BARRIERS TO IMPLEMENTATION OF CCS: CAPACITY CONSTRAINTS

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BACKGROUND TO THE STUDY

As part of its on-going work programme, the IEA Greenhouse Gas R&D Programme (IEAGHG) has undertaken a number of studies to assess potential barriers to the implementation of Carbon Capture and Storage (CCS). In the latest study in this series, the IEAGHG looks to explore whether there are supply and capacity constraints associated with equipment for CCS plants that might cause issues with CCS implementation. A related earlier study by the IEA Clean Coal Centre for new build coal fired power plant identified that there are potential areas of supply constraints in key components like castings for gas turbines and basic raw materials like steel and cement for plant construction. This study aims to build upon this earlier work by looking at the CCS components for new build plant to see if there are any additional critical component issues.

The IEA Technology Roadmap for CCS has been taken as the reference case for the study because it proposes an aggressive deployment strategy for CCS up to 2050[1]. This reference case, envisaged that 100 CCS projects need to be deployed by 2020 and suggested that by 2050 alone, up to 150Gt of CO_2 will need to have been captured and stored if CCS is to make the required contribution towards constraining temperate rise at 2^0C by 2050. To achieve such targets CCS will be ramping up production rapidly (at the same time as other low carbon technologies) and issues may arise regarding materials/equipment and services supply that need to be identified early to ensure that these issues do not represent barriers to the implementation of CCS.

A contract for this study was awarded to Ecofys, B.V. of the Netherlands.

SCOPE AND APPROACH TAKEN

The study tried to be as comprehensive as possible but to limit the scale of the study some compromises had to be made. The study was based on global requirements and essentially used a high level approach and did not consider regional differences in skills, manufacturing bases etc., The study considered the full CCS chain, i.e. capture, compression, transport and storage of CO_2 but excluded the power/industry equipment prior to the capture plant. It was considered that the manufacturing constraints for the equipment preceding the capture plant

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[1] The CCS Technology roadmap (IEA, 2011) builds on the IEA BLUE Map scenario in Energy Technology Perspectives 2010 (IEA, 2010), which combines the deployment of different (low carbon) technologies to achieve global CO_2 emission reductions: from just below current 30 $GtCO_2$ to 14 $GtCO_2$ by 2050 (the baseline scenario results in 57 GtCO2). In the BLUE Map scenario CCS contribution to the emission reduction in 2050 – compared to the base line scenario - is 19 %.

were already understood. For example, components needed in coal fired power plants were covered by an earlier IEA Clean Coal Centre report[2]. As far as the capture plants were considered, the focus of the study was on current state-of-the-art technologies, including pre-combustion, post-combustion and oxyfuel combustion technologies. Second generation capture technologies (i.e. solid looping, membrane technology etc.,) were not considered in the study, because it was felt that being at an early stage of their development it would be difficult to quantify future component needs and manufacturing constraints. The sectors considered were the heavy manufacturing industry, power generation and upstream oil and gas. The upstream oil and gas sector includes fuel and gas processing and is regarded as a sector with many opportunities for low-cost capture that will arise in the future as new gas resources come on stream in regions like South East Asia that have high CO_2 contents. For CO_2 transport the study focused on transport by pipeline only. It was considered that apart from offshore CO2-EOR operations the bulk of the CO_2 transported for emissions reduction will be by pipeline in the period of the scope of the review. Other transport mediums such as ship, truck and train were not considered for reasons that included lack of capacity (truck and train) and because the technology is not yet fully developed in the case of ships. CO_2 storage capacity assessment constraints were not included in the supply chain; this subject is covered in a separate IEAGHG report[3].

Prior to undertaking the detailed analysis the contractor first considered the scale of construction implied by the IEA CCS Road Map. The Road Map requires 100 CCS projects to be installed by 2020 capturing some 500 Mt/CO_2/yr. and 3,500 by 2050 capturing some 10,000 Mt/CO_2/yr.; an overall increase of 9.5Gt/CO_2/yr. in 30 years. The consultants then compared the rollout of the technology as required by the Road Maps implementation rate to prior developments in the power, industry and oil and gas extraction sectors. The aim of this exercise was to determine whether manufacturing constraints will arise depending on, amongst other factors, the deployment rates considered in the IEA CCS Roadmap.

Supply constraints were divided into those relating to **Equipment & Materials** and those relating to **Services & Skills**. The figure 1 overleaf outlines the approach used. Figure 1 shows that the operation of power plants with CO_2 capture requires human resources and raw materials (e.g. chemicals or metals). In essence, all parts of the supply chain(s) that are necessary to plan, design, construct and operate a (part of the) CCS chain require human resources and raw materials or sub-components from other industries or from the natural environment. In each part of the chain, a constraint may occur. This can be due to scarcity of natural resources, or the limited production capacity of a component, or a shortage of specialist technical skills, e.g. welders, drilling rig operators, electrical engineers etc.

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[2] “Meeting the demand for new coal-fired power plants”. IEA CCC Report No. 141. November 2008. ISBN 978-92-9029-460-3.

[3] IEAGHG Report No 2011-10, Global Storage Resources Gap Analysis for Policy Makers, November 2011.

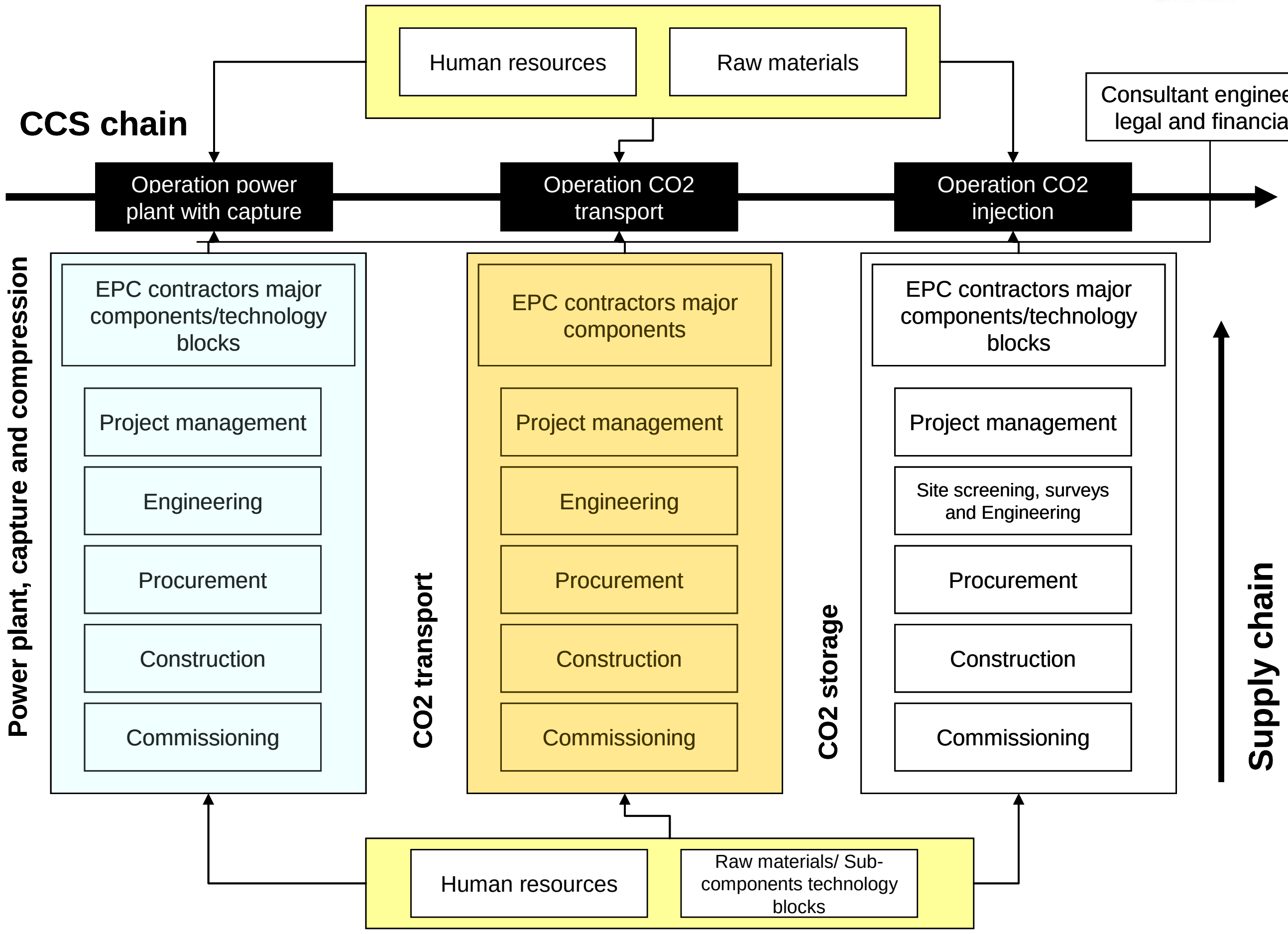


Figure 1 Graphical representation of the supply chains for CCS technologies. Horizontally the CCS chain is shown. Vertically the supply chain is shown for the three parts of the CCS chain.

Note EPC refers to: Engineering, Procurement and Construction

It was considered impossible to assess all components in a CCS chain (i.e. to the level of bolts and screws), so the contractors limited themselves to the main components in the CCS installations. In each case an equipment list was drawn up and from this the contractor selected components, using a screening assessment process, which is detailed in Chapter 3 of the main report. For human resources, the contractor considered job profiles that are needed for capture, transport or storage activities. Each individual component identified is then assessed in detail in Chapter 5 of the main report. Note: whilst regulatory/permitting approvals could also be considered as part of the CCS chain these were not considered as part of the scope of this study.

Results and Discussion

With regard to the envisaged technology roll out suggested in the IEA CCS Road map; the following points were noted:

- The highest growth rates in coal fired power capacity in the 20th century were achieved in 1950-1960 in OECD countries. In that period, the average annual growth rate (in power capacity) was 19%. To achieve the targets in the CCS Roadmap, the annual growth in coal CCS projects must reach an average of 17 GW (15 installations) per year in the period 2020-2030, 29 GW (24 installations) per year between 2030 and 2040 and 28 GW (22 installations) per year over the period 2040-2050. To compare, the deployment rate of coal-fired power plants globally in the period 1960 to 2000 was about 130 installations (27 GW) per year. The historical construction is therefore comparable to the needed future building rate of coal-fired power plants with capture installations. Over the last five years, there was a sharp increase in the construction rate of coal-fired power plants. This induced many supply chain problems, which are set out in the main report but include. For example, in China alone, more than 100 GW was under construction in 2009 (IEA, 2009b).

- For natural gas in terms of both the number of projects and the capacity per year, the historical building rate exceeds the projected future building rate of gas-fired CCS installations in the power sector. To achieve the targets in the CCS Roadmap, the annual growth in CCS projects in NG-fired power plants must reach an average of 4 GW (12 installations) per year in the period 2020-2030, 11 GW (37 installations) per year between 2030 and 2040 and 20 GW (63 installations) per year over the period 2040-2050. In comparison, the historical deployment rate in the period, 1960-1980 was approximately 170 installations (12 GW) annually. The building rate increased sharply in the period 1980-2000 to over 500 installations (24 GW) annually. In 2002, the construction rate peaked at 1,000 installations and 72 GW. This assures us that with the engineering resources power plant build rates as required by the CCS Roadmap could be attainable in the future.

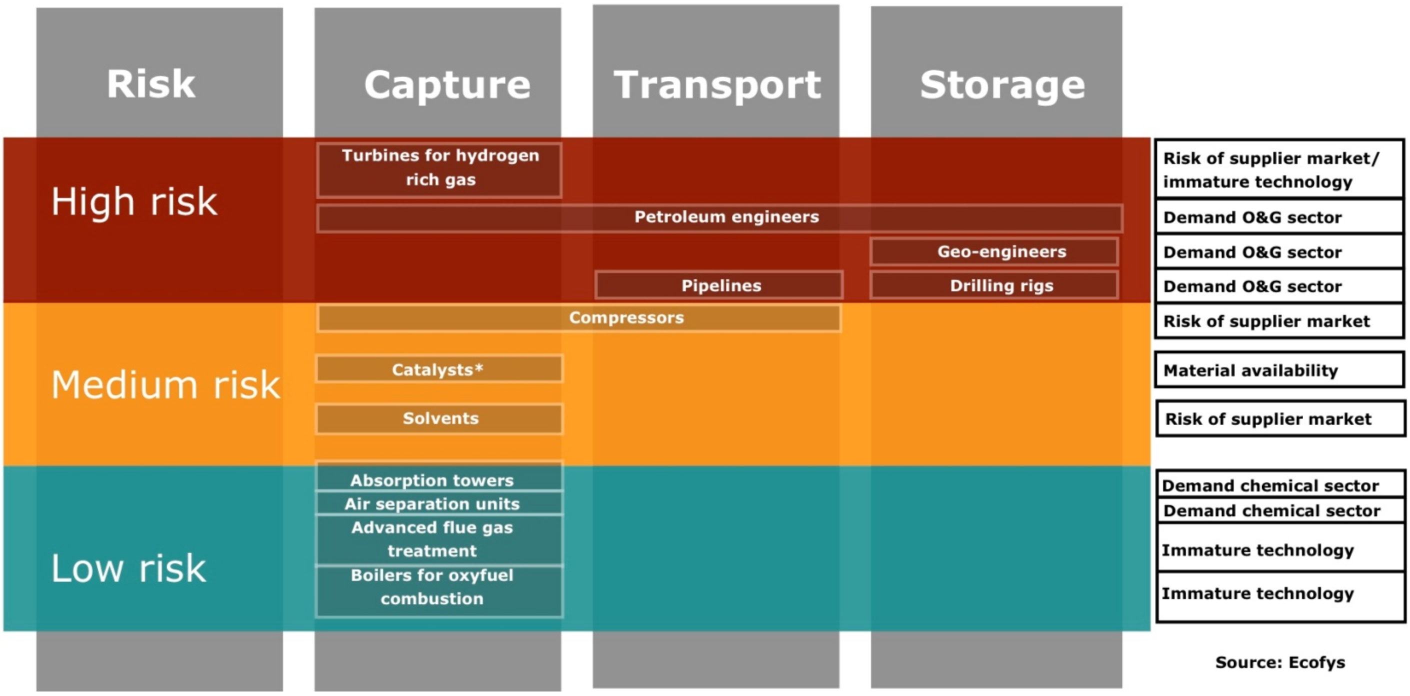
However it must be noted that the underlying assumptions in ETP 2010 requires high construction rates not just for coal fired power plants, but nuclear, wind and solar PV at the same time. It was felt there are no major components used in these technologies that were also needed for the CCS chain. Large-scale deployment of nuclear power and renewables might directly and indirectly compete for resources with CCS such as:

- technically skilled personnel for the construction of nuclear power plants
- drilling rigs for deep geothermal power production
- offshore cable laying vessels for offshore wind, or engineers that consider a career in wind power instead of CCS technology

In 2006, industrial emissions totalled 6.8 GtCO_2. The CCS Roadmap envisages 4.5 GtCO_2 captured annually by 2050 in the industry and upstream sector, i.e. about 65% of current industrial emissions. To achieve this, CCS in industry would need to grow 23% annually (in terms of captured emissions) between 2020 and 2030. There are no historical build rate data to compare with for industry plant. For industry it is probably optimistic to think this rate of CCS introduction can be achieved.

To gain an understanding of the magnitude of the transport and storage operations, the contractor compared the amount of captured and stored CO_2 in the CCS Roadmap with the annual production of crude oil and natural gas. After 2045, the CO_2 transport and injection capacity must be larger than the total transport and extraction capacity for oil and gas production. CCS shares part of the supply chain with the oil and gas sector; labour (e.g. experienced geo-scientists) and large facilities (e.g. ships, platforms and drilling rigs). Substantial competition between CCS industry and the oil and gas industry can be expected (especially in the field of transport and storage).

An overview of the potential of supply chain constraints for the assessed equipment and services and skills, is given in figure 2. Note: the figure is constructed around a risk element; that is the risk of a component in the CCS chain causing a capacity supply constraint. The causes of the high risk categories for individual components in the supply chain in each case are listed at the right of the diagram. The components that represent a high risk of causing a supply constraint are mainly related to storage and transport. These include: large scale pipelines (limited number of manufacturers with full order books) and availability of drilling rigs, competition from the oil and gas sector for petroleum engineers and geo-scientists and the availability of large CO_2 compressors (limited number of manufacturers with proven technology). For capture, supply chain issues are considered for pre-combustion capture namely hydrogen rich gas turbines as these are not yet commercially available or proven. Other low to medium supply risks are for catalysts, absorption towers, ASUs, and advanced flue gas treatment.



Source: Ecofys

Figure 2: Potential Supply Chain Constraints

For capture, supplier concentration is the main risk

Some components, such as advanced flue gas treatment, solvents and hydrogen rich gas turbines are still under development. There is a potential risk that the ‘winning’ technology results in a high supplier concentration; this makes it attractive for EPC contractors to vertically integrate their supply chain. Vertical integration in the chain may result in large conglomerations/joint ventures across the supply and value chain. One tipping point in the chain may result in constraints across the whole chain. For example, if one company offers a capture block and the preferred supplier is not able to meet demand, then the whole capture block faces longer lead times. It reduces risk for parties involved, but may create supplier dominated market conditions and result in inflexible markets.

An historical comparison showed that technological developments and knowledge diffusion can be realised within a relatively short time if sufficient demand-pull (via regulations/obligations/standards) is in place.

Differences in supply chain constraints for the various capture technologies

Based on the analysis undertaken, no firm conclusion can be drawn on which capture technology has the most significant supply chain constraints. All three capture technologies have components that may form a potential risk and may be a barrier for large scale deployment of CCS. For pre-combustion it is the gas turbine; for oxyfuel it is the; ASU, flue gas treatment and boiler; and for post-combustion it is expected to be the large scale absorbers and perhaps ‘monopolized’ solvents. Based on the methodology used in this study and current data availability it is not possible to firmly conclude on what the effect of any of these supply chain bottlenecks occurring would be on the deployment and market share of the three capture technologies.

Detailed data (i.e. below the level of EPC, large technology providers) on the CCS supply chain in many cases is difficult to collect, because of three main reasons. The first is that the supply chain of the large EPC contractors entails a large number of suppliers and sub-contractors which would require a more extensive study to map them all. The second reason is that competitive reasons limit the disclosure and thus an overview of all suppliers and sub-contractors in the supply chain to the EPC contractors. The third reason is that a detailed overview of the supply chain is mostly relevant for the short term (typically <5 years). Long-term dynamics in the full supply chain are extremely difficult to assess on a detailed level.

Meeting global demand for compressors and large scale CO_2 pipelines will be challenging task

CO_2 compressors are mature for lower pressure ranges but require R&D for the high pressure ranges often necessary for offshore CO_2 transport. All CCS projects would require compressors and it therefore faces high demands. Together with competition for natural gas compressors needed in the oil and gas industry, this may lead to shortage in supply capacity.

Pipe laying capacity faces competition with the oil and gas industry and the current market for laying very large scale pipelines is small. The scale and amount of pipelines needed for CCS may temporarily fill order books of pipeline laying companies and increase prices and lead times.

Oil and gas extraction will compete severely with CCS activities

For storage exploration, skilled engineers are needed, who are now mainly working in the oil & gas sector. Between 2020 and 2030, CCS activities already require equipment and staff, not only to construct capture installations, but also to assess and explore reservoirs, drill assessment wells, assess the reservoir capacity and test with injection trials. The oil & gas sector already experiences difficulties with staffing, and because of the specific skills and experience that is needed; suitable staff can hardly be recruited from other sectors. The most critical part is the data collection on CO_2 storage reservoirs: on-site measurements, modelling and monitoring will require the knowledge of skilled geo-scientists.

Knowledge and expertise is concentrated in the oil and gas industry, not only upstream (e.g. oil drilling) but also downstream (e.g. petrochemical refining) that relates to knowledge of CO_2 capturing process being partly concentrated in the oil & gas sector.

If there is continued, and in the worst case for CCS, increased exploration and production of oil and gas; a shortage of staff and equipment might cause problems, particularly for offshore drilling. This may then result in shortages in equipment and operators and higher costs for drilling offshore CO_2 wells.

Because of their knowledge, oil companies (and their contractors) will be critical facilitators for CCS, in both exploration of reservoirs and in constructing capture installations. This means that, in times of labour shortages, oil and gas companies may have to choose between CCS and oil and gas extraction activities. As the revenues from oil activities are likely to be higher than CO_2 (currently the price of CO_2 is very low <$10/t), there is a severe risk that CCS activities will become understaffed and underequipped, i.e. the cost of equipment and staffing increase. There is of course a risk that high staff costs and rig costs might render CCS uneconomic in the future.

EXPERT REVIEW COMMENTS

Expert review comments on the draft report were received from five reviewers. The comments provided were detailed and constructive, enabling the study contractors to respond accordingly in preparation of the final report.

A recurring theme in the general comments was the subjective nature of some of the views expressed in the report. Whilst it was applauded that ranking of the importance of issues had introduced some objectivity and structure, arbitrary opinion without detailed analysis remained in many cases. In the absence of the discovery of clear showstoppers it is inevitable that the essence of the report is subjective opinion.

The point was made that the title “Capacity Constraints” could lead to confusion with CO_2 storage volumetric capacity, which was outside of the scope of the study.

CONCLUSIONS

The study has concluded that there are no insurmountable obstacles to the implementation of CCS at the rate of the IEA CCS roadmap were identified. However the scale of CCS implementation to match the IEA CCS roadmap would be large

- In the power sector the construction rate of power plants with CCS would be lower than historical power plant construction rates;
- In the industry sector approximately 65% of current emissions would be captured by 2050 which is an optimistic target to achieve;
- In the oil and gas sector more CO_2 would be captured annually than the current volume of annual global oil and gas production.

The most significant risk to rapid CCS deployment comes from competition with oil and gas exploration activities for experienced staff and drilling equipment.

The pre-combustion and oxy-fuel capture technologies contain elements that are not mature technology. The post combustion capture technology may become constrained by availability of materials.

Shortages of technically skilled personnel are most likely to appear, particularly for job profiles that are also required for oil and gas extraction; i.e. petroleum engineers and geo-scientists.

RECOMMENDATIONS

The report formulates the following recommendations to mitigate the impacts of barriers to the implementation of CCS.

1. **There is a need to reduce the risks for upfront investments, particularly for reservoir exploration and CO_2 transport infrastructure.**
   For early operation of CCS installations upfront assessment and design of the transport and storage component is essential but is expensive.
2. **There is a need to mitigate competition with oil and gas extraction activities via education.**
   Students should be encouraged to view a career in CCS technologies as complimentary to a career in the oil and gas industry, requiring the same training and skill development.
3. **We need to investigate in detail the knowledge and expertise needed for storage assessment.**
   A knowledge gap is identified in the area of geological CO_2 storage assessment.
4. **Promote international data exchange.**
   Consistent and accurate estimates of storage capacity are needed in most world regions at an early stage of CCS deployment to prevent the storage component becoming a constraint.
5. **We should try and stimulate diversity of suppliers in R&D and in demonstration and pilot projects.**
   In order to avoid later constraints of a suppliers market, diversity at the RD&D stage should be encouraged.
6. **We need to encourage recycling and optimization of materials that are likely to be in short supply.**
   Recognition at an early stage of the intrinsic value of critical materials should help to reduce equipment supply constraints as CCS activities rapidly expand.
7. **We need to build up institutional knowledge.**
   Specialist knowledge will likely be pulled towards the active industries. However, technological knowledge is needed in regulatory authorities and other institutions to assist with the permitting/regulatory monitoring of CCS projects otherwise this could become a constraint on the deployment of projects.

