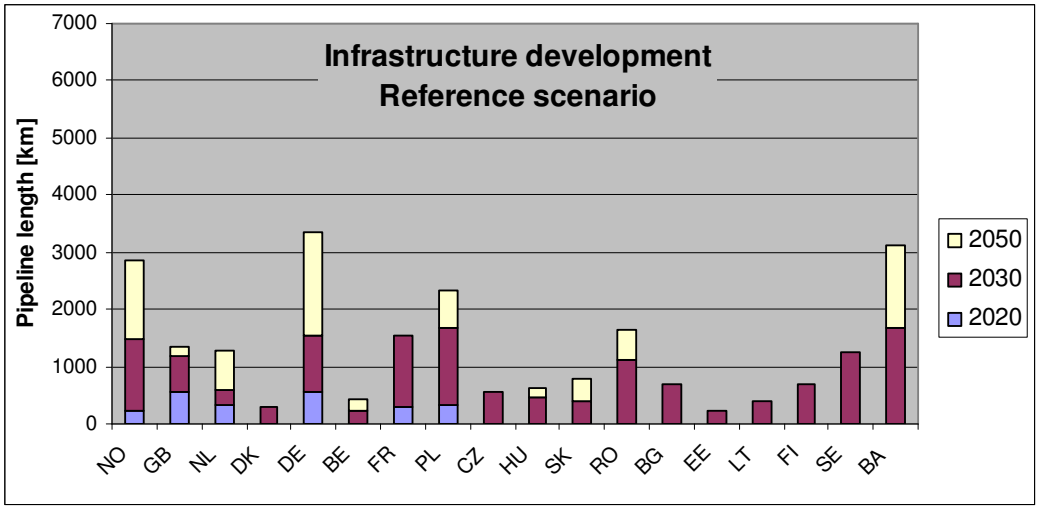

Figure G.1 National infrastructure development for the reference scenario.

Table G-1 Total transport length by country for the reference scenario.

	pipeline length [km]		
	2020	**2030**	**2050**
NO	230	1485	2845
GB	570	1170	1360
NL	345	600	810
DK	-	280	280
DE	557	1267	3354
BE	-	220	440
FR	300	1530	1530
PL	330	1215	2010
CZ	-	560	560
HU	-	290	470
RO	-	1110	1460
BG	-	400	400
EE	-	225	885
LT	-	385	385
FI	-	685	685
SE	-	1245	1245
BA	-	1668	3108
Total	**2332**	**14335**	**21827**

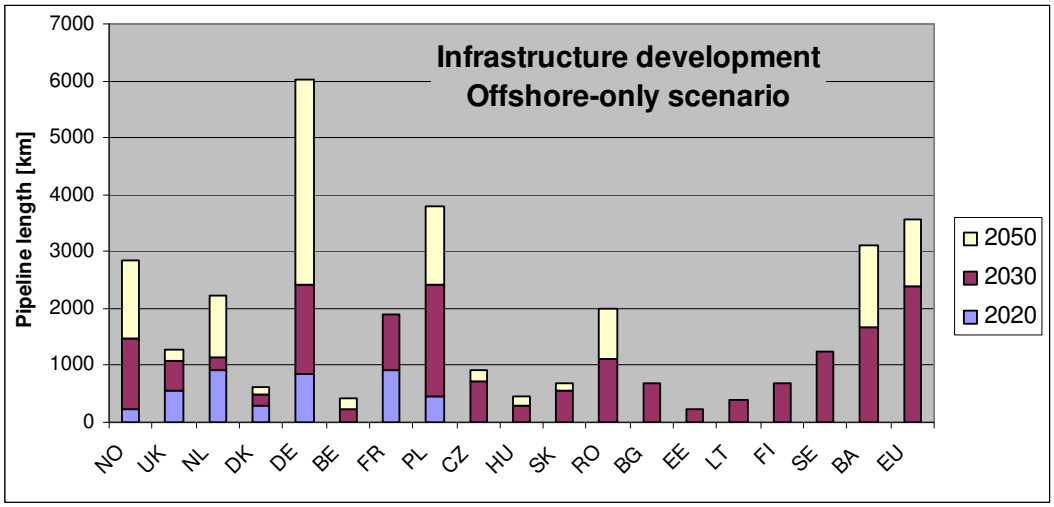

Figure G.2 National infrastructure development for the offshore-only scenario.