Barriers to implementation of CCS – Capacity Constraints

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Barriers to implementation of CCS – Capacity Constraints

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Project number: PSTRNL101195

by order of:
IEA Greenhouse Gas R&D Programme (IEAGHG)

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Glossary

AGR	Acid Gas Removal
ASU	Air Separation Unit
BAU	Business As Usual
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
EPC	Engineering Procurement and Construction
ETP	Energy Technology Perspectives (IEA)
FGD	Flue Gas Desulphurization
$GtCO_2$	Giga tonnes (billion tonnes) carbon dioxide
GW	Gigawatt (10^9 watt)
HR	Human Resources
IEA	International Energy Agency
IP	Intellectual Property
IGCC	Integrated gasification combined cycle
MDEA	Methyl-di-ethyl-amine
MEA	Mono-ethanol-amine
$MtCO_2$	Mega tonnes (million tonnes) carbon dioxide
MW	Gigawatt (10^6 watt)
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
OEM	Original Equipment Manufacturer
PC	Pulverised Coal
R&D	Research and Development
RD&D	Research Development and Deployment
SCR	Selective Catalytic Reduction
SNCR	Selective non-Catalytic Reduction
WEO	World Energy Outlook (IEA)

1 Introduction

Carbon Capture and Storage (CCS) is considered to be an important technology that could significantly contribute to a reduction of greenhouse gas (GHG) emissions. For example, in the BLUE Map scenario of the IEA Energy Technology Perspectives (ETP), 19% of the CO_2 abatement (relative to a BAU scenario) comes from CCS. The IEA's CCS Technology Roadmap (IEA CCS roadmap, 2009; part of the ETP[1]) suggests that up to 150 Gt of CO_2 needs to be captured and stored by 2050. This is greater than five times the global anthropogenic CO_2 emissions from fuel combustion in 2008.

To achieve this, CCS activities must grow from practically non-existent to approximately 850 installations by 2030 and 3,400 installations by 2050. Policies and regulations need to be in place to achieve this ambition, but the development of an efficient, environmentally friendly and safe technology and complex organisational issues also need to be adequately addressed. In addition, technologies with rapid deployment can experience severe constraints related to their supply chain. This also needs to be addressed

In this study, commissioned in 2010 by IEAGHG, we assess possible supply chain constraints that could arise if CCS is deployed according to the IEA CCS Roadmap. We look at physical constraints (equipment, materials) as well as those in skills and services (human resources). In the context of CCS, *capacity* generally refers to storage capacity, but storage capacity is not within the scope of the study presented in this report. We focus only on the future capacity of the supply chain for CCS technologies.

Reading guide

In the next chapter, we will explain the scope of the project, followed by an explanation of our approach in chapter 3. In chapter 4, we will detail the magnitude of the ambitions in the CCS Roadmap. In chapter 5 and 6 we will present our findings on supply chain constraints for equipment and human resources, respectively. For purpose of comparison and to put CCS deployment into a historical context, the future developments in CCS activities are compared to the introduction of FGD (Flue Gas Desulphurisation) in chapter 7. A summary of our findings is presented in chapter 8, followed by recommendations based on our findings, in chapter 9. Each of the chapters 4, 5, 6 and 7 begin with an overview of the key findings.

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[1] Energy Technology Perspectives

2 Scope

2.1 The IEA CCS Roadmap is the starting point of this study

In this study we assess the risk of supply chain constraints arising if CCS is deployed according to the CCS Roadmap of the IEA (IEA, 2009). This technology roadmap builds on the IEA BLUE Map scenario[2] (IEA, 2010), which combines the deployment of different (low carbon) technologies to achieve global CO_2 emission reductions: from just below current 30 $GtCO_2$ to 14 $GtCO_2$ by 2050[3] (the baseline scenario results in 57 $GtCO_2$). [4] In the BLUE Map scenario CCS contribution to the emission reduction in 2050 – compared to the base line scenario -is 19 %.

In this study we assume that society is willing to invest sufficiently in the deployment of CCS, negating constraints related to:

- Political support
- Regulations
- Public support
- Financing

2.2 CCS technologies and sectors

In this study we consider the full CCS chain, i.e. capture, compression, transport and storage of CO_2. The focus is on current state-of-the-art technologies, including pre-combustion, post-combustion and oxyfuel combustion technologies. Appendix B provides a general description and status of these three technologies. Advanced or 'second generation' conversion and capture technologies are not considered in this study.

The sectors considered are the industry sector, the power sector and the oil and gas upstream sector. The upstream sector includes fuel and gas processing and is regarded as a sector with many opportunities for low-cost capture. Components needed in the actual thermal power plants equipped with CO_2 capture facilities are not within the scope of this study, although this subject is briefly touched upon in section 4.3.

For CO_2 transport we focus on transport by pipeline. Other transport mediums such as ship, truck and train are not considered. CO_2 capacity is not included in the supply chain; this subject is treated in other IEAGHG projects (for example "Global Storage Resource Gap Analysis for Policymakers").

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[2] The BLUE Map scenario can be regarded as the extension of the 450 ppm scenario of the World Energy Outlook (WEO; IEA, 2009b), which has a time horizon of 2030.
[3] This figure represents CO_2 emissions from fuel combustion only.
[4] The CCS Roadmap is originally based on the Energy Technology Perspective (ETP) 2008, and in its baseline scenario, global CO_2 emissions reach 62 $GtCO_2$ by 2050.

2.3 Supply chains for CCS technologies

We do examine the entire CCS chain when analysing possible supply chain constraints (see figure below). We divided constraints into those relating to **Equipment & Materials** and those relating to **Services & Skills**. The figure below captures this approach in a more detailed manner. For example, we can see in the figure overleaf, that the operation of power plants with CO_2 capture requires human resources and raw materials (e.g. chemicals or metals). Before operation, the power plant has to be built, which requires Engineering Procurement and Construction (EPC) (sub)contractors to deliver the main technology blocks (i.e. components) for the power plant, including the components needed for CO_2 capture. The scope of such EPC contracts includes; project management, engineering, procurement of sub-components such as fans and pipes, construction of the technology block and commissioning. In essence, all parts of the supply chain(s) that are necessary to plan, design, construct and operate a (part of the) CCS chain require human resources and raw materials or sub-components from other industries or from the natural environment. In each part of the chain, a supply constraint may occur. This can be a scarce natural resource or limited production capacity of a component.

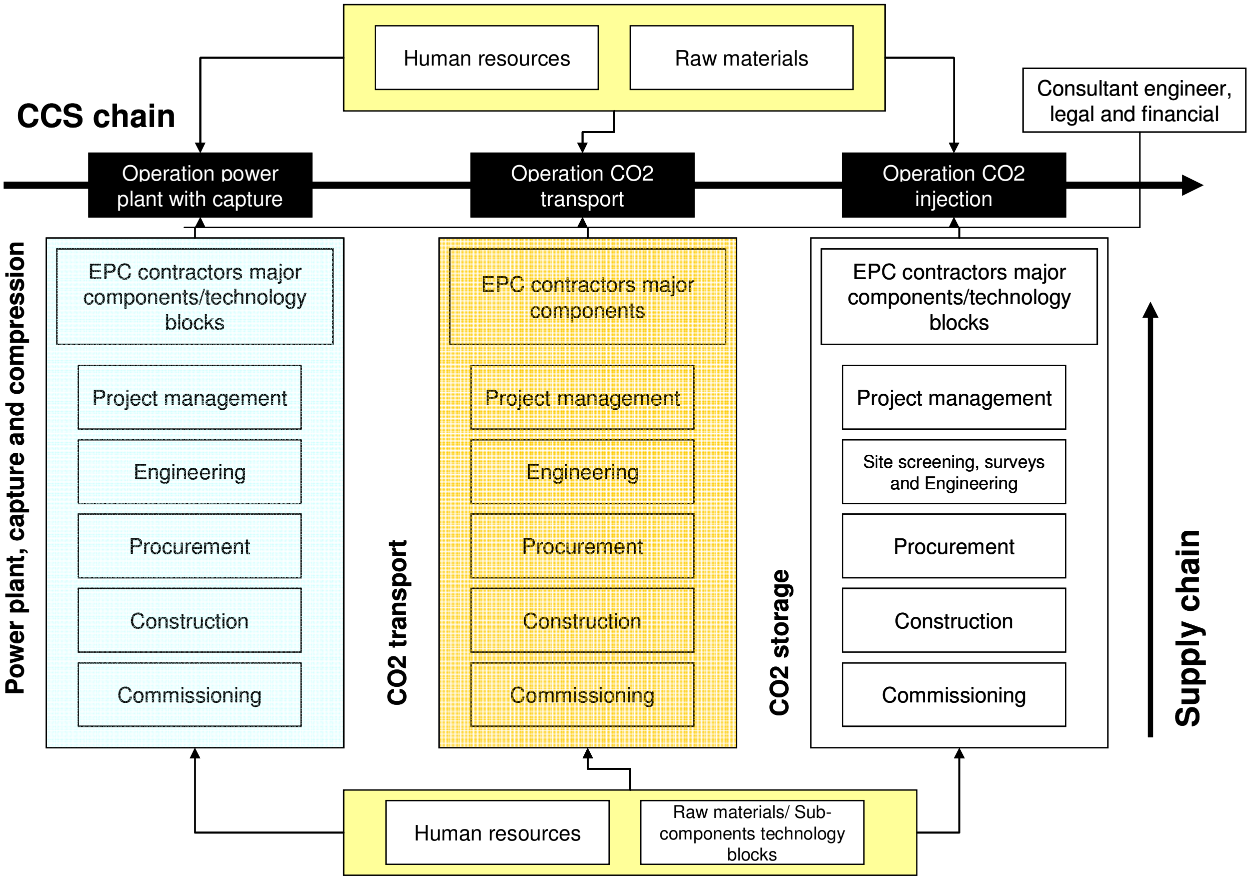

Figure 2 - 1 Graphical representation of the supply chains for CCS technologies. Horizontally the CCS chain is shown. Vertically the supply chain is shown for the three parts of the CCS chain.

A pragmatic approach

As it is impossible to assess all components in a CCS chain (i.e. to the level of bolts and screws), we have to limit ourselves to the main components in CCS installations. Therefore, we apply the following pragmatic and systematic approach.

First of all, we made a list of equipment (see Appendix A) that is used in CCS technology. From this list, we selected components, based on a number of criteria, (see chapter 3) - from which we expect to face possible constraints. The supply chain issues of these components are studied in detail in chapter 5. For human resources, we look at job profiles that are needed for capture, transport or storage activities.

3 Approach

In this study we will explore potential constraints by following a structural methodology. In this chapter, we explain the methodology we apply to determine possible constraints.

3.1 Introduction

This report covers a study of constraints in the supply chain, in the next few decades, for a technology that currently has a near-zero market share. The conclusions drawn from this study will therefore be subject to large uncertainties. With this in mind, it is important to follow a structural methodology that also considers development at a macro-level (i.e. sectoral, national and international level). To achieve this, our methodology combines three approaches:

1. A supply chain assessment for the **individual CCS components**, to identify which components/materials might constrain CCS supply. See section 3.2 and chapters 5 and 6…
2. A comparison of the CCS development, (as described in the CCS Roadmap), with **developments in the sectors** that will be involved in CCS activities**.** This gives an impression of the size of the activities in the CCS Roadmap and it also helps in identifying to what extent the introduction of CCS will compete with other developments in the investigated sectors. See chapter 4.
3. A case study of an **historic introduction of a technology.** With this exercise, we can identify prerequisites for a successful introduction of CCS and reflect on our findings. See chapter 7.

By comparing the projected activities in CCS with future and historical developments in several sectors, we can identify in which sector the highest risks can be expected. The third approach puts our conclusions from the first two approaches into a historical context.

3.2 Assessment of individual components

To identify potential supply constraints at a component level, we develop and examine different indicators of the most important components for CCS. Examples of these indicators are necessary market growth and availability of materials. Whether supply of a certain component runs the risk of being constrained depends on the *combination* of these indicators: If the current market is small (compared to demand for CCS), but ample resources are available, the risk of a constraint arising is lower than if resources are scarce. The different indicators considered are described below. We develop and assess different sets of indicators for equipment; we evaluate services & skills, on a less detailed level, though we take into account similar aspects. In chapter 5 (equipment), we will study the supply chain risks of individual components by assessing each different indicator. We will qualify and quantify the indicators with a focus on the period 2020-2030[5], when the most dramatic market growth for CCS must be realised.

3.2.1 Indicators for equipment

For equipment, we consider the following indicators in our assessment:

Annual market growth: We will compare the *current market size* for a component with the *future demand* for CCS. We assess the market in terms of the needed annual market growth to accommodate the CCS roadmap. We apply three classifications for the required annual growth (until 2030) of the current market: (1) more than 5%, (2) between 1 and 5% or (3) less than 1%.

Supplier concentration: How fast a market can adjust to the demand for CCS also depends on the type of competition in a market: Is the market a (1) monopoly, (2) oligopoly or an (3) open market? One speaks of an oligopoly if all suppliers in a market are aware of the all their competitors. Typically, a market with less than ten suppliers is an oligopoly. In this study, we examine the suppliers of components at the level of EPC (i.e. technology and service providers). Below the level of EPCs, there are manufacturers of subcomponents and services, but to keep the study comprehensive, these levels are generally not considered.

Technology status: If a technology is not yet mature, achieving the needed production capacity might take longer than if the technology were already mature. Is the technology: (1) in the R&D phase (2) in the demonstration phase or (3) commercially proven? We classify something in the R&D phase if a technology is not yet operating or has only been tested on a scale that is less than ten times smaller than the targeted commercial scale. We classify a technology as being in the demonstration phase if a small number of projects are running on a scale that is at least 1/10 of the targeted commercial scale.

Exogenous demand: Whether constraints might arise also depends on developments in other sectors. If the demand in other sectors also grows, CCS might compete with these sectors for components. However, if a market grows by exogenous demand more than proportionally, the relative market pressure caused by CCS will decrease. To account for both possibilities, we use the following qualifications: exogenous demand can be a (1) barrier; (2) neutral; or a (3) driver. In qualifying this indicator, we take into account the results presented in chapter 4.

Material availability The supply of components can also be restricted by scarcity of resources, such as raw or synthetic materials Therefore, we indicate whether the availability of material is (1) low (>5% of world production is needed

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[5] The needed market growth rates given in this report thus refer to the period until 2030, unless stated otherwise.

for CCS), (2) medium (between 1 and 5% of world production is needed for CCS) or (3) abundant (<1% of world production is needed for CCS).

The classification level (1 to 3) indicates the risk of a constraint arising, i.e. classification 1 indicates a higher risk and classification 3 a low(er) risk. The *combination* of different indicators, however, gives a much stronger picture of risk of CCS supply chain constraints. The indicators are also not independent from each other, for example: a product in the R&D phase will probably not be associated with an open market.

We will show the qualification and quantification in both tables and spider diagrams. Figure 3 - 1 shows a generic spider chart with the five indicators as axes. Generally, when an indicator does not indicate a barrier, i.e. classification 3, a line is drawn towards the outside of the diagram. With a lower classification (barrier) the line is drawn towards the centre of the diagram.

The information on which we base on our analysis comes from a broad range of literature: scientific papers, market reports, conference proceedings and publications from companies. This is complemented by information from interviews with stakeholders (companies, government agencies and consultants) and input we collected during a workshop held in December 2010. In this workshop we discussed intermediate results.

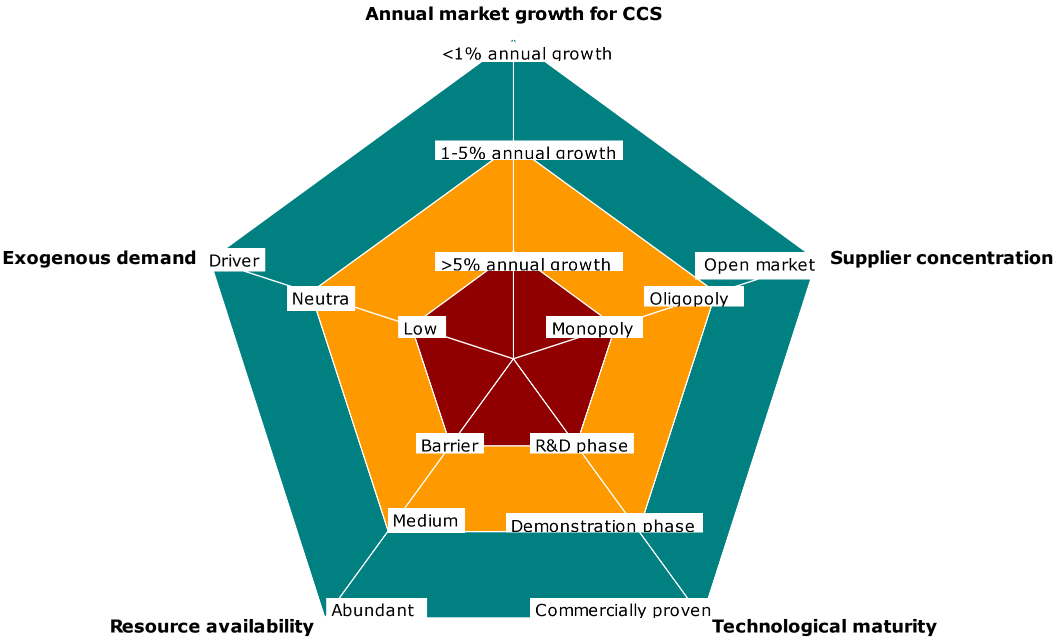

Figure 3 - 1 A spider diagram that summarises how the different indicators are assessed in chapter 5. The axis runs from an indication of a barrier (centre) to no barrier (outside).

3.2.2 Indicators for skills and services

Skills and services will be treated more generally, as a job market knows different dynamics than the equipment market. We will consider the following indicators to assess the job market:

- Anticipated exogenous demand growth in skilled labour
- Anticipated size of the workforce in specialised areas
- The time taken to acquire dedicated knowledge and skills

3.3 Risks for constraints

Based on the qualified and quantified indicators[6], we will indicate the risk of a constraint: A risk depends on the probability of a constraint appearing and its impact. An overview of how we classified the different risks, probabilities and impacts is provided in Figure 3 - 2.

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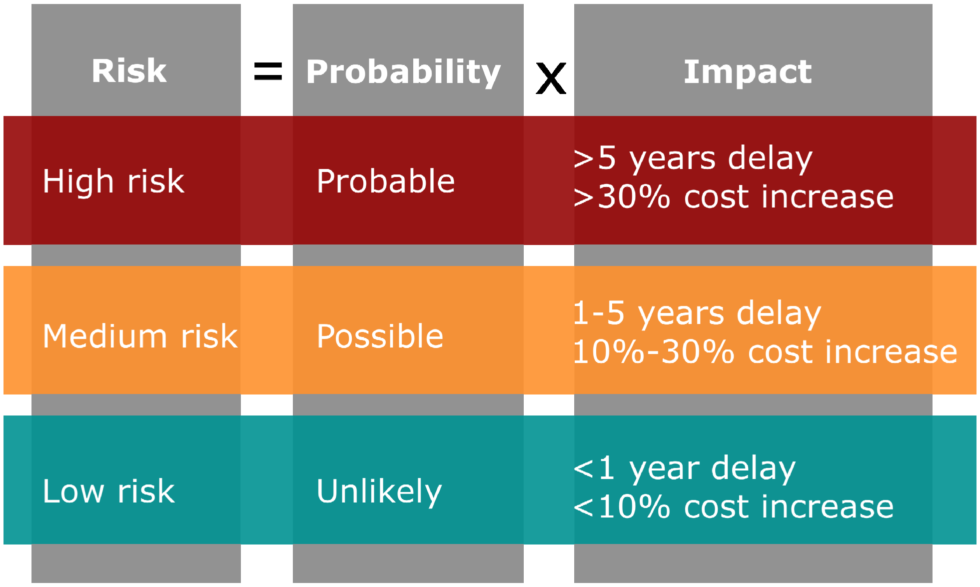
[6] For each component that is studied, the weighting of the individual indicators differs when assigning a risk, e.g. for some components the technological immaturity alone might lead to a high risk, while for other components, the current immaturity might lead to a medium risk. We did not directly assign a risk to a given set of indicators, but assessed the risk per component.



Risk	=	Probability	x	Impact
High risk		Probable		>5 years delay >30% cost increase
Medium risk		Possible		1-5 years delay 10%-30% cost increase
Low risk		Unlikely		<1 year delay <10% cost increase

Figure 3 - 2 Overview of risks: The risk depends on the chance that a constraint will occur and the impact it will have.

An example: If we think it is ‘probable’ (red area) that a certain constraint will arise and the impact is that a project is delayed by 1-5 years (orange area), we will assign it a ‘Medium to high risk’. The outcomes of the risk assessment are presented in the ‘key messages’ in chapters 5 and 6.

As it is impossible to quantify the probabilities and impacts in detail, the risk assessment should be treated as first order assessment.

4 The scale of the IEA CCS Roadmap

The CCS roadmap (IEA, 2009) outlines an ambitious rollout of CCS. This rollout should be realised in the power sector as well as in the industry and up-stream sectors. Whether supply constraints will arise depends on, amongst other factors, the deployment rates in the CCS Roadmap. In this chapter, the scale of the CCS Roadmap is compared to developments in the power sectors, industry and oil and gas extraction

4.1 Key findings

In the **power sector**, the construction rate of power plants with CCS is lower than historical building rates of power plants. Within the BLUE Map scenario, nuclear and renewable energy will also be deployed at high construction rates.

In the **industry sector**, approximately 65% of the current emissions should be captured by 2050. Between 2020 and 2030, the average annual growth of CCS in the industry should be 23% (in terms of $MtCO_2$).

In the CCS Roadmap, by 2045, more CO_2 will be captured annually than the current volume of the annual **oil and gas production** combined. In the BLUE Map scenario, global hydrocarbon fuel demand will decrease, although demand for oil and gas in China and India will increase.

The comparison with the power sector shows that historical deployment rates of power plants are comparable, or greater than, what is necessary for CCS. This indicates that a dramatic capacity increase for EPCs is not needed (although the expertise required will be different). High construction rates for nuclear power plants, wind and solar PV in the BLUE Map scenario indicate that the total capacity of the supply chain for power technologies must increase substantially.

The comparison of the amount of CO_2 that has to be stored with the current production of hydrocarbon fuels is an indication that severe competition for CCS activities will come from oil and gas production activities.

4.2 Overview of the CCS Roadmap

Following the CCS roadmap of the IEA from 2009 (IEA, 2009), by 2050, 3,400 installations should be operational, capturing about 10 $GtCO_2$ annually, see Table 4 - 1. Between 2020 and 2030, annual average CCS growth rates should be 24% (in terms of $MtCO_2$).

Table 4 - 1 Overview of the CCS Roadmap, in number of projects and $MtCO_2$ captured annually

	2020	2030	2040	2050
Number of projects	100	850	2,100	3,400
Mtonnes (CO_2)	299	2,536	6,143	10,080

The power sector will accommodate approximately half of the installations; the other half is covered by the industrial and upstream sector. In the period 2010-2030, a rapid acceleration in deployment must take place. This is the critical period in terms of supply chain capacities and we will focus on this period in this report.

The three subsectors with the largest contribution to the CCS Roadmap are 1) coal firing (power sector), 2) upstream (synfuels + hydrogen production, industry sector) and 3) gas firing (power sector), see Figure 4 - 1. Between 2020 and 2050, the average annual growth rate in CCS capacity needs to be 12%. The highest growth rates in CCS installations should be realised within this decade, because 100 installations should be operational by 2020; currently only five fully integrated, commercial-scale CCS projects are operational (IEA, 2009).

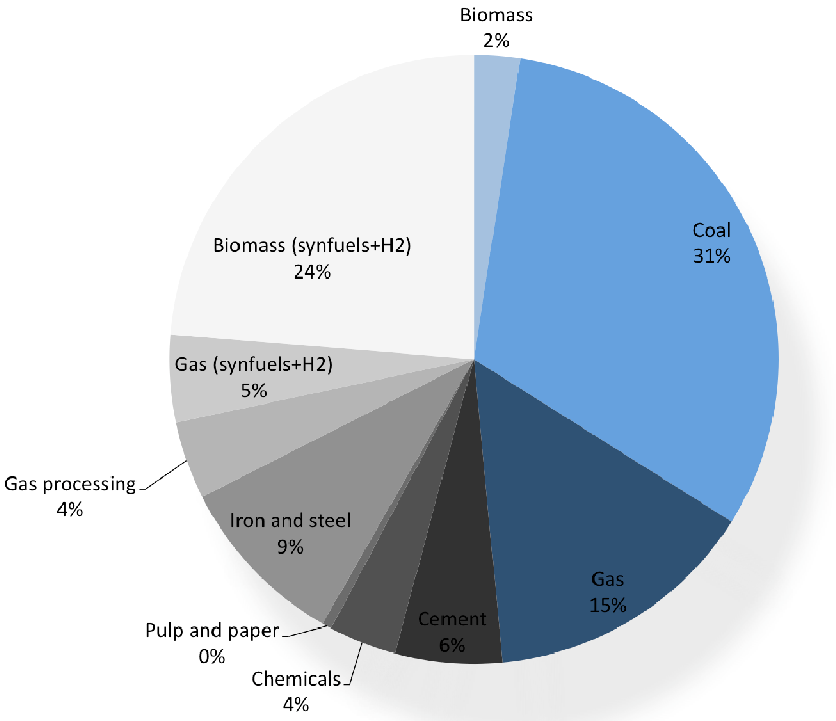


Figure 4 - 1 Share of (sub)sectors in number of projects (blue is power, gray is industry) in the CCS Roadmap by 2050. Total number of installations is 3,400. Source: IEA, 2009

4.3 The power sector

By 2050, the power sector should constitute 1,632 installations equipped with CCS that capture 5,500 $MtCO_2$ in total. Table 4 - 2 presents an overview for the years 2020 to 2050. Between 2020 and 2030, annual average CCS growth rates in the power sector should be 25% (in terms of $MtCO_2$).

Table 4 - 2 The CCS Roadmap for the power sector in number of projects and $MtCO_2$ captured annually

	2020	**2030**	**2040**	**2050**
Number of projects	38	357	945	1,632
Mtonnes (CO_2)	131	1,218	3,224	5,510

The primary fuel in the plants equipped with CCS will be coal (91% in 2020, 65% in 2050). The contribution of natural gas increases from 9% in 2020 to 30% in 2050. By 2050, biomass will have a share of 5% in CCS equipped installations; the developments up to 2050 are shown in Figure 4 - 2.

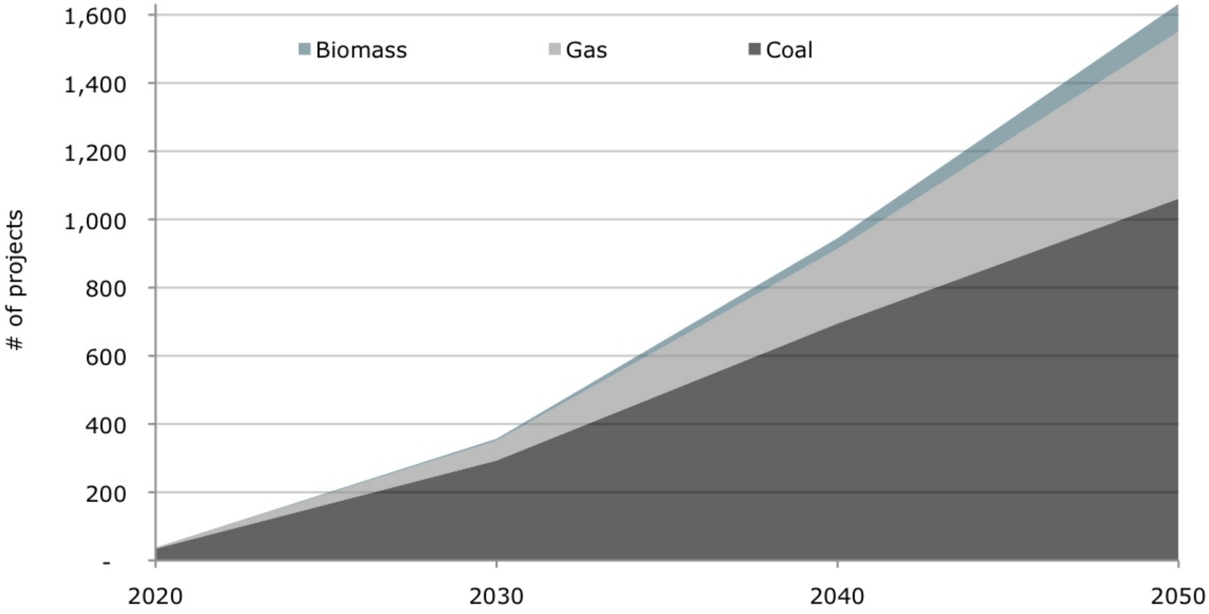


Figure 4 - 2 Developments of CCS in the power sector in the CCS Roadmap, in terms of number of projects (left axis).

Coal

The highest growth rates in coal fired power capacity in the 20th century were achieved in 1950-1960. In that period, the average annual growth rate (in power capacity) was 19%. To achieve the targets in the CCS Roadmap, the annual growth in coal CCS projects must reach an average of 17 GW (15 installations[7])

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[7] Assuming an average size of coal fired power plants, equipped with CCS, of 1 GW in to 2020 to 1.3 GW by period 2040.

per year in the period 2020-2030, 29 GW (24 installations) per year between 2030 and 2040 and 28 GW (22 installations) per year over the period 2040-2050. To compare, the deployment rate of coal-fired power plants in the period 1960 to 2000 was about 130 installations (27 GW) per year. The average size of the installations increased, from 120 MW between 1960 and 1970 to 285 MW in the first decade of the 21st century (2000-2006). The historical construction is therefore comparable to the needed future building rate of coal-fired power plants with capture installations.

Over the last five years, there was a sharp increase in the construction rate of coal-fired power plants. This induced many supply chain problems, summarised in Box 1. For example, in China alone, more than 100 GW was under construction in 2009 (IEA, 2009b).

BOX 1 – Supply chain constraints for coal-fired power plants

CCC (2008) studied current supply chain constraints for coal power in the years 2002-2008. The main conclusions were:

- Supply chain issues are mainly caused by a sudden rise in new coal power demand
- Most manufacturers of the main components are fully booked for several years
- Increasing lead times (several years) and costs of for example steam turbines, boilers and environmental control systems
- Higher costs (hour wages increased more than 40%) are caused by lack of skilled technical staff along the supply chain, construction, commissioning and operation. This sometimes resulted in a doubling of the construction period.
- Cost of raw materials increased sharply, causing a price increase of equipment
- There is limited production capacity for large forgings and castings

Most of the supply chain problems were caused primarily by a sharp increase in coal-fired power plant demand. The higher costs for raw materials are mainly triggered by demand in other sectors and by economic cycles. Availability of skilled staff is expected to remain a constraint in the coming years.

Figure 4 - 3 shows the stock development in coal-fired power, following the BLUE Map scenario (ETP; IEA 2010). In this figure we assumed that the operational lifetime of a plant is 40 years. Capacity older than 40 years is gradually phased out by 2020.[8] In the BLUE Map scenario, total coal capacity decreases to approximately 820 GW (from about 1290 GW in 2007), of which 91% is equipped with CO_2 capturing installations. We also assume that CCS is only applied to new installations. We see, that by 2030, coal power plants have to be forced into early retirement, existing plants have to be retrofitted with CCS and/or power plants

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[8] More than 200 GW of operational coal fired power plants is older than 40 years

should be equipped earlier with CCS (than planned in the CCS Roadmap). This is also indicated in the CCS Roadmap and the ETP.

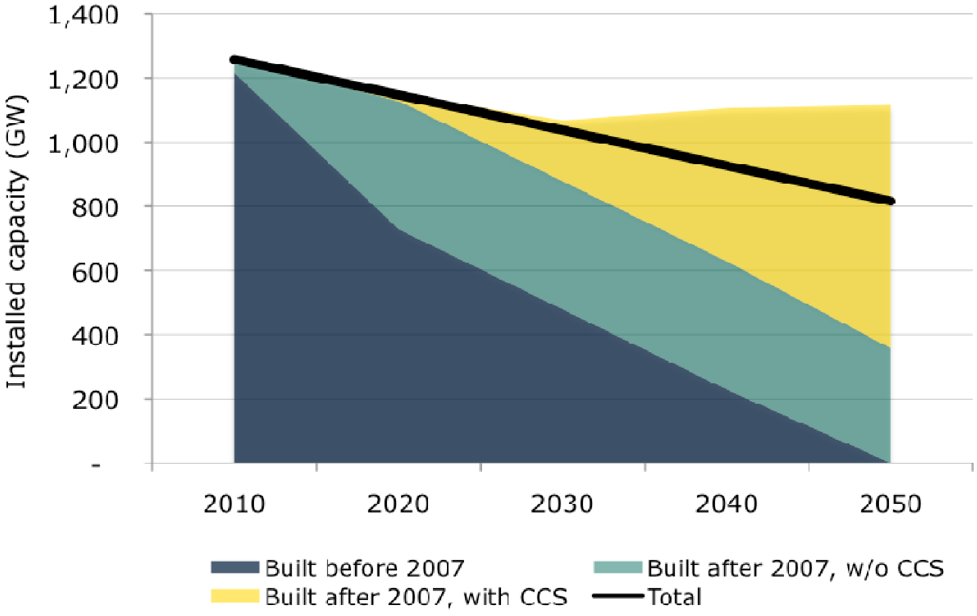

Figure 4 - 3 Development of coal-fired power capacity in the BLUE Map scenario, assuming an economic lifetime of 40 years. The blue wedge shows the development of the existing stock, the green wedge shows the deployment of new non-CCS capacity and the yellow wedge shows the deployment of CCS capacity, assuming it is deployed on new plants only. The black line indicates the desired pathway in the BLUE Map scenario (assuming a linear decrease). Source: IEA (2010); IEA (2009)

Biomass

Not much of the (dedicated) biomass capacity is currently operational[9], although co-firing of biomass with coal is common practice in modern coal fired plants. The BLUE Map scenario assumes an increasing share of electricity from biomass combustion. We estimate an installed capacity of biomass-fired plants by 2050 of about 720 GW[10]. This implies that the required construction rate needs to be approximately 18 GW per year.

Figure 4 - 4 shows that the decrease in coal power is compensated by a substantial increase in biomass capacity, of which 52 GW will be equipped with CO_2 capturing, by 2050.

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[9] According to REN21 (2010), 54 GW of biomass power is operational.

[10] Estimate from IEA (2010), which indicated the electricity production from biomass in the BLUE Map scenario. We assumed the same number of full load hours as was applied to coal in the ETP.

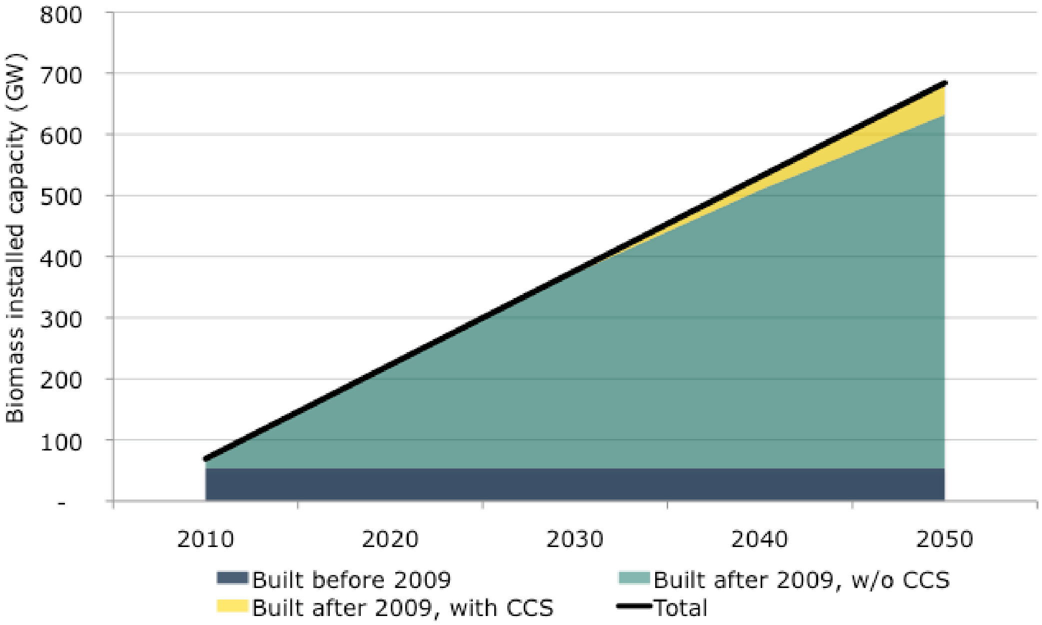

Figure 4 - 4 Development of biomass power capacity in the BLUE Map scenario. The blue wedge shows the development of the existing stock, the green wedge shows the deployment of new non-CCS capacity and the yellow wedge shows the deployment of CCS capacity, assuming it is only deployed in new plants. The black line indicates the desired pathway in the BLUE Map scenario. Source: IEA (2010); IEA (2009)

Gas

To achieve the targets in the CCS Roadmap, the annual growth in CCS projects in NG-fired power plants must reach an average of 4 GW (12 installations[11]) per year in the period, 2020-2030, 11 GW (37 installations) per year between 2030 and 2040 and 20 GW (63 installations) per year over the period, 2040-2050. In comparison, the historical deployment rate in the period, 1960-1980 was approximately 170 installations (12 GW) annually. The building rate increased sharply in the period 1980-2000 to over 500 installations (24 GW) annually. In 2002, the construction rate peaked at 1,000 installations and 72 GW. The average size of the installations varied greatly from year to year: between 50 and 100 MW in the second half of the 20th century. In the CCS Roadmap, the average capacity of a full-size gas fired power plant with CCS, is 800 MW.

In terms of both the number of projects and the capacity per year, the historical building rate exceeds the projected future building rate of gas-fired CCS installations in the power sector.

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[11] Assuming an average size of 260 MW by 2020 to 320 MW in the period 2040-2050. This is assumed for this study (i.e. not from the CCS Roadmap). Especially after 2040, the average size might be higher (up to 800 MW).

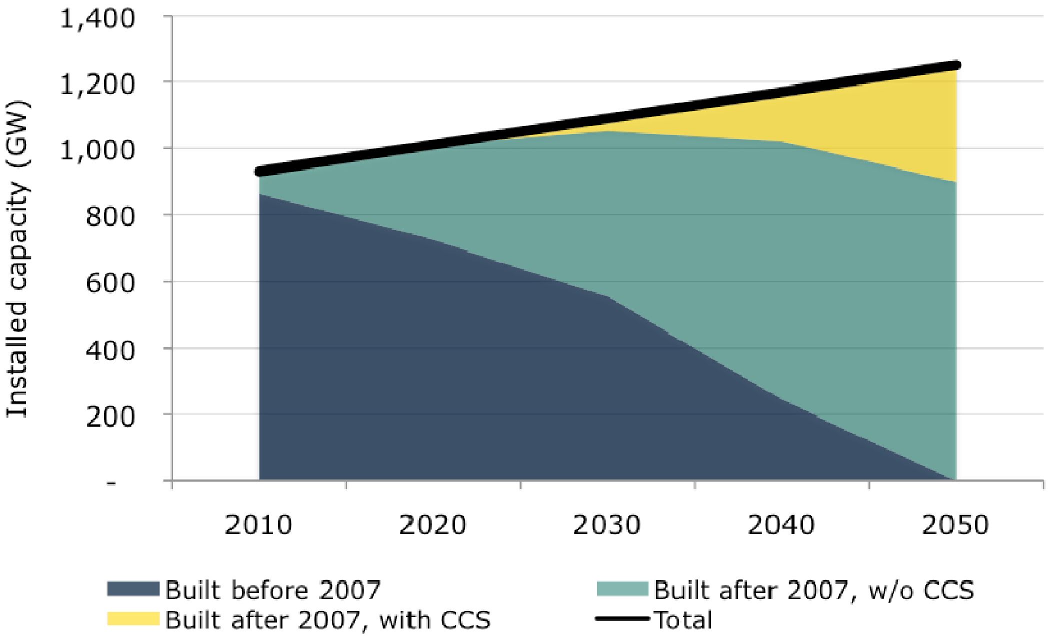

Figure 4 - 5 Development of gas power capacity in the BLUE Map scenario. The blue wedge shows the development of the existing stock, the green wedge shows the deployment of new non-CCS capacity and the yellow wedge shows the deployment of CCS capacity, assuming it is only deployed in new plants. The black line indicates the desired pathway in the BLUE Map scenario. Source: IEA (2010); IEA (2009)

Power production in the BLUE Map scenario

The CCS Roadmap is part of the BLUE Map scenario, which envisages a transition to a low carbon energy supply. For the power sector, this means that renewables, nuclear and CCS will be deployed at the expense of (non-CCS) coal and oil power. Annual capacity additions in the period, 2010-2030 for the other low carbon technologies are: 26 GW for nuclear, 20 GW for solar PV and 50 GW for wind. Figure 4 - 6 compares the power production of the main technologies in the BLUE Map scenario in 2050 with 2007 production.

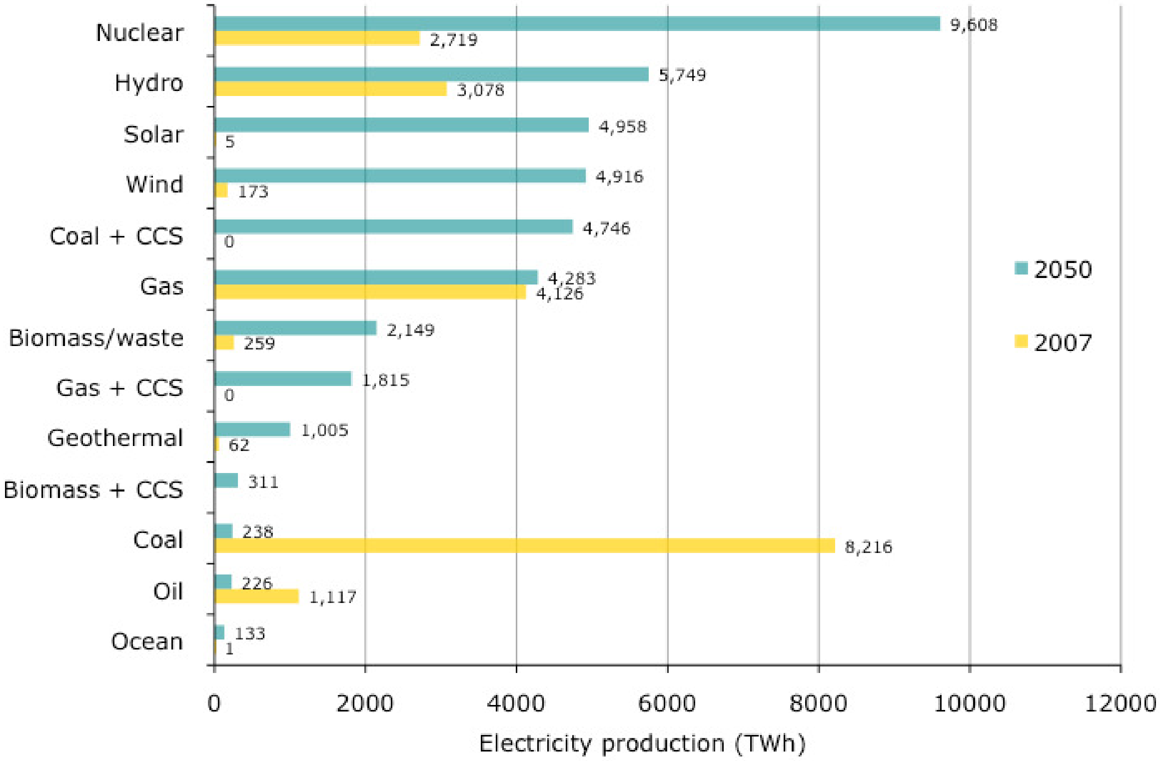

Figure 4 - 6 Electricity production by the different technologies in the BLUE Map scenario in 2050, the yellow bars indicate the contribution in 2007. Source: IEA (2010)

There are no major components used in these technologies that are also needed for CCS. However, large-scale deployment of nuclear power and renewables might directly and indirectly compete for resources with CCS:

- technically skilled personnel for the construction of nuclear power plants
- drilling rigs for deep geothermal power production
- offshore cable laying vessels for offshore wind, or engineers that consider a career in wind power instead of CCS technology

For nuclear, wind and solar PV, commercial applications already exist, but for CCS, technological and market maturity is still to be achieved. Therefore, compared to the other low carbon technologies, CCS will probably require more resources.

4.4 The industry sector

Table 4 - 3 The CCS Roadmap for the industry and upstream sector in number of projects and MtCO2 captured annually

	2020	**2030**	**2040**	**2050**
Number of projects	62	493	1092	1734
Mtonnes (CO_2)	168	1,318	2,918	4,570

Annual emissions in the industry rose by an average of 1% per year between 1970 and 2006[12] (IEA, 2009). In 2006, industrial emissions totalled 6.8 $GtCO_2$. The Roadmap envisages 4.5 $GtCO_2$ captured annually, by 2050, in the industry and upstream sector, i.e. about 65% of current industrial emissions.

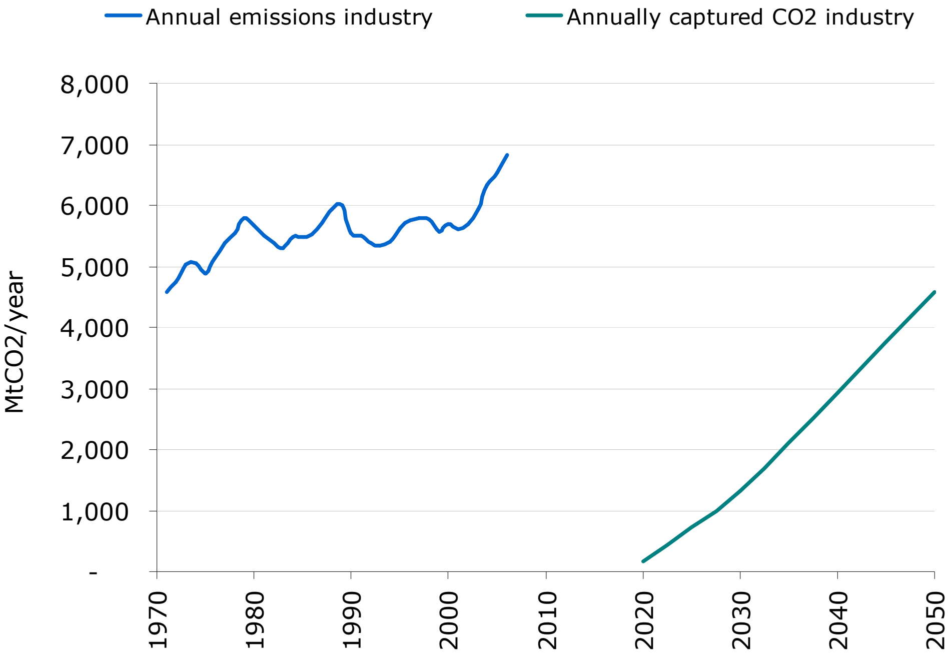

Figure 4 - 7 Developments of industrial CO2 emissions (blue) and caputed CO2 emissions (green) in the CCS Roadmap. Source: IEA (2010), IEA (2009)

To achieve this, CCS in industry should grow 23% annually (in terms of captured emissions) between 2020 and 2030.

4.5 The oil & gas sector

To gain an understanding of the magnitude of the transport and storage operations, we compare the amount of captured and stored CO_2 in the CCS Roadmap with the annual production of crude oil and natural gas. This comparison is shown in Figure 4 - 8. The volumes of CO_2 are given for CO_2 with a density in the liquid/supercritical state and for natural gas in liquid state (LNG)[13].

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[12] or, assuming a linear growth, a growth of almost 50 Mt CO_2 per year.

[13] Natural gas is extracted in gaseous form under high pressure. The extracted amount is converted to unit of LNG to make a comparison with CO_2 injection.