Table G-2 Total transport length by country for the offshore-only scenario.

	pipeline length [km]		
	2020	**2030**	**2050**
NO	230	1485	2845
UK	570	1090	1280
NL	900	1155	2215
DK	280	480	610
DE	840	2960	7100
BE	-	220	440
FR	915	1890	1890
PL	465	2405	3800
CZ	-	710	900
HU	-	290	470
SK	-	555	690
RO	-	1110	1990
BG	-	675	675
EE	-	225	225
LT	-	385	385
FI	-	685	685
SE	-	1245	1245
BA	-	1668	3108
EU	-	1860	2490
Total	**4200**	**19233**	**33043**

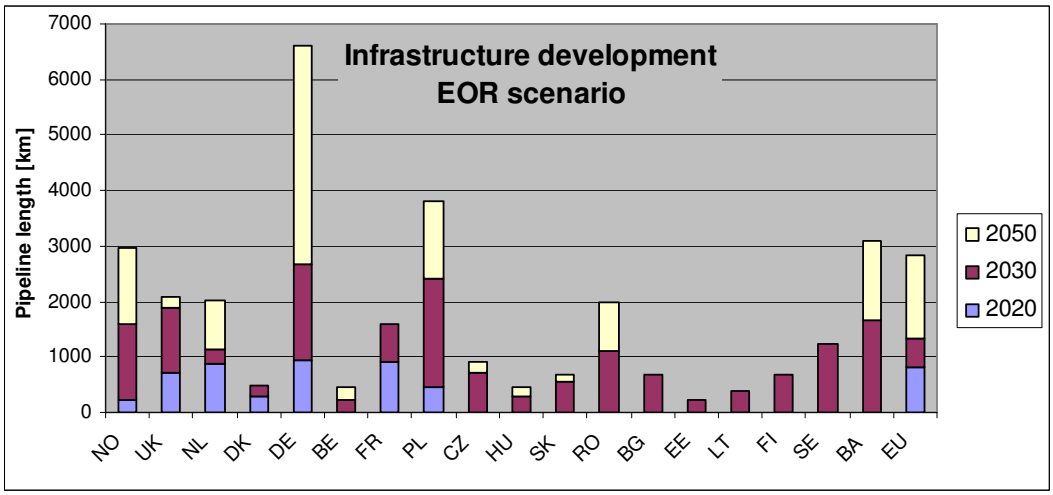

Figure G.3 National infrastructure development for the EOR scenario.

Table G-3 Total transport length by country for the EOR scenario.

	pipeline length [km]		
	2020	**2030**	**2050**
NO	230	1610	2970
UK	715	1880	2070
NL	895	1150	2020
DK	280	480	480
DE	960	2660	6620
BE	-	220	440
FR	915	1590	1590
PL	465	2405	3800
CZ	-	710	900
HU	-	290	470
SK	-	555	690
RO	-	1110	1990
BG	-	675	675
EE	-	225	225
LT	-	385	385
FI	-	685	685
SE	-	1245	1245
BA	-	1668	3108
EU	815	1345	2835
Total	**5275**	**20888**	**33198**