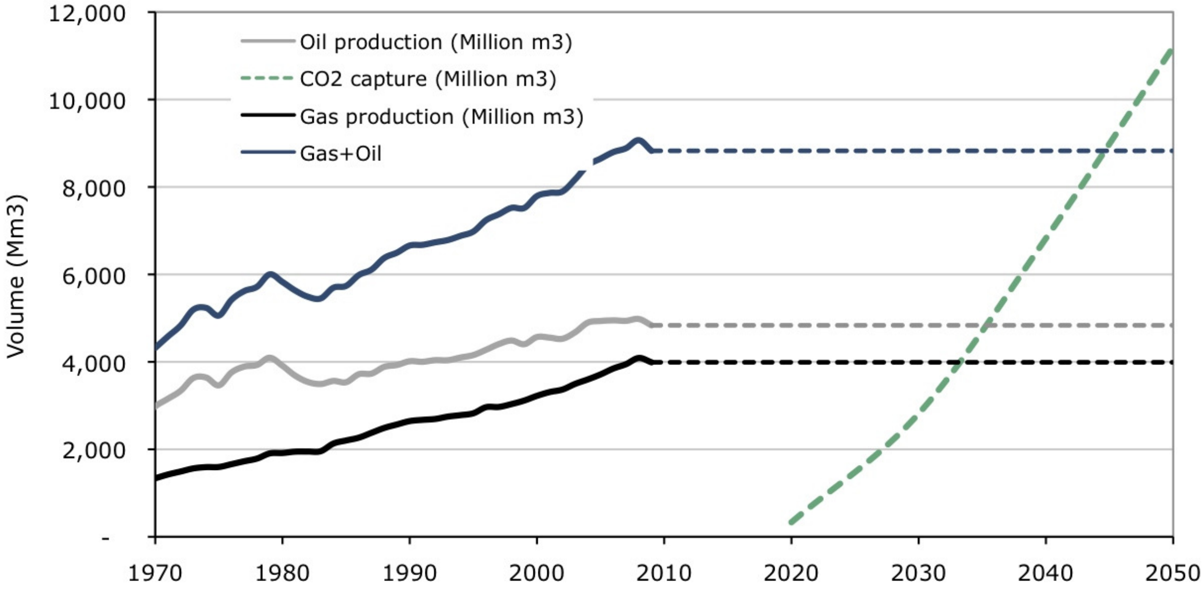

Figure 4 - 8 Comparison of the volume of oil and gas that has been produced annually (until 2009) with the volume of (supercritical) CO_2 that is captured in the CCS roadmap. The horizontal lines indicate gas and oil production in 2009. Source: BP, 2010

BOX 2 – Competition with oil & gas

Even in the BLUE Map scenario (IEA, 2009), an increase in oil and gas consumption is still expected until 2030. CCS shares part of the supply chain with the oil and gas sector; labour (e.g **experienced geo-scientists**) and large facilities (e.g. **ships, platforms and drilling rigs**). When the added value of oil/gas is (much) higher than of CO_2 storage, this will slow down investment in CO2 storage. Assuming added value of €50/barrel (315 €/m^3) and 5 €/tCO_2 (4 €/m^3), the revenues are 80 times higher for oil and gas by handling (injection/extracting) the same volume.

Figure 4 - 8 illustrates that, after 2045, the CO_2 transport and injection capacity must be larger than the total transport and extraction capacity for oil and gas production. We should note that the extraction of hydrocarbons is more complex[14] than CO_2 storage.

Substantial competition between CCS industry and the oil and gas industry can be expected (especially in the field of transport and storage). By applying enhanced oil recovery (EOR), CO_2 storage and oil and gas extraction can be combined, potentially reducing the total resource demand for both activities.

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[14] Hydrocarbon extraction involves higher explosion risks, multiphase flows and more complex pressure control.

Oil and gas demand in the BLUE Map scenario

In the BLUE Map scenario, oil demand in 2050 will be 23% below 2007 levels, pre-dominantly realised in the OECD region. In that same period, the natural gas demand decreases by 12% and the demand in non-OECD regions increases. The oil and natural gas demand will peak between 2020 and 2030. In China, oil consumption will decrease after 2030, while in India, demand stabilises after 2050. For both countries, natural gas consumption will continue to grow until 2050.

5 Equipment

Deployment of CCS, at the pace of the CCS Roadmap, evidently requires large quantities of physical resources, i.e. equipment and materials. The supply chain should be able to deliver ***on time*** *and* ***at the scale needed****. In this chapter, we assess the readiness of the supply chains of the required resources.*

As the first step in our assessment, we made a list of the primary components (equipment) that constitute CCS. This list can be found in Appendix A. From this list, we selected a shortlist of the most critical components, which we will assess in more detail. A component is considered to be critical if it meets more than one of the following criteria (see also the indicators in chapter 3):

- The technical state of the component is still immature and requires substantial R&D efforts
- The component is currently deployed in a niche market (i.e. small market size compared to what is needed for CCS)
- Severe demand competition with other applications is expected
- The component contains (potentially) rare materials

The risk of supply constraints arising for the individual components on this short-list will be investigated in the following sections, by quantifying and qualifying the different indicators. First we discuss equipment relevant for capture and combustion, followed by equipment for transport and storage.

5.1 Key findings

The most significant risks come from competition with the oil and gas activities, particularly for drilling equipment. Other supply risks come from equipment that is currently under development by a limited number of parties, resulting in a risk of high industry concentration and, consequently, a supplier market. The full shortlist, with the attributed risks, is provided in Table 5 - 1.

Table 5 - 1 Overview of assessed compenents and their supply chain risks

Component	**Phase**	**Risk**	**Explanation**
Gas turbines for hydrogen rich gas	Pre-combustion	High risk	*Is still under development, a few parties are developing this technology. Risk of industry concentration and a suppliers market.*
Drilling rigs	Storage	Offshore: Medium to high risks. Onshore: Medium risk	*Severe competition with oil and gas extraction activities is likely, especially for offshore rigs.*
Pipelines (incl. vessels)	Transport	Medium to high risk	*Pipelayers may have their order books full for several years, especially large diameter projects. Severe competition with NG transport can be expected*
Compressors	Capture/ Transport	Medium to high risk	*Only a few suppliers can deliver high pressure (>120 bar) compressors, especially those that can sustain* CO_2 *that contains impurities.*
Catalysts for DeNOx units	Post-combustion	Medium risk	*On the long term (>2030), shortages of metals such as tungsten and vanadium might occur.*
Solvents	Post-combustion	Medium risk	*High future demand together with limitations in the flexibility of the market, may lead to limited supply and/or higher costs. .*
Absorption towers	Post-combustion	Low to medium risk	*Technology is mature, but shortages of stainless steel or packing material might lead to longer lead times. Order books of suppliers might be full in times of high demand in other sectors.*
Catalysts for acid gas recovery unit and water gas shift conversion	Pre-combustion	Low to medium risk	*On the long term (>2030), shortages of metals such as cobalt might occur.*
Air separation units	Oxyfuel/pre combustion	Low to medium risk	*Increasing demand in other sectors is expected as well. Only a few suppliers for large ASUs are active.*
Advanced flue gas treatment	Oxyfuel combustion	Low risk to medium	*Existing technology, but is still in R&D to be adjusted for oxyfuel combustion.*
Boilers for oxyfuel combustion	Oxyfuel combustion	Low to medium risk	*Boilers for oxyfuel combustion are still in the R&D phase*

5.2 Capture - Oxyfuel

Oxyfuel combustion has not yet been implemented on a commercial scale. For oxyfuel combustion, we assessed (1) the advanced flue gas treatment and (2) air separation units (ASU) as the most critical components subject to supply chain constraints: The ASU, because it is also applied in a growing number of industrial processes and the advanced flue gas treatment, because it is still in the R&D phase.

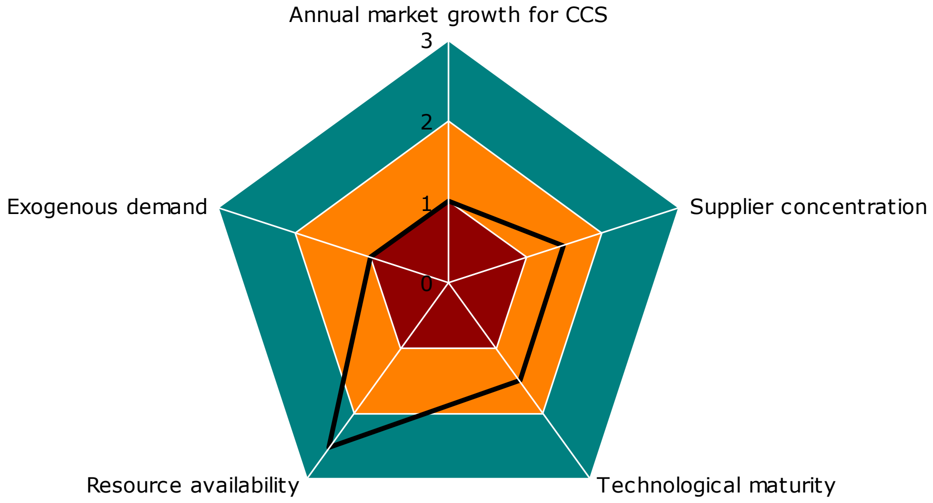
5.2.1 Boilers for oxyfuel combustion

Key message: *Low to medium risk: boilers for oxyfuel combustion are in the R&D phase and should be commercially proven to cope with changes in temperature profile, combustion characteristics and flue gas chemistry.*

Technology description
Combustion with nearly pure oxygen in an oxyfuel boiler changes the temperature profile in the boiler and flue gas chemistry. The combustion temperature is limited by the materials that are currently used. The steam cycle and boiler island therefore need considerable changes, unlike a conventional pulverised coal fired boiler. Examples include configuration and design of burners and heat exchangers.

Combustion with pure oxygen is the ultimate purpose of oxyfuel combustion, as this will significantly reduce mass flow in the boiler and flue gas cleaning sections. This will then reduce the specific investment cost of the boiler and power plant. The high temperatures and concerns about coal combustion chemistry encountered in pure oxygen combustion are partially averted by recycling a proportion of the flue gas. Recycling of the flue gas is necessary to control the temperature in the boiler. In the future however, development in high temperature resistant materials (e.g. nickel based alloys) may allow higher combustion temperatures in the boiler.

Important R&D issues for the heat exchangers are fouling and corrosion due to increased concentration of, sulphur oxides for example. Material selection and placement of heat exchangers should be optimised.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	Commercially proven	**High**	Driver
(2)	1-5%	**Oligopoly**	**Demonstration phase**	**Medium**	Neutral
(1)	**>5%**	**Monopoly**	**R&D phase**	Low	**Barrier**

Figure 5 - 1 Assessment of the indicators for boilers for oxyfuel combustion

Annual market growth for CCS/Supplier concentration

Oxyfuel combustion technology was originally researched to reduce NOx emissions from coal firing and is currently applied in the glass and metallurgical industry. The market for oxyfuel combustion could benefit from market growth in oxyfuel applications in other sectors, but it is more likely that the annual market growth for CCS applications would be much higher (i.e. >5%) if oxyfuel becomes the dominant CO_2 capture technology.

Several large scale and globally oriented technology suppliers are developing the technology for implementation. The most prominent suppliers are Alstom, Air Liquide, Doosan Babcock, Hitachi, IHI cooperation and Clean Energy Systems (gas fired oxyfuel). Supplier concentration is therefore scored between ‘Monopoly’ and ‘Oligopoly’.

Technological maturity

So far, the concept has not been applied to large-scale utility boilers for steam generation and power production.

R&D projects are in place to test and demonstrate oxyfuel combustion. A project undertaken by Total, encompasses the conversion of an oil fired steam boiler, CO_2

treatment and compression, transport and injection in a nearly depleted natural gas field. A coal fired oxyfuel pilot plant is being demonstrated by Vattenfall with a 30 MWth capacity. Vattenfall plans to systematically scale up the oxyfuel concept with a 300 MW demo plant in 2015 and a commercial 1000 MW power plant in 2020. A 40 MW oxyfuel combustion demonstration project in Renfrew by Doosan Babcock started, in 2009, firing pulverised coal with recycled flue gas. This test facility will focus on testing materials and acquiring knowledge on corrosion, fouling and slagging mechanisms within the concept. Technological maturity is therefore scored between 'R&D phase' and 'Demonstration phase'.

R&D is continuing to improve alloys for heat exchangers in future ultra supercritical pulverised coal fired power plants with high steam temperatures. Oxyfuel technology could benefit from this R&D as improved metallurgy is one of the drivers for advancing oxyfuel performance.

Exogenous demand

The development of oxyfuel boilers will only occur if there is demand for oxyfuel combustion. There is currently no exogenous demand and therefore no exogenous incentive to develop this technology. This absence of demand from other sectors can be regarded as a risk, because the only driver for the developments will then be CCS.

Conclusions

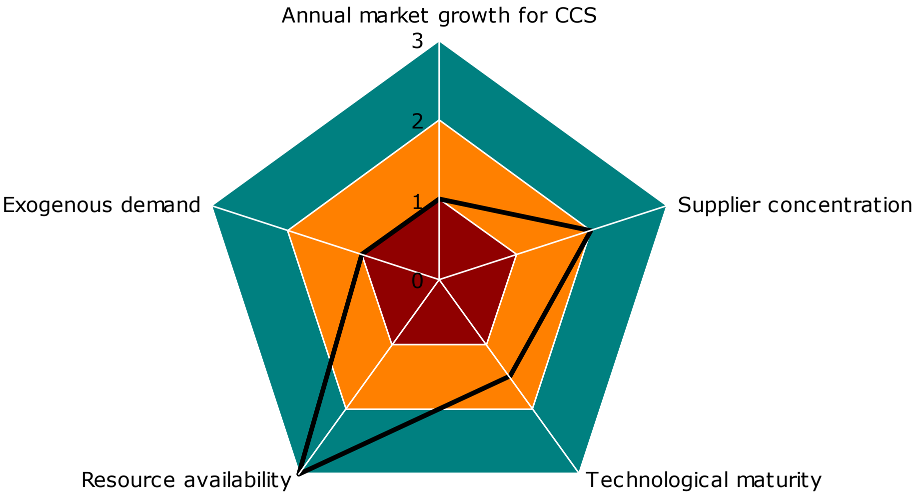
Boilers for oxyfuel combustion, including design and configuration of burners and heat exchangers, are currently in the demonstration phase and require further R&D before commercialisation. Demand for oxyfuel combustion is existent in other sectors but is not expected to be a significant driver or barrier for deployment. The timely supply of specific alloys to withstand corrosion and high temperatures may be a point of concern for future development. Several large international players are developing and testing the oxyfuel technology, including boilers, rendering the risk of one player dominating the market, low. Overall, oxyfuel boilers are considered to have a low to medium risk.

5.2.2 Advanced flue gas treatment

Key Message: *Low to medium risk: advanced flue gas treatment for oxyfuel combustion is in the R&D phase, but concepts are based on existing and mature technologies.*

Technology description

The flue gas from an oxyfuel installation has a high CO_2 concentration, but also contains NOx, Ar, N_2, O_2 and SO_2 when it enters the CO_2 treatment train. There are several options for the treatment of the raw CO_2 stream. The first option is to co-inject the contaminants together with the CO_2. This only requires the compression and drying of the flue gas stream. The second option is to purify the CO_2 with multiple auto-refrigeration flash steps. Here, the gaseous pollutants are separated from the CO_2 stream and vented into the atmosphere. The remaining fraction is co-injected. A deNOx installation may be used to clean the vent stream. Another concept is suggested and tested by White et al. (White, Torrente-Murciano et al. 2008; White, Torrente-Murciano et al. In Press, Corrected Proof) and incorporates compression of the flue gas and removal of NOx in the form of nitric acid (HNO_3) through a series of reactions. As suggested by White et al. the SO_2 may be recovered from the CO_2 stream in the form of sulphuric acid (H_2SO_4) through reaction with NO_2.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	Commercially proven	**High**	Driver
(2)	1-5%	**Oligopoly**	**Demonstration phase**	Medium	Neutral
(1)	**>5%**	Monopoly	**R&D phase**	Low	**Barrier**

Figure 5 - 2 Assessment of the indicators for advanced flue gas treatment

Annual market growth for CCS/Supplier concentration

Among others, Doosan Babcock and Air products (together with other parties) are developing and testing advanced flue gas technologies based on distillation, to clean NOx and SOx from flue gases from power and industrial (White, Strazisar et al. 2003; White, Allam et al. 2006; White, Torrente-Murciano et al. 2008; White, Torrente-Murciano et al. In Press, Corrected Proof). There is currently no mature market for advanced flue gas cleaning for oxyfuel configurations, although several large players (such as Linde, Air Products, Doosan Babcock, Air Liquide, Total, BOC and others) are active in oxyfuel combustion (R&D).

Technological maturity

Although oxyfuel fuel technology is applied in several industrial applications, advanced flue gas treatment is not yet proven for oxyfuel coal combustion. The absence of advanced flue gas treatment for oxyfuel configurations firing coal (or biomass) would not be a significant capacity constraint as conventional flue gas treatment technologies can also be used in an adapted form[15]. The oxyfuel demo plant operated by Vattenfall in Germany has begun with a more conventional set of (adapted) flue gas cleaning technologies, but advanced methods are being tested by Air Products at the demo site from May 2011. This incorporates sour compression of the flue gas that allows the removal of impurities during the compression process. Ongoing R&D is needed however, to optimise flue gas treatment in an oxyfuel configuration. Therefore, the technological maturity is rated between 'R&D phase' and 'demonstration phase'.

Exogenous demand

The development of flue gas treatment systems will only occur if there is demand for oxyfuel combustion. There is currently no exogenous demand and therefore no exogenous incentive to develop this technology. This absence of demand from other sectors can be regarded as a risk, as the only driver for the developments will be CCS.

Conclusion

Advanced flue gas treatment for oxyfuel combustion is still not proven. There is a risk that developments will take more time, especially because there is no demand for this technology for other applications, i.e. no other drivers for development than CCS. However, existing configurations could be slightly adjusted and implemented. Because there is an alternative, the supply of flue gas treatment is a low to medium risk.

5.2.3 Air separation units (ASUs)

Key message: *Low to medium risk: large ASUs are also required in other sectors, in times of peak demand order books of suppliers might be full and delayed deliveries.*

Technology description

The first step in oxyfuel and pre-combustion is producing an almost pure O_2 stream by separating air in an Air Separation Unit (ASU). The oxygen is then fed into to a gasifier where it reacts with the fuel to form syngas.

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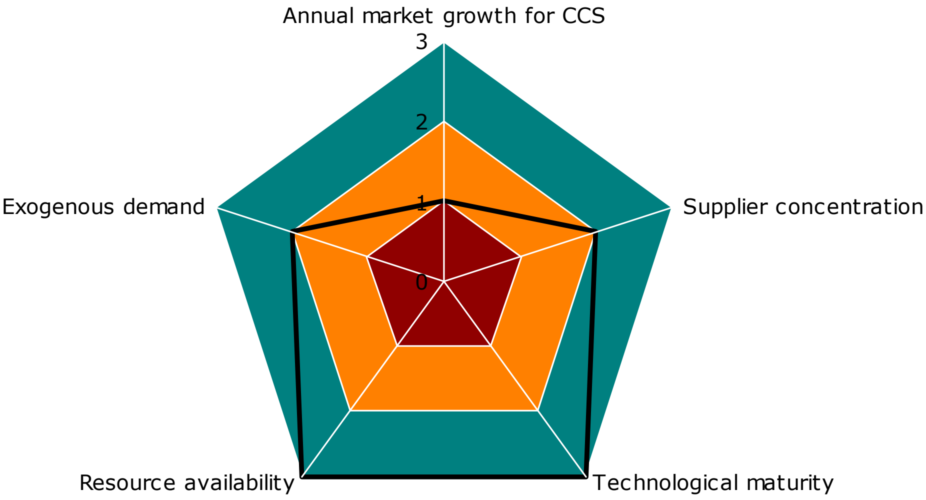
[15] The needed developments also depend on future environmental legislation, regarding the purity of the injected CO_2.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	**Commercially proven**	**High**	Driver
(2)	1-5%	**Oligopoly**	Demonstration phase	Medium	**Neutral**
(1)	**>5%**	Monopoly	R&D phase	Low	Barrier

Figure 5 - 3 Assessment of the indicators for ASUs

Annual market growth for CCS/Supplier concentration

There is already a large and increasing ASU demand in industries, such as the iron & steel, chemical industry[16], and the gas, coal- and biomass-to-liquids (XTL) manufacturing industry. Oxygen production has increased substantially over the past few decades and current production is estimated at 1.5 Mt per day (~0.5 Gt per year).[17] The four largest suppliers - Linde, Air Products, Air Liquide and Praxair - account for 70-80% of the global market (SRI, 2008).

Assuming two third of the CCS capacity to be equipped with oxyfuel- and pre-combustion, oxygen demand for CCS could be in the region of 2 GtO_2 by 2030 and 6 Gt O2 by 2050.[18] To accommodate for the demand for oxyfuel- and pre-combustion, the ASU market should grow by over 5% per year until 2030 to accommodate the demand for CCS. Nevertheless, the required growth of the ASU market for CCS purposes is estimated to be smaller than the growth that has been realised for ASUs in the past decade (about 20% per year).

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[16] For example for ethyleen oxide, reforming processes, methanol production

[17] This is an Ecofys estimation, no comprehensive statistics are available

[18] This demand will be lower if innovative integrated concepts are applied, for instance using oxygen conduction membranes (OCM) which combines/integrates oxygen separation and oxyfuel combustion.

Technological maturity

ASU is a mature and proven large-scale technology, but new developments are still expected for membrane separation technologies that will allow oxygen removal with lower energy penalties. Incremental improvements in cryogenic ASUs are expected in terms of economies of scale and efficiency. No significant technological bottlenecks are expected for ASUs used for oxyfuel or pre-combustion.

Resource availability

Common construction materials such as carbon and stainless steel, aluminium and copper are used extensively in fabricating air separation plant components. Carbon steel is a preferred material, used for milder temperature piping and construction (above -30°C). For low temperature heat exchangers and columns, aluminium alloys are used[19].

Exogenous demand

ASUs are also needed in other industries, such as chemical, steel and XTL facilities. These sectors will are likely to grow in the coming decades, particularly in Asia. Increasing demand may be a constraint for CCS if a large share of CCS is fulfilled with oxyfuel or pre-combustion technology. Rapidly increasing demand or peak demands for ASUs in other sectors may result in full order books of suppliers that are able to supply large scale ASUs, affecting lead-time and prices of this component.

Conclusions

The technology is mature, applied in many industrial processes and faces increasing demand, particularly in Asia. This could result in order books and longer lead-times, i.e. temporal constraints. Because these constraints will probably be temporarily, the supply chain risk is ranked between low and medium.

> *"If scaleup efforts are successful and the existing fleet of coal-fired power plants adopts it broadly, the resulting oxygen demand will be phenomenal."*
> Ramachandran of BOC (now Linde Group) in Goliath, 2006

5.3 Capture - Post-combustion

Post-combustion can be applied to flue gases from fossil thermal power plants that currently dominate the power sector and to existing or future industrial installations in, for example, the cement and steel producing sector. For post combustion, we identified three critical components: (1) Absorption towers, because they need to increase in size and require substantial amounts of packing

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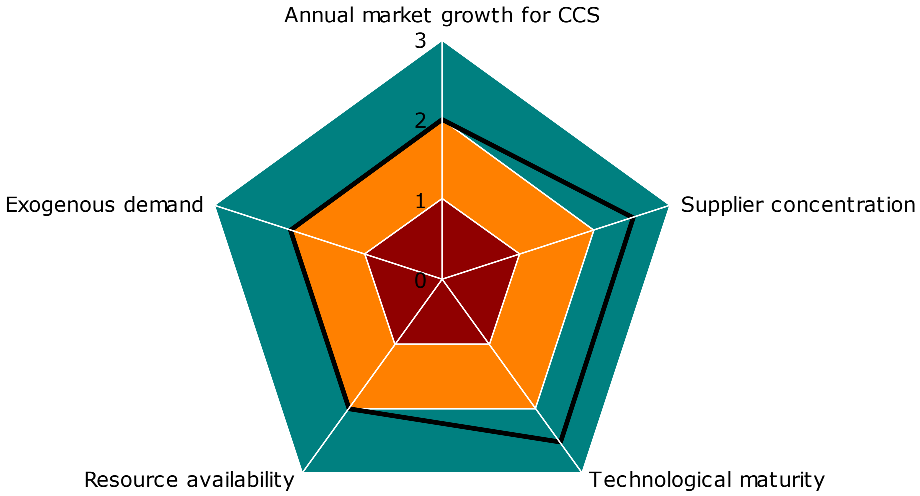
[19] See http://www.asiaiga.org/docs/AIGA%20056_08_Safe%20practices%20guide%20for%20cryogenic%20air%20separation%20plants.pdf

material; (2) Solvents, mainly because patents may result in market concentrations; (3) Catalysts for the deNOx units, because scarce materials are required.