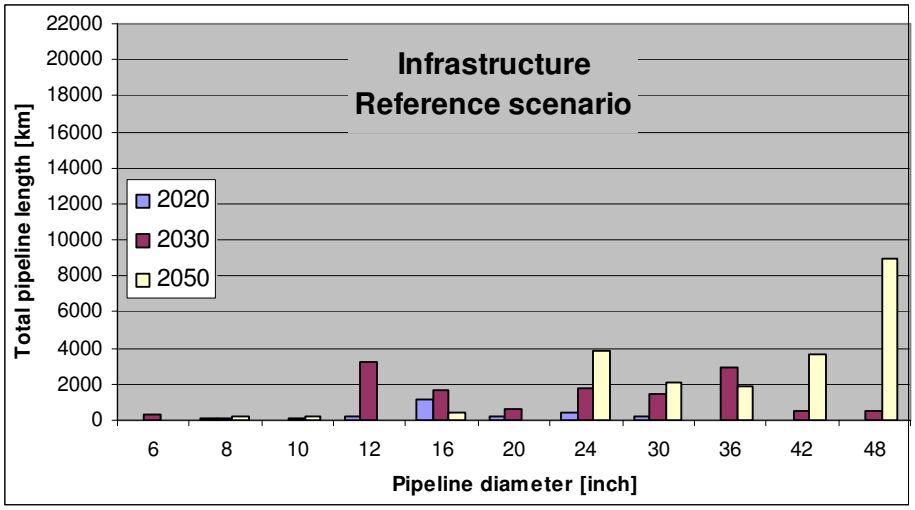

Figure G.4 Required pipeline length per diameter for the reference scenario.

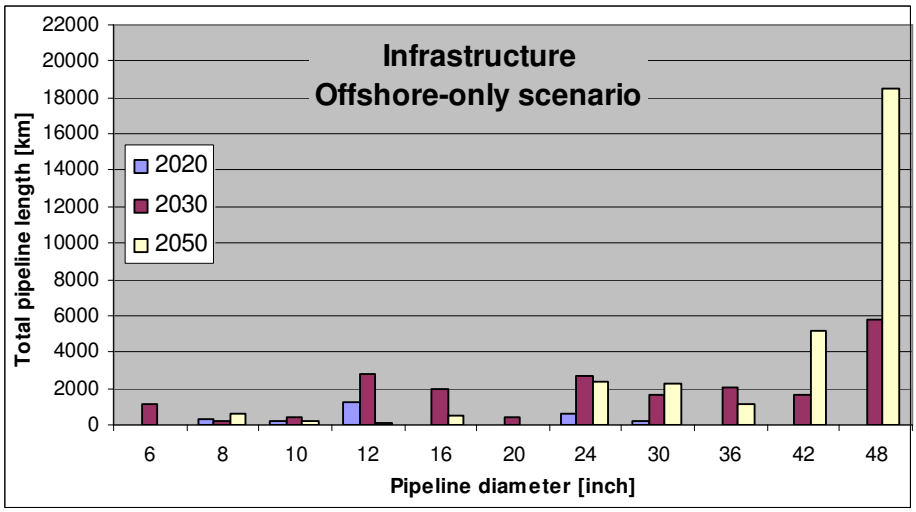

Figure G.5 Required pipeline length per diameter for the offshore-only scenario.

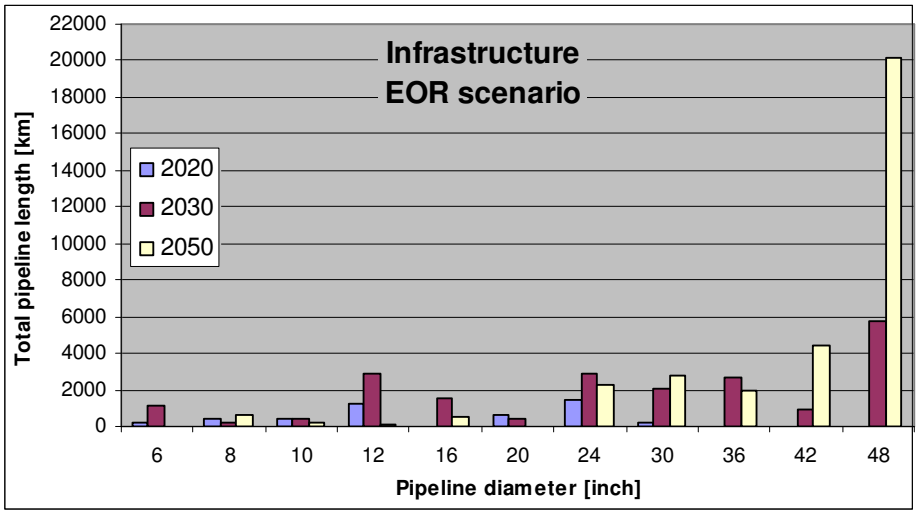

Figure G.6 Required pipeline length per diameter for the EOR scenario.