5.3.1 Absorption towers

Key message: *Low to medium risk: There are many players and the technology is mature. Absorption towers will also be needed in other sectors and in times of peak demand, order books of suppliers might be full. Temporary shortages of stainless steel and packing materials could also create longer lead times.*

Technology description
In the absorber tower, the CO_2 is removed from the flue gas and absorbed by the solvent; it is typically a large steel or concrete structure that contains packing material that creates a greater contact area between the flue gas and the solvent.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	**Open market**	**Commercially proven**	High	Driver
(2)	**1-5%**	**Oligopoly**	**Demonstration phase**	**Medium**	**Neutral**
(1)	>5%	Monopoly	R&D phase	Low	Barrier

Figure 5 - 4 Assessment of the indicators for absorption towers

Annual market growth for CCS/Supplier concentration
A large variety of suppliers (Fluor, Linde, Siemens, Powerspan, Aker, MHI, BASF, HTC Pure Energy and Alstom) are active worldwide, although for the very large towers, only a limited number of suppliers might be available. Therefore, we rank the supplier concentration between Oligopoly and Open market.

Technological maturity

Absorption in packed columns/towers is a very mature technology. Development is ongoing to optimise the columns and packing for CO_2 capturing to reduce capital cost and the need for raw materials.

Although the absorber is essentially a mature technology, engineering limits do apply to the size of absorbers most likely needed for large-scale CCS projects. Absorption towers at the size envisaged for full-scale CCS plants – in the region of 10m x 15m x 50m - are currently not applied in other sectors. Given possible engineering and supply limits of large scale absorbers, a multi-train approach might be adopted that runs smaller parallel absorbers (Mott MacDonald 2010; Simmonds, Lonsdale et al. 2010).

BOX 3 – Steel demand for CCS

Steel requirement for a large super critical coal boiler and its associated high pressure steam parts easily amounts to approximately 10,000 tonnes of specialist steels and alloys (MottMacdonald, 2010). The total steel requirement for a 1 GWe pulverised coal fired power plant with capture and compression amounts to approximately 100,000 tonnes of steel, including various grades (estimate is based on Koornneef et al, 2008). By adding the steel requirements for pipelines and storage facilities (predominantly steel requirements for well bores) this can be increased by several 10,000s of tonnes, largely dependant on the transport distance and depth of wells. If we assume 125,000 tonnes of steel per GW, up to 6 million tonnes of steel would be required on an annual basis in the CCS Roadmap by 2030 (14 million tones by 2050). The annual crude steel production in 2009 amounted to 1,219 Mtonnes of steel (www.worldsteel.org). The steel requirement for CCS projects therefore constitutes approximtely 0.5% of the current global production in 2030 (1% by 2050). In 2010, approximately 23 Mtonnes of stainless and heat resisting steel was produced (www.worldstainless.org): If 10% of steel for CCS were stainless (which is an overestimation, and can be regarded as an upper limit), a 2.5% (5% in 2050) increase of the stainless steel production would be

Resource availability

An absorber tower is a steel vessel supported by a steel or concrete frame. Concrete absorber towers are also being proposed[20]. Packing (metal or plastic) in the absorption column is used to increase the contact area. Simmonds et al (Simmonds, Lonsdale et al. 2010) reports an interesting quote by an absorber supplier stating that, one large scale absorber (out of two needed for a large scale CCS plant) would require the entire global production capacity of their preferred packing supplier. This implies that absorber suppliers might run into supply shortage.

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[20] The CO_2 capture test facility in Norway (Mongstad) uses a concrete absorber with internal lining.

Furthermore, corrosion resistant steel may be required, as potential corrosive inductive materials such as amines are used in the capture process. The supply of stainless steel might encounter (temporarily) shortages as demand varies strongly with economic conjuncture. Because the shortages are probably only temporal and not structural, we rated the risk for resource availability, as medium. Both the steel and concrete absorber vessel will use stainless steel, although the concrete version will use less. A stainless steel related capacity constraint will affect the concrete version to a lesser extent and the supply chain risk is likely to be lower.

Conclusions

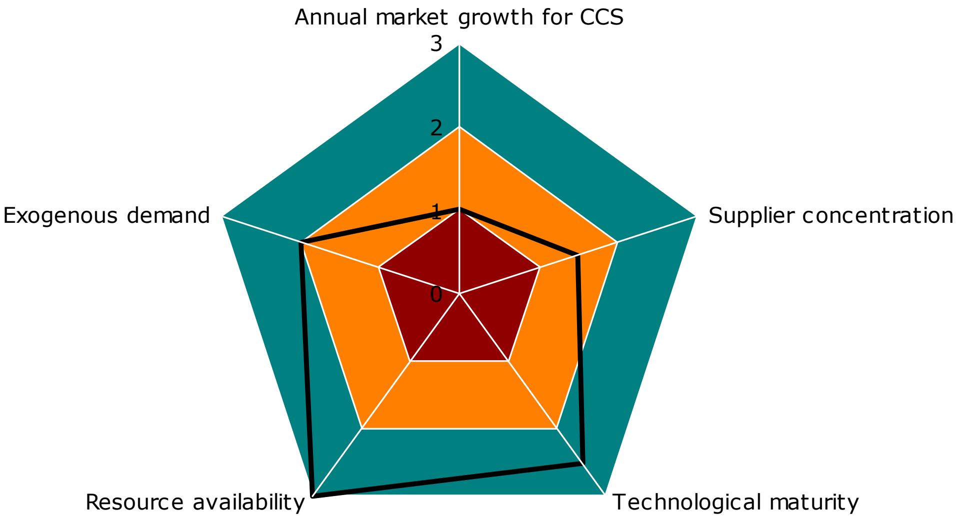
Absorption towers are applied in several industrial applications and are a mature technology. However, absorption towers at the size envisaged for full-scale CCS plants do not currently exist. Alternatively, a multi-train approach could be applied. The main barrier could be the supply of stainless steel and packing materials, which would lead to temporal constraints. The potential temporal shortages of resources translates to a low to medium risk for the supply of absorber towers.

5.3.2 Solvents

Key message: *Medium risk: high future demand for solvents and limitations in the flexibility of the market (vertical supply chain integration and interdependency) may lead to supply chain constraints for projects using post combustion capture. Research is also still needed to optimise the solvents of CO_2 capture.*

Technology description

In the absorber tower, the CO_2 is removed from the flue gas and absorbed by the solvent. The CO_2 is removed again from the solvent by the addition of heat and/or lowering the pressure.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	**Commercially proven**	**High**	Driver
(2)	1-5%	**Oligopoly**	**Demonstration phase**	Medium	**Neutral**
(1)	**>5%**	**Monopoly**	R&D phase	Low	Barrier

Figure 5 - 5 Assessment of the indicators for solvents

Annual market growth for CCS/Supplier concentration

Current solvent production to remove acid gases is large but not as large as future demand for CO_2 capture. Hundreds of AGR (acid gas removal) units are operating worldwide and solvents are highly proprietary and shielded by patents. Monopolies exist for some solvents and their application to the CO_2 capture system. The increase in patents (as indicated in Figure 5 - 6) indicates that there is increasing activity in this field that may suggest a future diversification of capture options and suppliers. There is however a risk that the ‘winning’ or most advanced solvents will be owned by a limited number of parties. A limited number of large companies in both the oil and gas and heavy equipment sector hold many of the patents. This could result in higher costs, than if the supply of solvents were taking place in a (more) open market. Lee et al (Lee, Iliev et al. 2009) however note that “specific market conditions play an important role in the extent to which intellectual properties may be a barrier to deployment of the latest technologies”.

Most solvents currently used for CO_2 separation are based on ethanol amines. In Box 4, we discuss limitations to production capacity of ethanol amines which may result in supply chain constraints if solvents continue to rely on ethanol amines, solvent consumption is not reduced or the production capacity of these chemicals is not expanded by 2050.

Future joint ventures may be undertaken (as is already the case) by chemical suppliers and OEM (original equipment manufacturer) companies and service providers[21] to offer complete capture systems, i.e. the complete technology block[22]. These joint ventures may have their preferred suppliers of sub-components. This means that suppliers of solvents, equipment and complete technology blocks may be ‘linked’ and become interdependent. A constraint in the supply of materials and equipment for one supplier in such a joint venture may result in a constraint for the complete CO_2 capture technology block. Theoretically, this decreases the flexibility of the suppliers market to meet significant changes in demand.

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[21] In Appendix C, we discuss the difference and overlap between technology providers and service providers

[22] Examples of vertically integrated joint ventures are: Doosan-Babcock (OEM) and HTC Purenergy (solvent); Alstom (OEM, Solvent) and Schlumberger (storage); Linde (OEM), BASF (solvent) and RWE (utility); MHI (OEM, solvent) and Kansai Electric Power Company (utility);

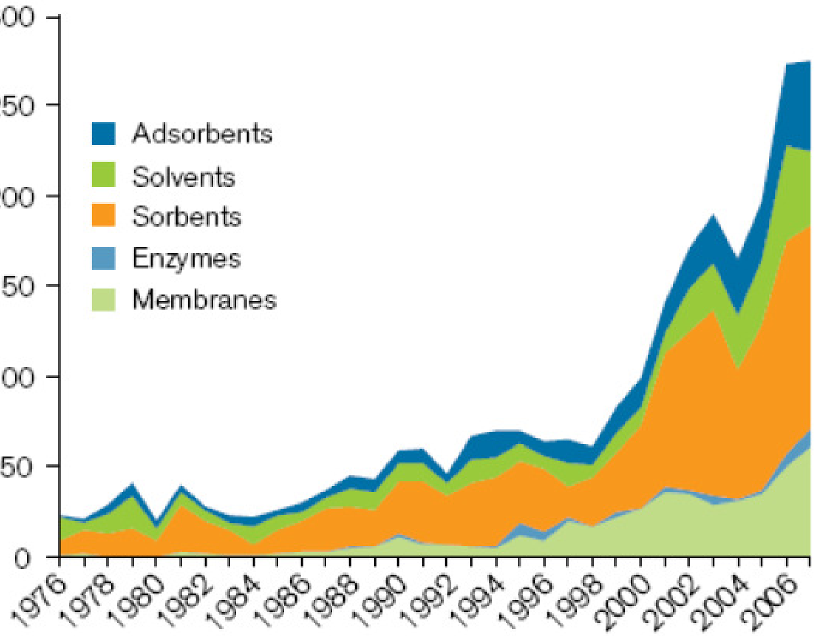


Figure 5 - 6 Over 9,000 patents and patent applications were identified as being generally relevant to the technology of carbon capture. This related to post combustion carbon capture and compression and did not include an assessment of the CO2 pipeline and storage of CO_2. Source: (Lee, Iliev et al. 2009)

Technological maturity

R&D is focused on improving the performance of existing solvents and searching for new solvents. Solvents have been used for decades to remove CO_2 from gas streams

and are proven to work. Energetic and environmental performance is important in solvent R&D. Additional points of attention in R&D are cost and material optimisation, lowering capital and operational cost of CO_2 capture.

BOX 4 – Solvent demand for post-combustion

Solvent consumption in post-combustion capture concepts is currently an important topic of R&D, especially when applied to flue gases with high concentration of impurities. Solvent consumption during pilot testing using mono-ethanol-amine (MEA) was found to be in the region of 1.5 kg/tonne of CO_2 captured. Lower values in the region of 0.1 kg/tonne for other solvents have also been reported (see Koornneef (2010) for an more detailed overview). Here we conservatively take the 1.5 kg/tonne to estimate the required annual production of solvents in 2050. Annual capture of CO_2 amounts to approximately 10 Gt in 2050. If we assume that 50% of that CO_2 is captured using post-combustion solvents we find the highest end of the range of required solvent production in 2050: about 7,500 ktonnes of solvent. The production capacity of ethanolamines was 1,500 ktonnes in the year 2004 (Goliath, 2006). Solvent consumption for CCS projects would therefore consume about five times the annual production capacity installed in 2004. This estimate is very much at the high end of range, as MEA is not likely to be the dominant solvent in 2050. Consumption rates are at the high end and no growth in production capacity is assumed here. Nevertheless, it shows that CCS results in a significant increase in demand for solvents and that supply chain bottlenecks may occur under very specific conditions.

Resource availability

Solvents are produced using base chemicals, such as ammonia, hydrogen and nitrogen. Most solvents are therefore composed out of abundant substances.

Exogenous demand

Developments must occur to optimise the solvent for CCS. These developments are only driven by potential CCS demand. However, existing production capacity can be adjusted to make solvents for CCS, but whether this is possible depends on the winning types of solvents. We therefore rank exogenous demand as neutral.

Conclusions

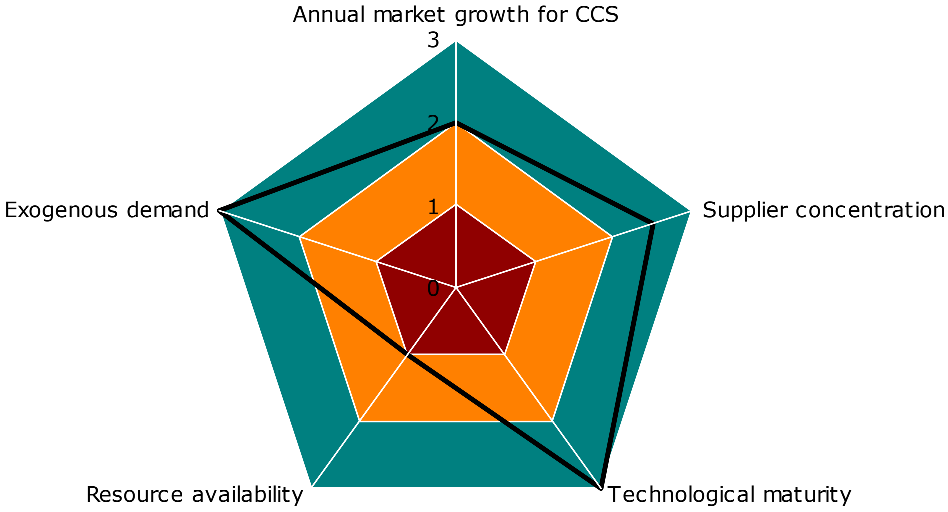
The current production capacity of ethanol amines is not sufficient to meet the demand for solvent production. There is however sufficient time to increase production capacity. A more significant barrier might be that ‘winning’ solvents could be limited due to intellectual property (IP) restrictions. This might trigger vertical supply chain integration and interdependency, leading to a limited number of suppliers. The possibility of limited production capacity of ethanol amines and a limited number of suppliers, makes solvents a medium risk.

5.3.3 Catalysts for deNOx units

Key message: *Medium risk: DeNOx is a mature technology that has been heavily implemented over previous decades. The catalysts applied in DeNox installations may include scarce metals. Beyond 2030, large quantities are needed and resource availability may become a high risk.*

Technology description

With catalysts, NOx is turned into nitrogen and water. DeNox units are not only applied on thermal power plants with CCS, but also on plants without and in many countries, environmental performance standards force utilities to apply these environmental control systems. We decided to include catalysts for the deNOx process in this assessment because if post-combustion capture is applied, this process step is indispensable.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	**Open market**	**Commercially proven**	High	**Driver**
(2)	**1-5%**	**Oligopoly**	Demonstration phase	Medium	Neutral
(1)	>5%	Monopoly	R&D phase	**Low**	Barrier

Figure 5 - 7 Assessment of the indicators for catalysts for deNOx units

Annual market growth for CCS/Supplier concentration

NO_x and SO_2 control systems are already applied to a substantial number of fossil fuel power plants (see Graus & Worrell, 2007).[23] Based on Platts (2006), we

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[23] E.g. in Japan and Germany more than 50% of the coal-fired power plants is equiped with flue gas treatment for NOx emissions. SO_2 control systems are even
more widely applied: In Korea, Japan, Germany and the Nordic countries, more than 70% of the coal-fired power plants is equipped with SO_2 control.

estimate that around 30% of the coal plants are equipped with some sort of NOx control system, of which about 5% (60GW) is Catalytic Reduction (SCR)[24]. The type of deNOx systems that will be used for CCS depends on the environmental standards and technical requirements of the capture system. Assuming that the standards will be high, SCR is a technology likely to be implemented for CCS. If 1/3 of the CCS plants are post-combustion, the SCR technology should grow by approximately 4% per year. However, it is very likely that demand will increase in a scenario without CCS as well: China is currently increasingly the application of environmental control systems and it is very likely that other regions will also enforce NOx regulation. Consequently, the discussion in this section does not apply solely to CCS, but for deNOx systems in general[25], although purity standards (lower NOx levels) might be lower for CCS because of the tolerance levels of MEA solvents.

The number of suppliers is currently limited to a few large players (SCR Tech, Cormetech (owned by Mitsubishi Heavy Industries and Corning, Inc.), Johnson Matthey, Argillon (formerly Siemens), BASF / CERAM, Haldor-Topsoe, Hitachi America and Enerfab. It is possible that there are also local players, but detailed market information has not been found.

Technological maturity

DeNox technology such as SCR is a mature and proven technology that is increasingly applied worldwide (Graus & Worrell, 2007).

Resource availability

Catalysts for NO_x removal consist of relatively scarce materials, such as vanadium and tungsten. EC (2010) assessed tungsten as being, 'a critical material with a high supply risk' (see Figure 5 - 8), although recycling of catalyst can mitigate the risk. Supply may become a risk after 2030, when large quantities are needed, see Box 5. For SO_2 control systems in the combustion based concepts, abundant resources such as calcium carbonate can also be used and typically, no catalysts are used.

Exogenous demand

NO_x and SO_2 emissions standards will probably be implemented and tightened in more regions of the world, such as India and China. CCS is likely to replace conventional coal plants, so the demand for NO_x and SO_2 control systems is expected to be high, irrespective if they are installed in power plants with or without CCS. Exogenous demand is considered to be a driver, as exogenous demand assures a market for the coming decades.

Conclusions

The main risk arises from the availability of relatively scarce materials, but probably only after 2030. If no measures are taken, severe supply issues might

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[24] Statistics on the application of deNOx systems in the industry are not available
[25] e.g. deNOx demand will probably not grow due to CCS deployment

arise. However, recycling will reduce the consumption of these rare materials and therefore, we rate the risk as medium.

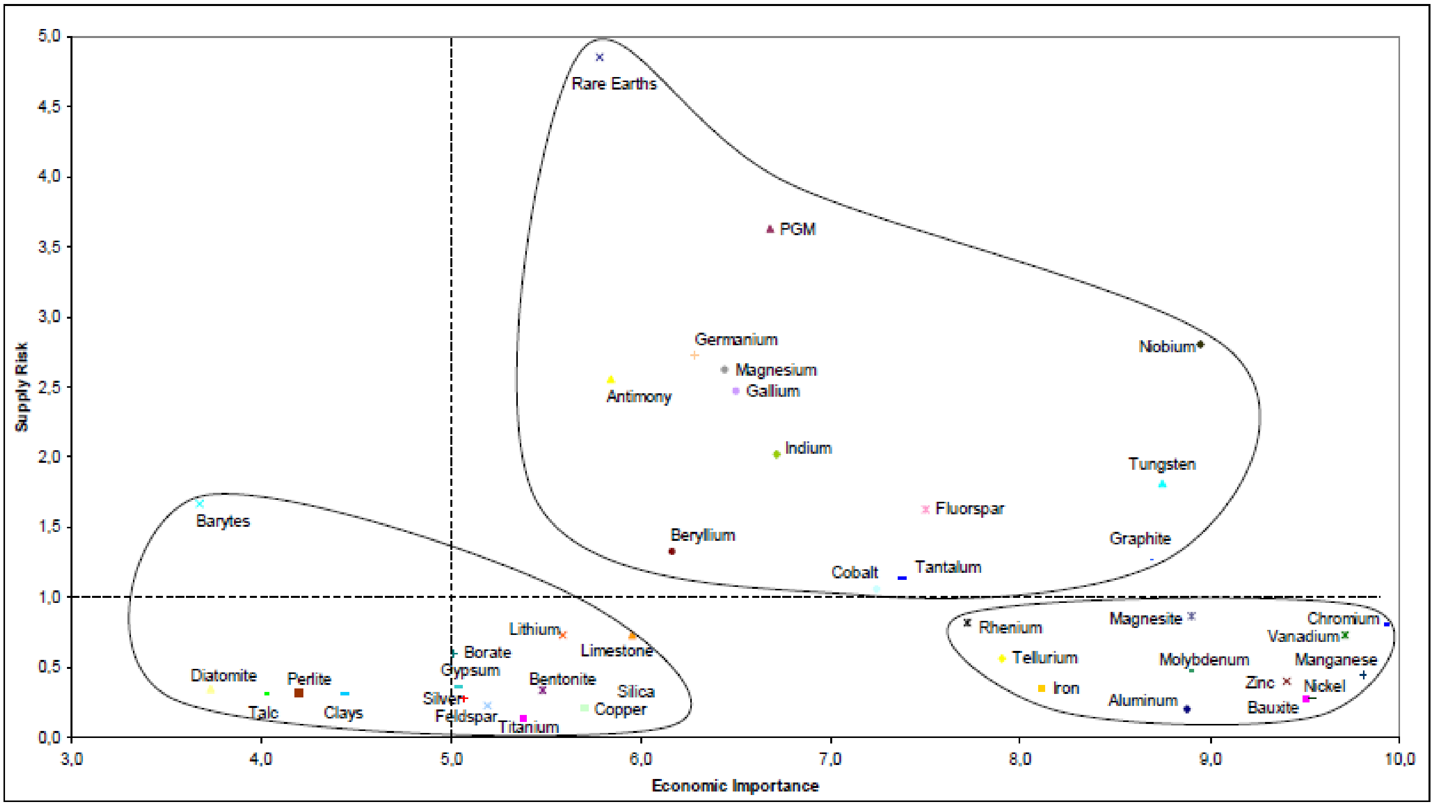


Figure 5 - 8 Supply risk versus economic importance of 41 important materials, assessed by the European Commission. The supply situation of a group of 14 materials was assessed as being critical, of which tungsten and cobalt are being used in catalysts for CCS installations. Source: EC, 2010

Box 5 – Material demands for catalysts for SCR

The current generation of catalysts for SCR units uses oxides of titanium ($\mathrm{TiO2}$) as a carrier and oxides of vanadium (V_2O_5) and tungsten (WO_3) as active components. This breaks down into 90% TiO_2, 0.5-5% V_2O_5 and 5-10% WO_3. Approximately 0.9 t/MW of catalyst material is needed and the lifetime of catalysts is 5 to 10 years, which equates to a reduction of approximately 25 kg/t NOx (Arcadis 2006; Röder, Bauer et al. 2004). We can derive from this rough estimate that up to 2030 (2050) approximately 0.1 (0.5) Mt of catalyst is needed. This does not include the spent catalyst for existing capacity or capacity of power plants not equipped with CCS. This means that by 2030 (2050), 1% (10%) of the 2009 global TiO_2 production, 2% (9%) of the 2009 vanadium global production and 8% (35%) of the global tungsten production are needed for catalysts for the deNox units on post-combustion plants.

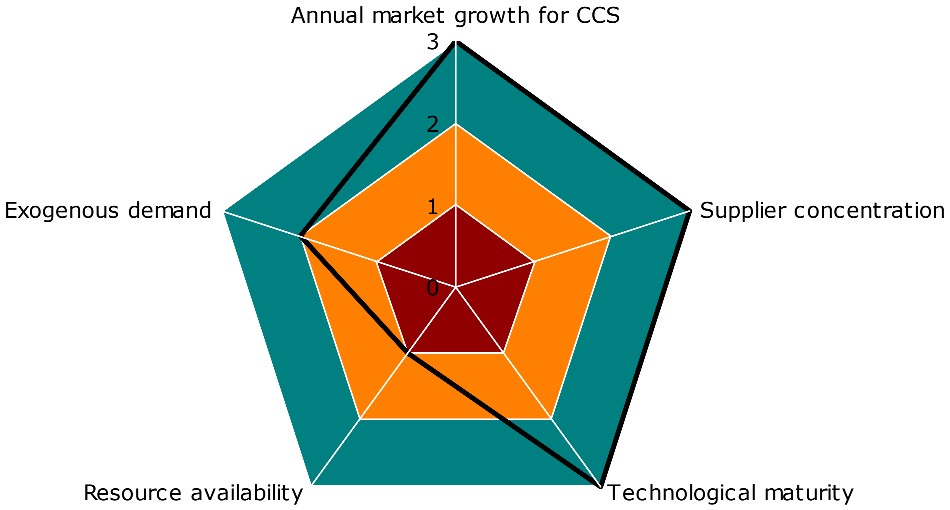
5.4 Capture - Pre-combustion

The main challenge for pre-combustion is the engineering of the complete system, integrating predominantly existing, already-scaled components in a complex facility. For pre-combustion, we assessed the following three components: (1) air separation units (ASU), already discussed in section 5.2, (2) catalysts, because some rare and maybe scarce materials are used and (3) gas turbines, because they still require developments for low-caloric gaseous fuels and are only produced by a few suppliers.

5.4.1 Catalysts for acid gas recovery units and water gas shift reactors

Key message: *Low to medium risk: considered to be mature technology and market with many players. However, over a longer-term, raw material supply (e.g. copper, cobalt) may become a (temporal) supply chain bottleneck, particularly after 2030.*

Technological description
Catalysts are used in pre-combustion to convert CO to H_2 and CO_2 in the water gas shift reactor in the sulphur recovery unit.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	**<1%**	**Open market**	**Commercially proven**	High	Driver
(2)	1-5%	Oligopoly	Demonstration phase	Medium	**Neutral**
(1)	>5%	Monopoly	R&D phase	**Low**	Barrier

Figure 5 - 9 Assessment of the indicators for catalysts for acid gas recovery units and water gas shift reactors

Annual market growth for CCS/Supplier concentration

The sulphur recovery and water gas shift process is widely applied. Aggregated market data is not available, but a stakeholder did indicate that catalysts can be procured from many parties, without lead times. We therefore do not see any barriers in the existing market.

Technological maturity

Both the sulphur recovery and water gas shift process has been widely used in the (petro-) chemical industry for decades and a variety of alternative processes are available. The water gas shift conversion step is one of the oldest industrial process using catalysts. The development of catalysts to improve the efficiency is an ongoing process and it is possible that new catalysts based on other materials will be used by 2050.

Exogenous demand

Given the expected demand growth for gas, coal and biomass to liquid (XTL) production facilities and deep desulfurisation requirements in the oil and gas industry, it is expected that the demand for catalysts used for the desulphurisation, recovery of sulphur and for the water gas shift process will increase. The growth in these sectors will be in addition to the replacement of spent catalyst.

Resource availability

Some metals used or being proposed for use in catalysts, such as copper and platinum are expected to face limitations for long-term supply. Copper based catalysts, including zinc and aluminium oxide can be used in the low temperature shift reaction (Cai et al). For the high temperature shift, a catalyst can be used based on iron oxide promoted with chromium oxide and copper oxide. Sour shift catalysts may contain activated metal oxides such as sulphided cobalt oxide, molybdenum oxide and copper-promoted iron chromium oxide.

Conversion of carbonoxysulfide (COS) to H_2S based on hydrogenation and hydrolysis and sulfur recovery includes the use of alumina cobalt-molybdate, cobalt-molybdenum and/or cobalt-nickel based catalysts (Kohl and Nielsen 1997). The required catalyst depends on the applied COS conversion and recovery process. See for more information (Kohl and Nielsen 1997; Stirling 2000; Liu, Song et al. 2010).

Cobalt was assessed by EC (2010) as being a critical material with a high supply risk (see Figure 5 - 8). The other metals used in catalysts are of lower risk but may face long-term supply limitations.

Conclusions

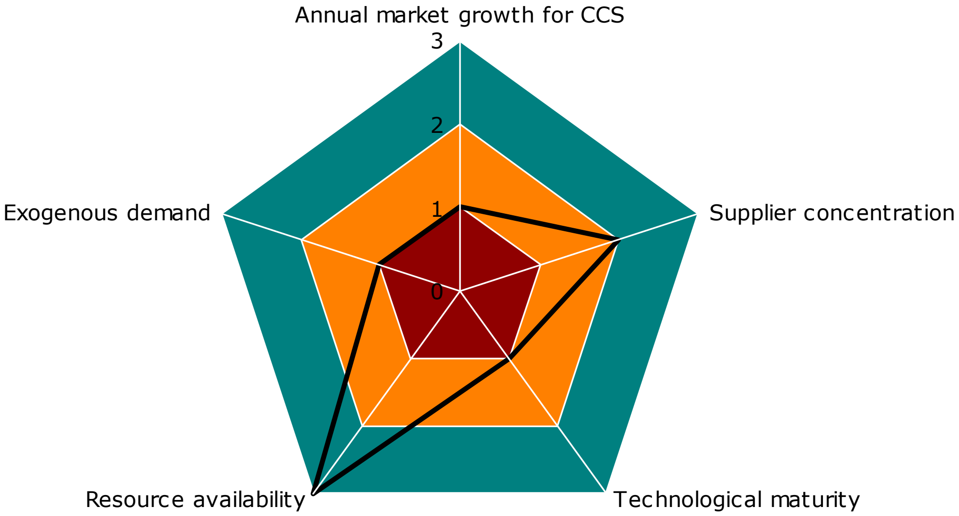
As with catalysts for SCR, the most significant risk arises from the supply of critical materials. After 2030, there other serious constraints may appear in the supply of less critical materials, such as cobalt. Recycling of catalysts is a good option to reduce consumption by catalysts and will reduce the overall risk. Because the risk can be mitigated, we rate the risk as low to medium.

5.4.2 Gas turbines for hydrogen-rich gas

Key message: *High risk: capacity constraints for this component or technology block will depend on the (peak) demand and whether all manufacturers will develop this type of gas turbine in the long-term. The most critical period is that before 2030 because the technology is not yet mature.*

Technology description

In a hydrogen gas turbine, hydrogen rich gas is combusted to produce electricity. Heat is recovered from the gasifier and the flue gas is utilised to drive a steam turbine for additional power generation.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	Commercially proven	**High**	Driver
(2)	1-5%	**Oligopoly**	Demonstration phase	Medium	Neutral
(1)	**>5%**	Monopoly	**R&D phase**	Low	**Barrier**

Figure 5 - 10 Assessment of the indicators for gas turbines for hydrogen-rich gas

Annual market growth for CCS/Supplier concentration

Demand for gas turbines that are fed with gas of a high hydrogen content, will probably be dominated by the deployment of pre-combustion technology. There are currently only four main suppliers offering or developing gas turbines suitable for an IGCC with pre-combustion capture: GE, Mitsubishi Heavy Industries, Siemens Westinghouse and Alstom.[26] Whether they all continue to develop and offer turbines in the long-term is uncertain.

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[26] See websites of Alstom: http://bit.ly/hnDdCn GE: http://bit.ly/dCROmb, MHI: http://bit.ly/hSRZ9U and Siemens: http://bit.ly/frXIfr (all pdf)

Technological maturity

The hydrogen-fuelled gas turbine is the least developed technology block in the IGCC configuration with pre combustion capture. Commercial high hydrogen- and syngas-fuelled gas turbines exist and have operational experience. However, current advanced gas turbines for large combined cycles can, so far, operate only at reduced firing capacities under these conditions. Gas turbines suppliers announced that they are prepared to guarantee advanced turbines for the hydrogen-rich fuels to apply in pre-combustion-based CO_2 capture plants. As well as stability of combustion, efficiency and environmental performance (NOx formation) also need to evolve towards the same level of performance of the natural gas fired turbines. GE, MHI and Siemens are all involved in R&D and test programmes to demonstrate adapted combustion systems for hydrogen fuel gas in advanced class (F/G) gas turbines. Alstom is not developing gas turbines for pre-combustion concepts with high capture rates and high hydrogen content in the fuel gas. The technological maturity of these types of turbines is a short-term to mid-term constraint (period 2010-2030).

Conclusions

Hydrogen turbines are still under development and CCS demand will be the sole driver for this development. There is therefore a medium risk that turbines will not be ready in time and a severe risk that it will be a suppliers market. Based on these considerations, the risk is high.

5.5 Transport

For transport, the main components are compressors[27] pipelines and both key components are discussed in the following sections. Availability of pipe laying vessels is also assessed.

5.5.1 Compressors

Key message: *Medium to high risk (for high pressure range): CO_2 compressors are mature for onshore applications (lower pressure range) but require R&D for high pressure ranges and larger scales that are often needed for offshore CO_2 transport. Ordinarily, all CCS projects would require compressors and there is therefore, a high demand compared to natural gas demand. In combination with competition for (natural gas) compressors needed in the oil and gas industry, this may lead to shortage in supply capacity.*

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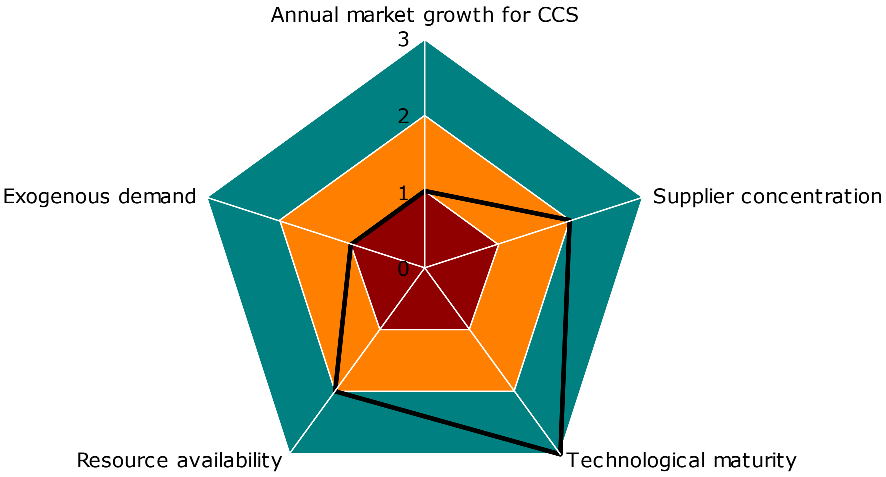
[27] mainly for injecting CO_2 into the transport network. We treat it in the transport section, though it could also be regarded as part of the capture installations. We treat it here because it is required for all three capture technologies.



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	**Commercially proven**	High	Driver
(2)	1-5%	**Oligopoly**	Demonstration phase	**Medium**	Neutral
(1)	**>5%**	Monopoly	R&D phase	Low	**Barrier**

Figure 5 - 11 Assessment of the indicators for gas turbines for compressors

Annual market growth for CCS

Compared to the compressor market for natural gas (NG) transport, the demand for CCS will be very large. Based on key figures from INGAA (2009), which estimated the current and future USA market for compressors in CCS applications, and the historic development in NG demand, we estimate that the current global market for NG compressors is almost 2 GW.[28] Based on the assumptions of INGAA (2009), we estimate that a cumulative compressor capacity demand of 120 GW for CCS would be required by 2050. Figure 5 - 12 provides an overview of the estimated annual compressor demand (current, 2020 and 2030). By 2030, the global demand for compressors for CCS will be between 5 and 6 GW. By 2020, the compressor market (relative to the current compressor demand for NG) should grow between 1 and 5%. Between 2020 and 2030, the growth rates should be between 5 and 20%. The demand will increase substantially, particularly in the Pacific region and China and India.

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[28] i.e. we applied the US pipeline need for maintenance and expansion to the natural gas production in the rest of the world. The resulting figures are thus a first order estimation.

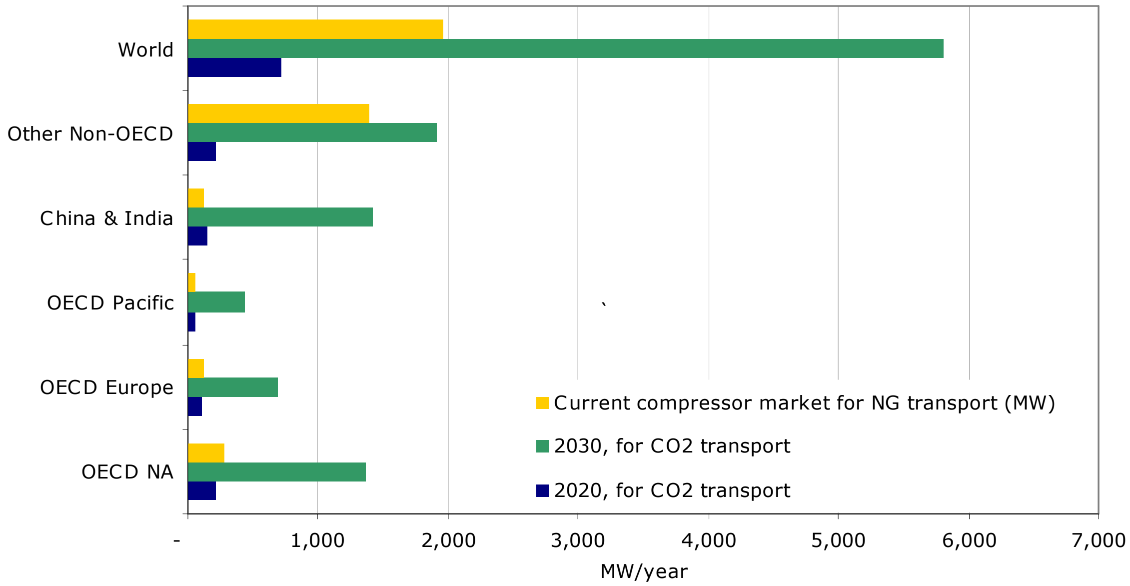

Figure 5 - 12 Estimation of the current compressor market for natural gas transport (yellow) and the demand for CCS compressor capacity in 2020 (yellow) and 2030 (green). The estimations are based on INGAA (2009) and IEA (2010).

Technological maturity

CO_2 compression is a mature technology based on technology used in (natural) gas compression, specifically adapted to CO_2 properties. New compression technologies (RAMGEN) are being developed for lower energy use, manufacturing and operational costs. Compressors are available on the scale required, at least for onshore applications (for large volumes in the lower pressure range, e.g. urea production) and are used offshore (jointly with pumps) for very high pressure ratios (above 800 bar). However, the existing compressors are typically not of the same scale as those required for large-scale CO_2 compression.

CO_2 in the dense liquid phase can be pumped using high-pressure pumps with delivery pressures up to >500 bars. Booster pumps are used to maintain the desired pressure in the pipeline (to avoid two phase flow), which is particularly necessary when long pipelines are used to transport CO_2. Pumps are also used in combination with compressors. Compressors increase the pressure of the CO_2 to reach the dense liquid phase and the desired transport pressure. CO_2 pumping is considered a mature technology.

Certain challenges do remain when applying CO_2 compression in oxyfuel technologies. This may include the compression of CO_2 with relatively high levels of impurities with integrated removal of water, SO_x and NO_x. Offshore transport of CCS will also require compressors that are able to pressurise CO_2 to higher pressures (>120 bar). These compressors are not currently available in the quantities required.

Supplier concentration

Only a few suppliers are equipped to produce compressors at the size required. The compressor market is dominated by manufacturers in Germany, Japan and the USA. Simmonds et al (Simmonds, Lonsdale et al. 2010) report that manufacturing capacity may increase if the EU market grows rapidly. Specific knowledge on compression of CO_2 may provide a 'first mover advantage' for manufacturers already supplying CO_2 compressors and/or supply to first generation compressors for CCS purposes (not expected to be very different from existing CO_2 compression installed base). Only a few suppliers can deliver high pressure compressors (>120 bars). Examples of manufacturers[29] that supply very large compressors are Dresser Rand, GE, Siemens, Mitsubishi, Hitachi and MAN Turbo (Wolk 2009). Suppliers of large CO_2 pumps are for instance Sulzer, Flowsense and GE.

Resource availability

The compressor is constructed from stainless steel. Stainless steel contains manganese, nickel and chromium and some forecasts predict a shortage of this type of alloy, particularly in times of global peak demand. Corrosion resistant materials are also required in the heat exchangers in the compressors. Stainless steel is not necessarily required if the captured CO_2 has a (very) low water content, i.e. when it does not form free water under any condition. This will, however, seldom be the case.

Exogenous demand

The natural gas market is expected to grow over the coming decades; even in the WEO 450 scenario[30], a moderate increase of natural gas demand is projected: 15% between 2008 and 2035. Natural gas production has also grown over the past few decades and the current compressor market size is probably sufficient to accommodate the future demand for NG compressors. However, in combining the demand for CO_2 compression with the demand for NG, we can expect severe competition. For CO_2 pumps we expect a less critical situation. The demand for CO_2 pumping capacity will be less than the demand for compression capacity.

Conclusions

The main risks are created by technological maturity and exogenous demand. Severe competition can be expected with the NG market. Particularly high pressure compressors (for offshore transport) are not produced in the required quantities. Technical challenges exist for CO_2 with relatively high levels of impurities. Combining these factors, we rate the supply risk for compressors to be medium to high. For CO_2 pumps we anticipate this risk to be lower.

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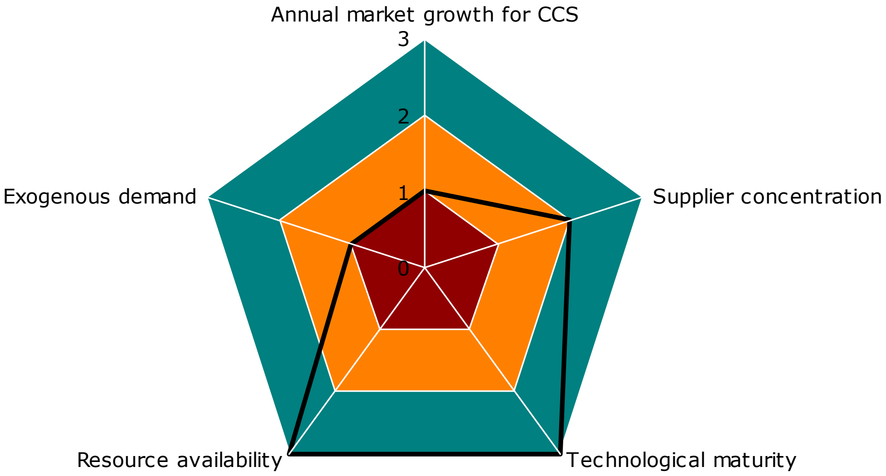
[29] Just a sample of compressor vendors: ABB, Curtiss-Wright, Elliott, Florida Turbine Technologies, Mitsubishi Heavy Industries, Solar Turbines, Turblex . (Wolk, 2009)

[30] After 2035 the demand decreases in the BLUE Map scenario (which runs until 2050)

5.5.2 Pipelines

Key message: *Medium to high risk: pipeline laying and manufacturing for CCS is mature but pipe laying capacity faces competition with the oil and gas industry. The current market for very large scale pipelines is small. The scale and amount of pipelines needed for CCS may temporarily fill order books of pipeline laying companies and increase prices. This can result in major delays in pipeline projects.*



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	**Commercially proven**	**High**	Driver
(2)	1-5%	**Oligopoly**	Demonstration phase	Medium	Neutral
(1)	**>5%**	Monopoly	R&D phase	Low	**Barrier**

Figure 5 - 13 Assessment of the indicators for pipelines

Annual market growth for CCS

Figure 5 - 14 shows the annual demand in 2020 and 2030 for pipelines for CCS in the different regions against the current demand for natural gas transmission. Estimations for the global pipeline market are based on US data from INGAA (2009), combined with NG production data from IEA (2010). We based the annual demand for CCS on the total pipeline demand from the CCS Roadmap.[31] The figure shows that, demand for CCS is lower that the current demand for NG transmission: it requires a market growth of between 1 and 5% annually. There

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[31] We assumed that the pipeline infrastructure grows with the same rate as the amount of captured CO_2. The CCS Roadmap provides a range in the estimation of pipeline demand; we used the average of this range.

are regional differences: Pipeline markets in China, India and the Pacific will probably experience higher growth rates of up to 9% per year.

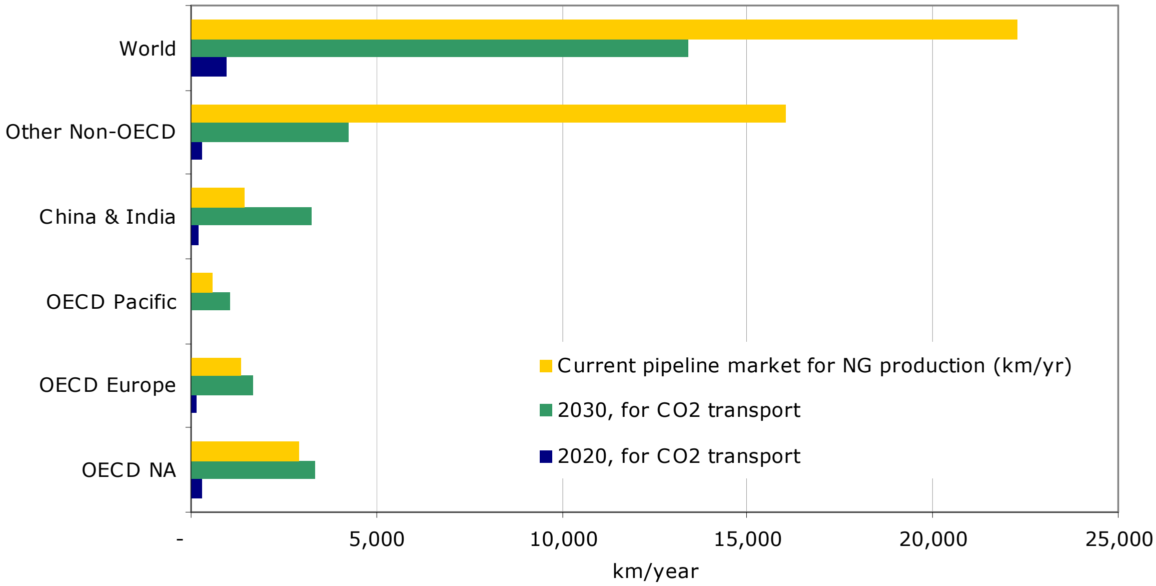


Figure 5 - 14 Estimation of the current pipeline market for natural gas transport (yellow) and the demand for CCS pipelines capacity in 2020 (yellow) and 2030 (green). The estimations of the current pipeline market for NG are based on INGAA (2009) and IEA (2010).

Supplier concentration

The number of suppliers is limited, particularly for larger pipelines, i.e. with a diameter larger than 50 cm. One interviewee (involved in a tender in a large CCS project) remarked that for some large distance projects, only three potential contractors could be found. One large-scale project can occupy the full capacity of a company for multiple years. This means that when several large-scale NG projects are initialised, supply constraints for CCS pipe laying may appear. Additionally, experienced pipe layers are scarce which means that supply cannot adapt to short-term demand increases. Long term planning is therefore of pivotal importance, although CCS may not offer sufficient guarantees for projects to do long-term planning with high investment needs.