APPENDIX H. CROSS BORDER TRANSPORT

Cumulative cross border transport of CO_2 [Mt/yr] represents the absolute amounts of CO_2 transported across the border. It can include CO_2 from countries in the hinterland. Net cross border transport of CO_2 [Mt/yr] represents the amount of CO_2 stored abroad.

Table H-1 Total CO_2 captured and net cross-border transport [%] by country for the reference scenario

		Net cross border transport [Mt/yr]					
		2020		2030		2050	
From	To	[Mt/yr]	%	[Mt/yr]	%	[Mt/yr]	%
BE	NL	-	0	-	0	15	23
PL	DE	-	0	28	31	-	0
RO	SK	-	0	36	100	51	71
HU	SK	-	0	9	100	25	100
LT	NO	-	0	0.5	100	-	0
LT	LV	-	0	-	0	3	100
EE	NO	-	0	6	100	-	0
EE	LV	-	0	-	0	10	100
FI	NO	-	0	7	100	70	100
SE	NO	-	0	2	100	41	100
Total		**0**	**0**	**89**	**25**	**215**	**18**

Table H-2 Total CO_2 captured and net cross-border transport [%] by country for the offshore-only scenario.

		Net cross border transport [Mt/yr]					
		2020		2030		2050	
From	**To**	**[Mt/yr]**	**%**	**[Mt/yr]**	**%**	**[Mt/yr]**	**%**
NL	UK	-	0	-	0	21	43
FR	NL	0.4	27	3	60	-	0
BE	NL	-	0	8	78	-	0
FR	UK	1.1	73	2	40	94	100
BE	UK	-	0	2	22	66	100
DE	DK	-	0	12	16	-	0
DE	NO		0	24	32	189	50
PL	DE	1.8	100	-	0	-	0
PL	NO	-	0	89	100	133	100
CZ	NO	-	0	27	85	80	100
SK	NO	-	0	-	0	17	100
HU	NO	-	0	4	43	25	100
RO	NO	-	0	31	86	72	100
BG	NO	-	0	8	62	39	100
CZ	UK	-	0	5	15	-	0
SK	UK	-	0	5	100	-	0
HU	UK	-	0	5	57	-	0
RO	UK	-	0	5	14	-	0
BG	UK	-	0	5	38	-	0
LT	NO	-	0	0.5	100	3	100
EE	NO	-	0	6	100	10	100
FI	NO	-	0	7	100	70	100
SE	NO	-	0	2	100	41	100
Total		**3**	**7**	**249**	**70**	**861**	**70**

Table H-3 Total CO_2 captured and net cross-border transport [%] by country for the EOR scenario.

Net cross border transport [Mt/yr]							
		2020		2030		2050	
From	**To**	**[Mt/yr]**	**%**	**[Mt/yr]**	**%**	**[Mt/yr]**	**%**
NL	DK/UK/NO	-	0	5	23	17	34
FR	NL	2	100	6	100	-	0
FR	DK/UK/NO	-	0	-	0	94	100
BE	NL	-	0	10	100	-	0
BE	DK/UK/NO	-	0	-	0	66	100
DE	DK/UK/NO	5	100	35	48	189	50
PL	DK/UK/NO	2	100	89	100	133	100
CZ	DK/UK/NO	-	0	32	100	80	100
SK	DK/UK/NO	-	0	5	100	17	100
HU	DK/UK/NO	-	0	9	100	25	100
RO	DK/UK/NO	-	0	36	100	72	100
BG	DK/UK/NO	-	0	13	100	39	100
LT	NO	-	0	0.5	100	3	100
EE	NO	-	0	6	100	10	100
FI	NO	-	0	7	100	70	100
SE	NO	-	0	2	100	41	100
Total		**9**	**19**	**254**	**71**	**857**	**70**