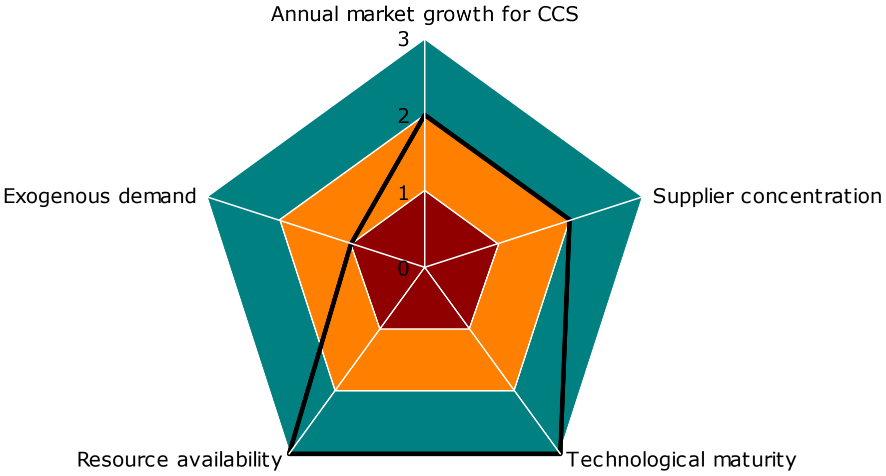
Exogenous demand

The natural gas market is expected to grow over the coming decades; even in the WEO 450 scenario, a moderate increase of natural gas demand is projected: 15% between 2008 and 2035. Natural gas production has grown over the past few decades and, like the compressor market, the current market size for pipelines is probably sufficient to accommodate the future growth in NG transport capacity. However, (as with compressors) combining the demand for CO_2 compression with the demand for NG, we can expect severe competition.

Conclusions
Demand for CO_2-pipelines will be high, compared to the current market size and severe competition with the NG market can be expected, particularly for large diameter pipelines. For large diameter pipelines, we therefore rate the supply risk to be medium to high.

5.5.3 Pipe laying vessels

Key message *Medium risk: additional demand for pipe-laying vessels because although CCS deployment is not very high, there are only a few contractors and lead times can be long.*



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	<1%	Open market	**Commercially proven**	**High**	Driver
(2)	**1-5%**	**Oligopoly**	Demonstration phase	Medium	Neutral
(1)	>5%	Monopoly	R&D phase	Low	**Barrier**

Figure 5 - 15 Assessment of the indicators for pipe laying vessels

Annual market growth for CCS/Supplier concentration
There are currently about 40 operational pipe laying vessels and 29 of which, are able to operate in deep water, owned by 15 different contractors (Quest Offshore, 2010). One vessel can place about 2 km per day, so with strong planning, one vessel can construct approximately 500 km of offshore pipeline annually. If we assume that a quarter of the total pipeline length will be located offshore, then up to eight vessels are required to construct offshore pipelines for CCS.

Exogenous demand

As mentioned previously, the natural gas market is expected to grow over the next few decades. However, the current number of vessels will probably be sufficient to maintain and extend the offshore natural gas transmission pipelines (as natural gas production has been growing in the past decade as well). A serious risk is that lead times can be long, when a large-scale project is commissioned. When structural demand is there, new vessels may be constructed, which takes about three years.

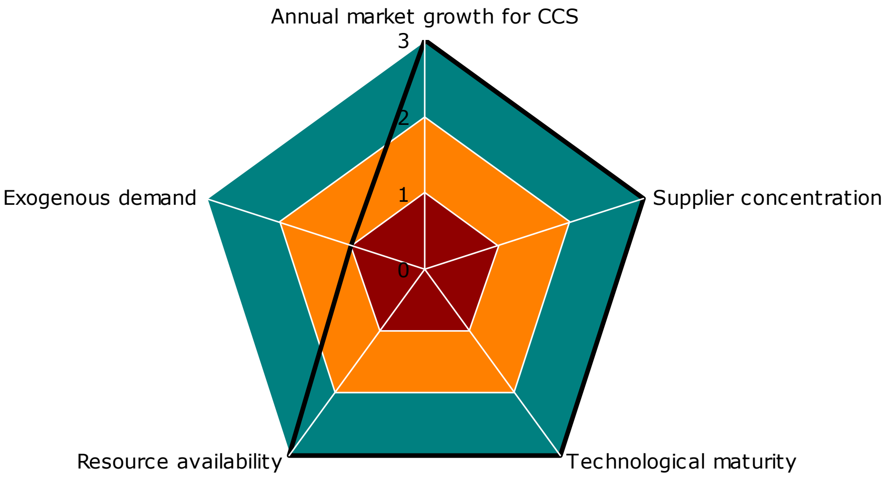
Conclusions

In competition with NG production, there is a risk of long lead times and higher day rates of vessels. Based on this, we rate the supply risk as medium.

5.6 Storage

5.6.1 Offshore drilling rigs

Key message: *Medium to high risk: In times of high oil prices, there is a severe risk that offshore drilling activities for CCS will be restricted by rig shortages or high prices.*



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	**<1%**	**Open market**	**Commercially proven**	**High**	Driver
(2)	1-5%	Oligopoly	Demonstration phase	Medium	Neutral
(1)	>5%	Monopoly	R&D phase	Low	**Barrier**

Figure 5 - 16 Assessment of the indicators for offshore drilling rigs

Annual market growth for CCS/Supplier concentration

The demand and cost of drilling rigs varies greatly with oil price. In the period, 2007-2008, during a dramatic increase in oil prices, the demand could not be met, despite a fast construction of new rigs. In 2007, in the USA alone, 349 rigs (mainly onshore) were built (NOV, 2010).

The number of drilling rigs that are needed for CO_2 storage strongly depends on the average volume of CO_2 that is injected annually per well. Furthermore, the future demand will depend on the characteristics (e.g. size, permeability) of the reservoir. The assumptions below are subject to large uncertainties.

Assuming that the average capacity of a well varies between 1 $MtCO_2$/year per well (as is the case in the Sleipner project in the North Sea) and 1 $MtCO_2$ per 3 wells (as is the case in the In Salah project in Algeria), between 10,000 and 30,000[32] wells are needed by 2050 to inject all the captured CO_2. If we assume a quarter of these wells to be located offshore, between 40 and 125 wells should be drilled annually between 2020 and 2050[33]. If we assume that, annually, about 10 wells can be drilled by one offshore rig[34], between 4 and 13 rigs are needed for CCS. In April 2011, Schlumberger counted over 500 active offshore rigs[35]. Even if the demand for rigs for CCS is tenfold of our estimation, it is still moderate compared to the total number of active rigs.

Exogenous demand

The increasing exploration of deepwater hydrocarbon fields will probably result in an increase in demand for offshore drilling rigs. Rig demand in the oil and gas industry may also increase as oil and gas will be extracted from smaller hydrocarbon fields when the oil price increases and new drilling technologies become available. Despite the construction of new rigs by 2008, rig shortages were still reported, most notably deepwater rigs, peaking in 2007 (World Oil, 2009). These shortages resulted in high day rates (they have been doubled in some cases[36]) in times of peak demand. In times of high (increase of) oil prices, there is a severe risk that drilling activities for CCS will be restricted by rig shortages or high prices (see also Box 2 in chapter 4).

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[32] We assume that for all reservoirs, wells have to be drilled. It is possible that existing O&G wells can be used for CO_2 storage.

[33] In the period 2020-2050 storage reservoirs might get saturated. In this case, additional wells have to be drilled. This is not included in this analysis, however, it willl not change the conclusion of our analysis.

[34] This is a high estimate, especially for offshore rigs, because wheater conditions can reduce the activity of these drilling rigs.

[35] Baker Hughers counts less rigs than Schlumberger, which counted more than 5000 rigs. Baker Hughes only counts 'those rigs that are significant consumers of oilfield services and supplies'. Schlumberger also takes into account smaller rigs. See http://investor.shareholder.com/bhi/ (Baker-Hughes) and http://www.apps.slb.com/rigcount/ (Schlumberger).

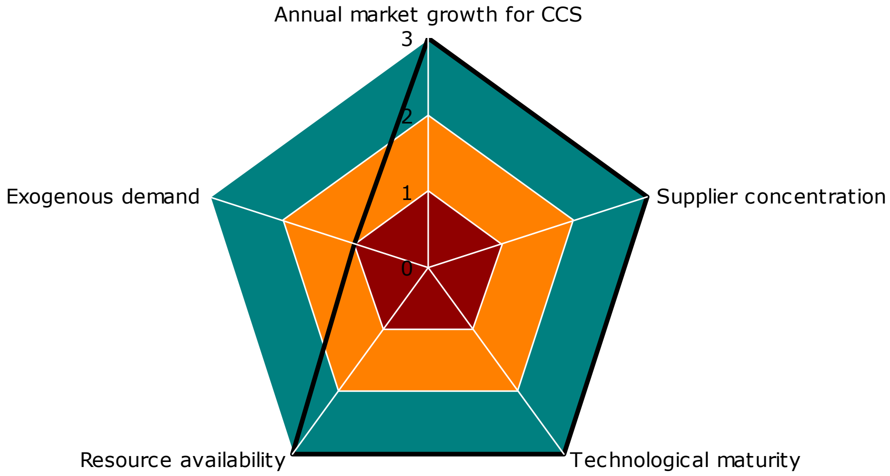
[36] Statement from a commercial manager in the gas industry.

Conclusions

The competition from the oil sector for drilling rigs will be severe and day rates for rigs may increase dramatically. This severe competition indicates a medium to high supply chain risk for drilling rigs.

5.6.2 Onshore drilling rigs

Key message: *Medium risk: In times of high oil prices, there is a risk that costs for land drilling for CCS will be inflated by rig shortages.*



Indicator	Annual market growth for CCS	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(3)	**<1%**	**Open market**	**Commercially proven**	**High**	Driver
(2)	1-5%	Oligopoly	Demonstration phase	Medium	Neutral
(1)	>5%	Monopoly	R&D phase	Low	**Barrier**

Figure 5 - 17 Assessment of the indicators for onshore drilling rigs

Annual market growth for CCS/Supplier concentration

As for offshore, we assume that the average capacity of a well varies between 1 $MtCO_2$/year per well and 1 $MtCO_2$ per 3 wells and between 10,000 and 30,000 wells are needed by 2050 to inject all the captured CO_2. Assuming three quarters of these wells to be located on land, between 120 and 380 wells should be drilled annually between 2020 and 2050. If we assume that, annually, about 15 wells can be drilled by one land based rig[37], then between 8 and 25 rigs are needed for CO_2 well drilling on land. In April 2011, Schlumberger counted over 4,600 active land rigs. The demand for onshore drilling rigs is very moderate.

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[37] Land based rigs are smaller than offshore rigs, more mobile and less restricted by wheather conditions.

Exogenous demand

As mentioned before, in the period 2007-2008, shortages of drilling rigs have also been reported for onshore drilling. An increase in oil and gas extraction from smaller reservoirs will probably result in an increased demand. This may result in higher day rates, however, it will be a less dramatic increase than the costs for offshore drilling, as investment and operating costs for onshore rigs are lower and smaller and more mobile drills are being developed.

Conclusions

The competition from the oil sector for drilling rigs will be serious and day rates for rigs may increase, but less so than for offshore rigs. This severe competition will introduce a medium supply chain risk for drilling rigs.

6 Skills and services

Successful deployment and operation of CCS will require a skilled workforce. The CCS Roadmap details an ambitious implementation and substantial job opportunities will become available in the CCS sector. In this chapter, we will discuss potential constraints related to human resources.

We assessed a range of job profiles by looking at the current and future[38] job market. As well as the size of the job market, another important determinant was how quickly new employees can acquire the required skills and expertise.

6.1 Key findings

Of all the different job profiles, shortages of technically skilled personnel are most likely to appear, particularly petroleum engineers and geo-scientists[39].

Experienced and skilled personnel in the field of geo-engineering are currently scarce. They will become even scarcer in the near future because a substantial part of the workforce will retire in the coming decade. In China, the number of engineers grew explosively in the last 20 years, but in other regions, such as Europe and the USA, the number of engineers that graduate annually is insufficient to meet expected demand. CCS-activities may therefore face severe competition with oil and gas extraction activities.

This shortage of labour availability will present a risk for the storage of $CO_{2.}$ Substantial labour is required as all individual reservoirs have to be assessed, drilled and monitored by, often experienced, geo-scientists and petroleum engineers.

Recently, technically skilled personnel shortages led to higher costs for the construction of new coal plants. Demand for technically skilled staff for plant construction will also increase due to the construction of nuclear power plants and renewables in the BLUE Map scenario.

6.2 Technical personnel

Key message: *High risk: Technical personnel may become a constraint; particularly with skilled, experienced employees who are also required for oil and*

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[38] Based on the US Occupational Outlook Handbook, 2010-11 Edition of the Bureau of Labor Statistics of the US Department of Labor.

[39] When we refer to geo-scientists, we also include geo-engineers, geologists and other specialists in the field of reservoirs

gas extraction. Severe competition with oil and gas extraction activities can be expected.

For capturing, experienced petroleum/chemical engineers and process engineers are needed primarily, during the construction phase. Over the past few years, there are already shortages of technically skilled staff in the construction of coal-fired power plants, caused by a sharp increase in the construction of new plants (see Box 1 in chapter 4).

Once a capture plant is operational, technicians are then needed, but those needed, require less experience and training, as it involves primarily executive, standarised tasks. For this reason, we do not foresee personnel shortages for the operation of capturing installations. For storage, petroleum and geo-scientists are needed for exploration, drilling and monitoring of reservoirs.

The highest risks of constraints in services and skills will be for job profiles that are also needed for oil and gas extraction:
- Petroleum engineers
- Geo-scientists

The main reasons are provided in the paragraphs below.

Workforce to operate a capture plant
According to Dynamis (2008), a typical capture installation requires approximately 30 additional FTEs (i.e. on top of the workforce on a thermal power plant). The assessment in Dynamis (2008) was performed for a typical 400 MW power plant and we assume that due to learning, the same number of employees could also operate larger plants in the CCS Roadmap and industrial installations. Most of the employees must be educated to an upper-secondary to post secondary education level (medium), and only about two employees per installation need to be educated at a tertiary and post-graduate level (high).

By 2050, the total workforce to operate all the capturing installations should then be: around 95,000 employees with medium education and 8000 employees with a higher education. Compared to the current workforce in the chemical industry in Europe (in 2005), the workforce needed (globally) to operate capture installations is much lower: More than 300,000 employees in the chemical industry in Europe were educated to a higher level and almost 700,000 employees possessed a medium level education (CEFIC, 2010).

Competition with the oil and gas extraction
There is currently relevant experience and knowledge in the oil and gas sector and to a lesser extent, in the chemical and power sector (GCSSI, 2009; Chatham House, 2009). Shortages in petroleum engineers are widely reported and regarded as a major risk to the oil and gas sector (E&Y, 2010; Van Kirk, 2007), although there is no long-term demand decrease expected. Competition for

personnel currently occurs primarily *within* the oil and gas sector, i.e. it is difficult to find experienced engineers in other sectors. SBC (2006) shows that shortages are regional: North America[40], Iran and the Middle East may face shortages, while an excess of engineers arises in China, for example (see next paragraph). This excess refers to graduated engineers however, not necessarily to an experienced workforce.

Despite relatively high numbers of students with a technical background, shortages of *experienced* personnel can also be expected in China and India. This is because an increasing oil demand and production is forecasted in these nations, even in the BLUE Map scenario (IEA, 2010). Shortages of experienced staff are already predicted for the oil and gas sector in India (E&Y, 2010b).

Currently, reservoir knowledge is concentrated mainly within oil and gas companies (GCSSI, 2010) and their contractors. These companies (e.g. Shell, BP, ExxonMobil) will probably become key players in CO_2 storage. This means that the flow of employees between oil and gas extraction and CO_2 storage will be more intracompany and fluid. An increase in oil demand, with far greater profit margins, might therefore quickly lead to personnel shortages for CO_2 storage. As mentioned in section 4.5, EOR activities might create synergy that will both mitigate the staffing requirements and decrease competition between the two activities.

Experienced personnel will retire

The work of petroleum and chemical engineers involves many autonomous decisions, i.e. the execution of non-standardised tasks. Depending on the culture[41] of a company, it takes 4 to 12 years before a petrochemical engineer is fully autonomous (SBC, 2006). Senior personnel are therefore important for two reasons: 1) to take autonomous decisions and 2) to guide and supervise less experienced engineers.

In the short-term, a problem will arise: In the demographic distribution of the oil and gas sector workforce, there is a large number of employees aged between 50 and 55. For geo-scientists, this is shown in Figure 6 - 2. More than half of the workforce in the oil and gas sector is expected to retire within a few years (SPE, 2010; SBC, 2006; E&Y, 2010b). This retirement will result in a decrease in experienced engineers, because the younger generation, around age 40, is underrepresented in the workforce. This drain of experience will intensify the shortages of petroleum and geo-scientists. Attention should be paid to less experienced engineers, because on-the-job learning is crucial and should be facilitated by more experienced colleagues.

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[40] See also BLS (2010) on engineers

[41] In a conservative organisational culture, it usually takes longer before an employee is autonomous, compared to an innovative culture

Because the needed skill set is very specific, it is unlikely that suitable, experienced, employees can be recruited from other sectors. It is therefore important that available capacity is conserved and used in an optimal way.

> *"I can cite some observations made while travelling within the Middle East (…) I have talked to officials in many national oil companies, including Saudi Aramco, ADNOC in the UAE, Kuwait Oil and several companies in Egypt. Time and again, they have told me that one of their dire needs is manpower at all levels, but especially older, experienced people that can be mentors to the youngsters. This is one of their biggest deficiencies. "*
>
> Dr. Craig W. Van Kirk, Head, Petroleum Engineering Department, Colorado School of Mines, Golden, Colorado in World Oil, 2007

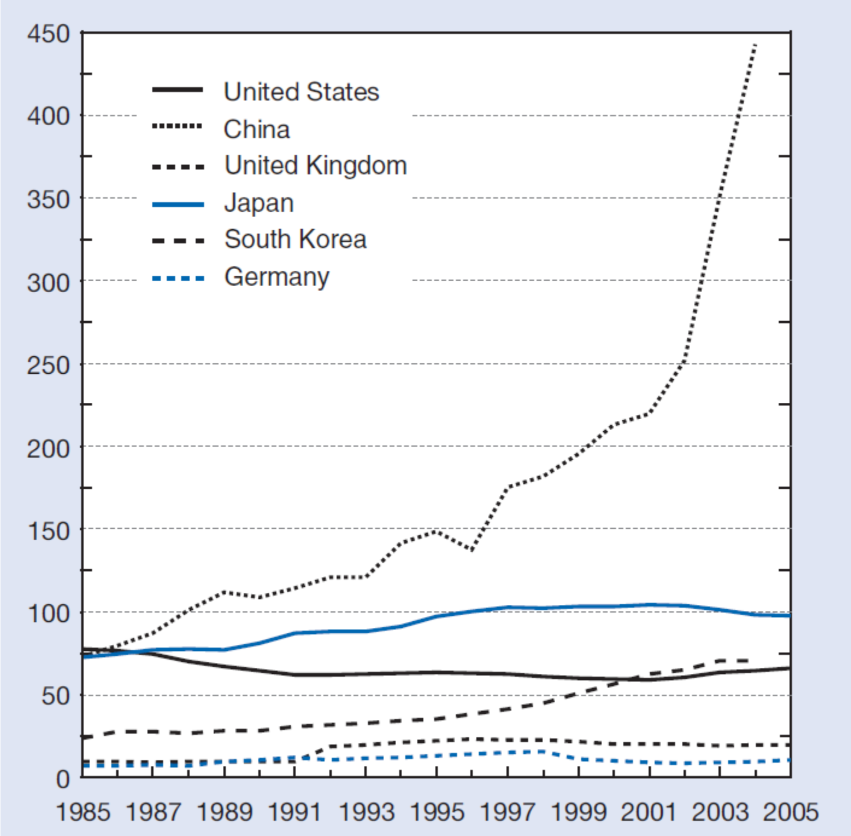
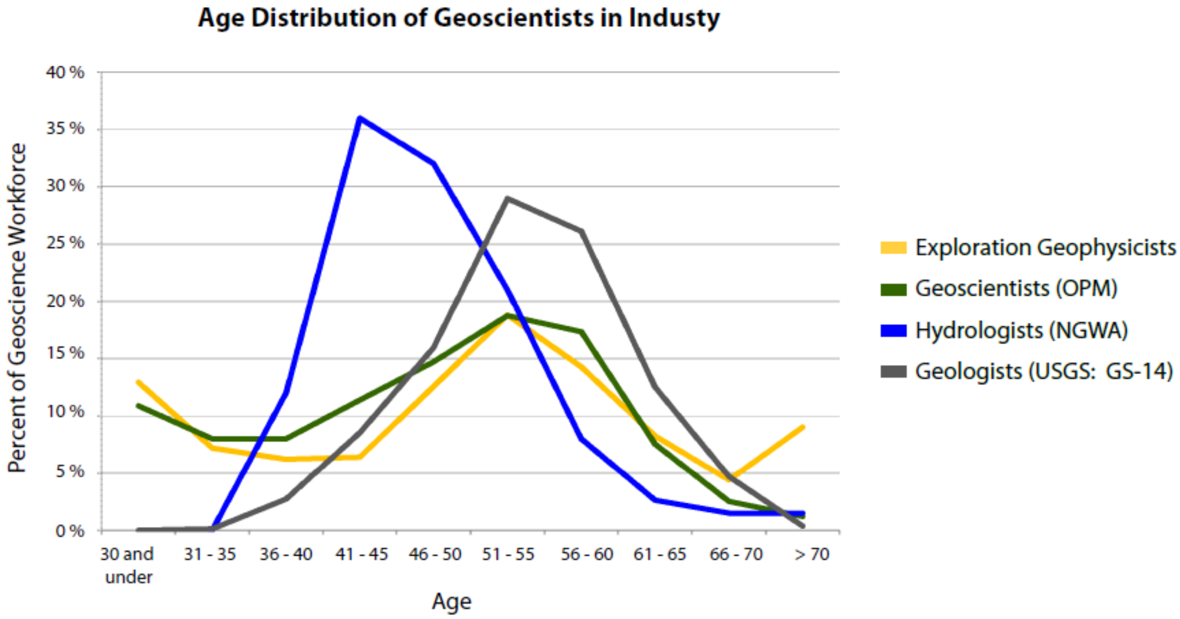


Figure 6 - 1 Number of university engineering degrees in thousands (Source: National Science Board, 2008)

As shown in Figure 6 - 1, the number of obtained engineering degrees increased spectacularly in China from below 100,000 in 1985 to over 450,000 by 2005. In developed countries, the number of graduates was more or less consistent. In recent years, the number of graduates in the field of petroleum engineering increased in the US (SPE, 2010), but not by enough to compensate for the employees that will retire in the near future. In China, there will be many young engineers, but this young workforce needs to be supervised and trained by (scarce) senior staff.



Data Sources: Society of Exploration Geophysicists (SEG), US Office of Personnel Management (OPM), National Groundwater Association (NGWA); *USGS Workforce Demographics and Trends*, Peter T. Lyttle 33rd IGC, Oslo, Norway, August 10, 2008 (USGS)

Figure 6 - 2 Age distribution of geoscientists in industry. Source: America Geological Institute

Assessing potential storage sites will be labour intensive

Particularly for storage, a large volume of expertise and knowledge is needed and must be developed. The storage of 2.5 $GtCO_2$ by 2030 and 10 $GtCO_2$ by 2050 requires many reservoirs, of which the majority are still to be assessed for suitability for storage.

The behaviour of reservoirs needs to be modelled and data collected, as an input for these models. For (depleted) hydrocarbon fields, extensive datasets are available, particularly for regions where environmental regulations are strict. However, in many regions and for many reservoirs, data is still to be collected, particularly for reservoirs that are/were not used for hydrocarbon production, e.g. aquifers.

This work therefore requires measurements of individual sites, modelling, testing and monitoring by geo-scientists. Again, this type of knowledge currently resides in the oil and gas sector, so we expect that CCS will compete with oil and gas extraction activities for human resources. An increase in exploration activities to find new oil and gas reserves might increase the demand for personnel.

The need for geo-scientists might be relatively low during the initial deployment of CO_2 storage, because this will probably take place in previously assessed deployed hydrocarbon fields. However, when storage activities intensify, an increasing number of (previously) unexplored reservoirs might be needed. These reservoirs then have to be assessed by geo-scientists.

6.3 Legal and financial expertise

Key message: *There are no indications that availability of employees with legal or financial expertise will become a constraint. Job markets in both areas are expected to remain 'keen'*[42]*.*

Legal expertise is very important and relevant knowledge can only be fully developed if (national) regulation on CCS is in place. Consequently, legal experience and knowledge (e.g. liability issues, building permits) are currently not widespread. Most legal knowledge is hired from firms or independent professionals[43] and these firms are expected to be flexible and adjust expertise to the new demand for CCS.

Many, thousands, law students graduate each year and this will continue to be the case in the near future. Therefore the USA job competition is expected to remain 'keen'. This makes the market relatively flexible and many students adjust their specialisation on the job market. Availability of legal personnel will therefore not be a constraint to the deployment of CCS.

The job market in the financial sector is also expected to remain 'keen', because positions within the sector are generally well paid. Furthermore, financial institutions are expected to build up expertise on CCS projects (carbon trading, project risks) and renewable energy projects (IEA-RETD, 2010), quickly.

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[42] Defined by the US Bureau of Labor Statistics as: Job openings compared to job seekers is few.

[43] Currently, in the US, only about 500 lawyers are working in the oil & gas extraction industry, about 1200 are working for utilities and 100 in the chemical sector.

7 Historical comparison - Flue Gas Desulphurisation

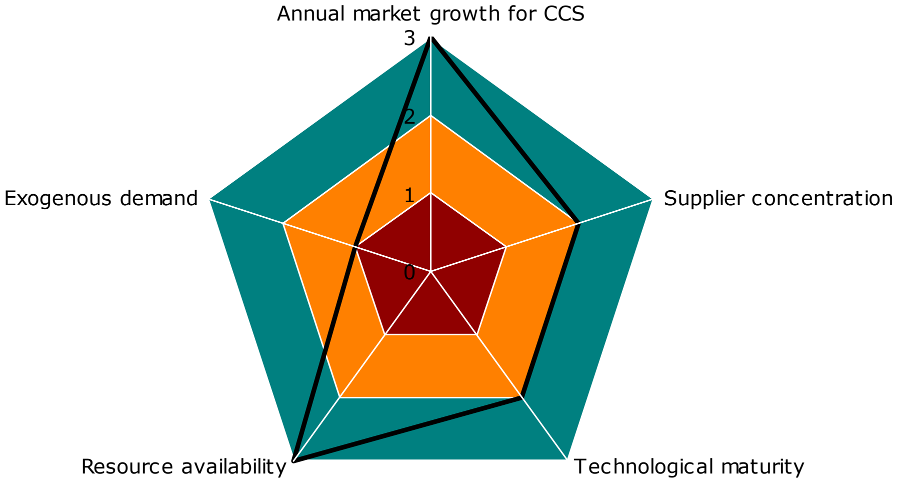
In this chapter, we take a closer look at the market introduction of technologies, other than CCS, in the power plant sector. We first address the circumstances of the market introduction and identify the conditions that lead to a successful or unsuccessful introduction of a specific technology. Secondly, we analyse the speed of technology implementation and compare this to the required speed of implementation, as stipulated in the IEA Roadmap.

The technology selected for the historical comparison is Flue Gas Desulphurisation (FGD), a technology that removes sulphur dioxide (SO_2) from the exhaust flue gases of fossil fuel power plants. FGD units are chemical plants (CAPEX is around 100 million dollars in the early 1980s) and like CO_2 capture units, they can be retrofitted to existing power plants. In complexity and sector of application, these types of technologies are comparable to CO_2 capture technologies. One important difference is that CO_2 also requires a transport and storage infrastructure and that the scale of a full-size capture system (in CAPEX, but also in size) is bigger. This comparison is only relevant for the introduction of capture technologies and not for the entire CCS chain. In this chapter, we will study the FGD technology by evaluating how the technology scored against the different indicators we used in chapter 5 to assess equipment for CCS.

7.1 Key findings

In the figure below, we evaluated how FGD would have scored against the indicators we defined and applied in the previous sections, if assessed in the 1970s. We can see that the technology was still in demonstration phase, facing many technological issues and a high supplier concentration.

FDG could be deployed quickly, despite technological problems during the first phase of implementation. The FGD history in Germany shows that if sufficient regulation is in place (i.e. facilitating a structural demand), high implementation rates can be realised: In the 1970s, there were still many technological problems, but this did not prevent a successful, large scale implementation in the mid-1980s, in Germany. In the United States, concerns over the capacity of suppliers led to lower standards and consequently lower implementation rates than in Germany.



Indicator	Annual market growth for FGD	Supplier concentration	Technological maturity	Resource availability	Exogenous demand
(1)	<1%	Open market	Commercially proven	**High**	Driver
(2)	1-5%	**Oligopoly**	**Demonstration phase**	Medium	Neutral
(3)	**>5%**	Monopoly	R&D phase	Low	**Barrier**

Figure 7 - 1 Assessment of the indicators for FGD. Resource supply issues have not been encountered; therefore we evaluate 'Resource availability' as high. 'Exogenous demand' is set as a barrier because there was no demand from other sectors that stimulated FDG-developments.

7.2 Technological maturity

In the United States, research and development activities on scrubber technology started in the 1950s. These early R&D activities addressed the cost-effectiveness of different sorbents for wet and dry scrubbing technologies. During these years, efforts were conclusively directed at demonstrating the technical and economic feasibility of wet limestone scrubbers. By the time that clean air legislation was enforced, wet FGD became the process of choice because this was the only developed technology at that time. Public R&D support, directed at solving specific operational problems, complemented with the support for demonstration scale plants, are considered to be crucial in the reductions of capital and operational cost and it builds confidence among utilities and vendors. The pilot FGD of 1968 already removed 98% of the SO_2. Although the average FGD system had relatively low removal efficiency in the early decades (1950's and 60's), reliability of the systems was a much bigger issue. Underestimation of corrosion resulted in reliability problems.

> *“The utilities, which were forced to abide by the revised clean air act of 1970, suddenly found themselves in the position of being “chemical plant operators”, a role for which they were ill prepared. Their expertise in mechanical engineering, electrical engineering, water chemistry and coal management was of little or no use, thus leading to an onslaught of monumental corrosion problems, unscheduled shut downs, soaring maintenance costs, lost revenues and the penalties imposed from buying power from the grid, while quick fixes were being developed.”*
>
> D.C. Agarwal in a 1996 analysis of the introduction of flue gas desulphurisation systems

7.3 Supplier concentration

Both smaller firms and departments of larger corporations were involved in the US FGD market in the 1970s. Larger corporations then generally acquired the smaller firms during the following years, as the FGD market was expected to become very profitable (Taylor, 2001, p. 40). This resulted in the top five FGD suppliers accounting for almost 73% of the FGD market in the 1980s in the US.

7.4 Market development

During the 1970s and 1980s, acid rain became an important environmental problem, caused primarily by emissions of sulphur dioxide and NOx. This problem was partially caused by coal fired power plants. In the United States, clean air legislation on sulphur dioxide emissions came into effect in the 1970s and forced many new and existing coal fired power plants to adopt FGD. This demand-pull initiative was the driving factor behind the market for FGD systems.
Since the market introduction of wet scrubbers in 1972, the technology has been applied on a cumulative 200 GW of coal-fired power plants around the world by 2000. On average, over this 30-year period, annually 6.6 GW of coal-fired power capacity have been equipped with FGD. As of late 2000, FGD installations were in operation in 670 coal-fired units with a total capacity of over 250 GW, showing that 25% of all pulverised coal-fired plants have some form of FGD (IEA, 2006). Figure 7 - 2 gives the installed capacities of coal-fired power plants with FGDs in the United States and Germany. The uptake of FGD technologies in these countries shows significant differences. In the United States, the market size of FGD systems has been limited until the 1990s due to concerns about the capacity of suppliers of components such as “slurry pumps, centrifuges and vacuum filters” but equally for “large” compressors and gas flow modelling concerns have been expressed in 1991 (Smock, 1991). Only 17% of new built coal fired power plants were equipped with FGD in the period, 1970 – 1980. The share of new built coal-fired power plants equipped with FGD increased to 50% between 1980 and 1990 and to almost 95% in the period 1990 – 2000. Germany enacted stringent regulations in 1983, stipulating that all coal-fired power plants in operation should install an FGD system, including the existing stock. From 1985 to 1988, approximately 27 GW of coal-fired capacity has been equipped with FGD systems.

In the peak year, 1988, 16 GW of coal-fired capacity was retrofitted or newly built with FGD.

China began to implement FGD systems on a larger scale in the 2000s. Although in 2006, no more than a 22% of the installed thermal power plants during that year were equipped with FGD systems, there is a steep rise in FGD penetration. In 2005, only 14% of the installed capacity was equipped with FGD systems and in 2004, this was only 2%.

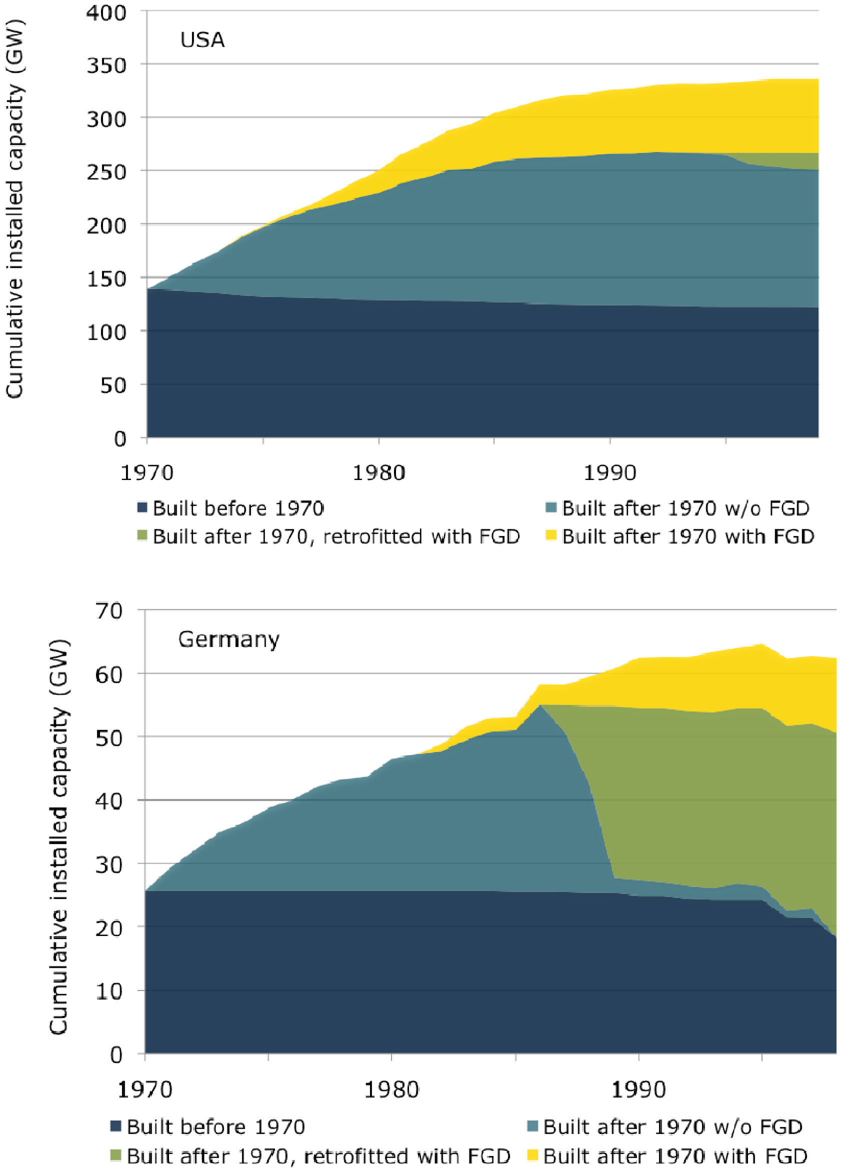


Figure 7 - 2 Total operational fossil-fired power capacity in Germany and the United States over the period 1970-1999. Sources*: Platts (2006) and Rubin (2004).*

7.5 Comparison with CCS

To achieve the targets in the CCS Roadmap, the annual growth in coal CCS projects must reach an average of 17 GW (15 installations) per year in the period, 2020-2030, 29 GW (24 installations) per year between 2030 and 2040 and 28 GW (22 installations) per year over the period 2040-2050. In this scenario all new coal-fired power plants should be equipped with CCS from 2020 onwards. This implementation path is more ambitious than what we have seen in the implementation of FGD technology. However, the FGD growth figures in Germany alone were similar to the growth figures required for CCS projects, on average 9 GW per year in the period 1985 to 1988 and 16 GW in the year 1988.

Another important observation is that the deployment of the FGD technology is the result of demand-pull incentives. The stringent requirements on SO_2 emissions from coal-fired power plants resulted in a fast global uptake of FGD technology. Despite technical problems at the start of the implementation, the technology could be implemented at a high pace. This means that if sufficient ‘pull’ is in place, quick technology development and knowledge diffusion are possible. The fears for supply chain issues in the US resulted in lower ambitions, although in Germany, it was demonstrated that large-scale implementation of FGD could be realised quickly.

In chapter 5, we found that there is medium to high risk for supply constraints for hydrogen rich gas turbines and a low to medium risk for solvents. For these components, further R&D is needed. This chapter shows that necessary developments can take place quickly, provided that a strong ‘pull’ is established by governments.

8 Overview of risks and discussion

In this chapter, we will summarise the main findings from the previous chapters. Based on these findings, recommendations are formulated in the next chapter.

> ***"I confess that in 1901, I said to my brother Orville that man would not fly for fifty years . . . Ever since, I have distrusted myself and avoided all predictions."***
>
> \- Wilbur Wright, 1908

8.1 Introduction

The statement of Wilbur Wright illustrates that any outlook on technological developments is subject to (large) uncertainties. A technology can develop very rapidly, a competing technology can quickly emerge and societal conditions can change. The conclusions below do not summarise our predictions, but we merely assessed the supply chain, assuming that our global society wants CCS and regulation, public acceptance and supporting policies and financing are all in place. We assessed whether the supply chain for CCS can be ready *in time* as well as at the *scale needed*, if CCS is deployed in the context of the IEA BLUE map scenario.

8.2 Identified supply chain risks

The assessed supply chain risks for the studied components (equipment and services & skills) are provided in Figure 8 - 1. The high risks are mainly related to storage and transport: Pipelines, drilling rigs, petroleum engineers, geo-scientists and (large) compressors[44]. For capture, supply chain risks for hydrogen gas are high. Other low to medium supply risks are for catalysts, absorption towers, ASUs, and advanced flue gas treatment.

8.3 Discussion

For capture, supplier concentration is the main risk
Some components, such as advanced flue gas treatment, solvents and hydrogen turbines are still under development. There is a risk that the 'winning' technology results in a high supplier concentration; this makes it attractive for EPC contractors to vertically integrate their supply chain. Vertical integration in the chain may result into large conglomerations/joint ventures across the supply and value chain. One tripping part of the chain may result in constraints across the

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[44] Compressors can also be regarded as part of the capture process as most compressor capacity is located at the capture installations.

whole chain. For example, if one company offers a capture block and the preferred supplier is not able to meet demand, then the whole capture block faces longer lead times. It reduces risk for parties involved, but may create supplier dominated market conditions and result in inflexible markets.
The historical comparison showed that technological developments and knowledge diffusion can be realised within a relatively short time if sufficient demand-pull (via regulations/obligations/standards) is in place.

There is no clear indication that there are strong differences in supply chain constraints for the various capture technologies
Based on our analyses, no firm conclusion can be drawn on which capture technology has the most significant supply chain constraints. All three capture technologies have components that may form a potential risk and may be a barrier for large scale deployment of CCS. For pre-combustion it is the gas turbine; for oxyfuel it is the flue gas treatment and boiler; and for post-combustion it is expected to be the large scale absorbers and perhaps ‘monopolized’ solvents. Based on the methodology used in this study and current data availability it is not possible to firmly conclude on what the effect of any of these supply chain bottlenecks occurring would be on the deployment and market share of the three capture technologies.

Detailed data (i.e. below the level of EPC, large technology providers) on the CCS supply chain are many cases difficult to collect, because of three main reasons. The first is that the supply chain of the large EPC contractors entails a large number of suppliers and sub-contractors which would require a more extensive study to map these all. The second reason is that competitive reasons limit the disclosure and thus an overview of all suppliers and sub-contractors in the supply chain to the EPC contractors. The third reason is that a detailed overview of the supply chain is mostly relevant for the short term (typically <5 years). Long-term dynamics in the full supply chain are extremely difficult to assess on a detailed level.

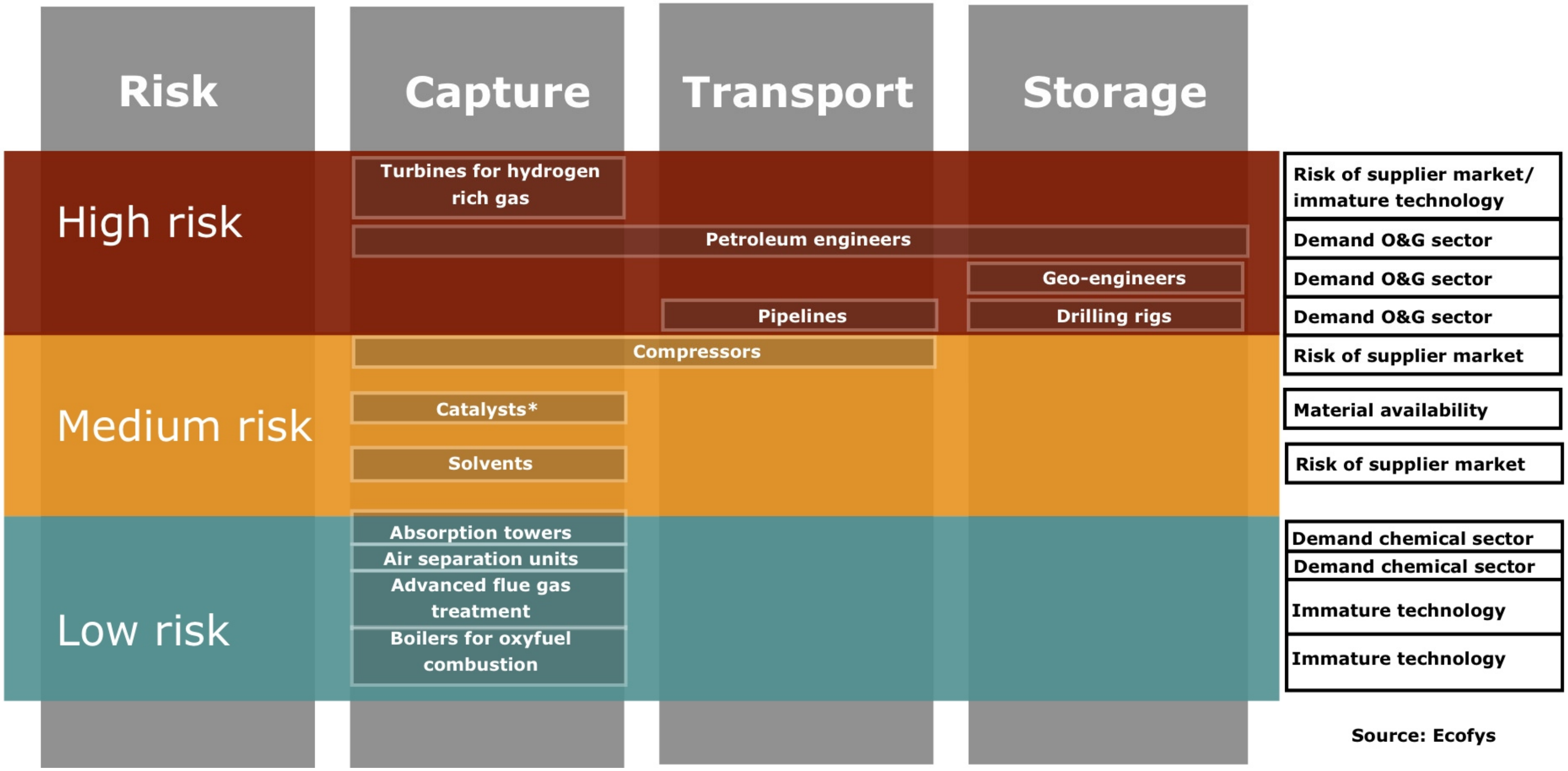
Meeting global demand for compressors and large scale CO_2 pipelines will be challenging task
CO_2 compressors are mature for lower pressure ranges but require R&D for the high pressure ranges often necessary for offshore CO_2 transport. All CCS projects would require compressors and it therefore faces high demands. Together with competition for (natural gas) compressors needed in the oil and gas industry, this may lead to shortage in supply capacity.

Pipe laying capacity faces competition with the oil and gas industry and the current market for laying very large scale pipelines is small. The scale and amount of pipelines needed for CCS may temporarily fill order books of pipeline laying companies and increase prices and lead times.

Oil and gas extraction will compete severely with CCS activities
For storage exploration, skilled engineers are needed, who are now mainly working in the oil & gas sector. In the BLUE Map scenario, oil and natural gas demand is expected to decrease 23%, respectively 12% by 2050, so part of the capacity (equipment and staff) could be employed for CCS. Already between 2020 and 2030, CCS activities already require equipment and staff, not only to construct capture installations, but also to assess and explore reservoirs and drill wells. The oil & gas sector already experiences difficulties with staffing, and because of the specific skills and experience that is needed; suitable staff can hardly be recruited from other sectors. The most critical part is the data collection on CO_2 storage reservoirs: on-side measurements, modelling and monitoring will require knowledge of skilled geo-scientists.
But not only upstream (e.g. oil drilling) knowledge is concentrated in the oil and gas industry, also downstream (e.g. petrochemical refining) that relates to knowledge on CO_2 capturing process is partly concentrated in the oil & gas sector.

When oil prices peak, a shortage of staff and equipment might cause problems, particularly for offshore drilling. This may then result in shortages and higher costs for offshore CO_2 wells.

Because of their knowledge, oil companies (and their contractors) will be critical facilitators for CCS, in both exploration of reservoirs and in constructing capturing installations. This means that, in times of labour shortages, oil and gas companies may have to choose between CCS and oil and gas extraction activities. As the revenues from oil activities are likely (also in the BLUE Map scenario) to be higher than CO_2, there is a severe risk that CCS activities will become understaffed and underequipped, i.e. cost of equipment and staffing increase.



Source: Ecofys

Figure 8 - 1 Overview of the risks of supply chain constraints to appear for the assessed equipment and services and skills, the main risk factor is also given at the right. *Risk after 2030

9 Recommendations

Based on the supply chain risks identified in the previous chapters, recommendations are formulated to prevent constraints occurring or to mitigate the impact of those constraints.

9.1 Transport & storage

There are recommendations to mitigate supply chain risks for: drilling rigs, pipelines, petroleum engineers and geo-scientists

Risks should be reduced for upfront investments, particularly for reservoir exploration and transport infrastructure
To allow CCS to become established in the period, 2020-2030, large investments should be made during 2010-2020: Storage reservoirs need to be assessed and transport networks must be designed and prepared. Special attention to storage and transport 'preparation' is required: There is a lot of necessary effort, yet return on investments can only be expected many years later. If the investments are not made in time, there is a risk of having capture installations in place without sufficient transport and storage capacity.

It is necessary that investors are confident that CCS deployment will happen. This means that *obligations to apply CCS* and/or *an emissions trading system* should be in place over a long period (e.g. in the EU, there is currently only an emissions trading system in place, until 2020).

In addition, the oil and gas activities will compete with CCS for skills and equipment, probably *within* the same companies. This means that there should be an incentive to deploy resources for CCS activities instead of oil and gas extraction: It is very likely that the revenues from oil and gas extraction will remain higher than for CO_2 capture, even in the BLUE map scenario.

Mitigate competition with oil and gas extraction activities
Experience over the past decades demonstrates that in times of peaking fuel prices, capacity problems appear or intensify. Scenarios where oil and gas demand do not increase, or even decrease, provide preferable conditions for the deployment of CCS.

If CCS is deployed, oil and gas companies will be the most suitable and experienced organisations to carry out CO_2-injection activities. In times of decreasing oil production, it is important that they do *not decrease capacity* (i.e. jobs and equipment) but re*deploy this capacity to CO_2 injection activities*.

Personnel active in CO_2 injection, reservoir assessments and monitoring, should be *trained and guided thoroughly*, so that they will become independent workers within a relatively short period (i.e. about 4 years). Apprenticeship programmes should be thoughtfully coordinated: Allowing employees to gain experience in the CO_2 storage projects at the appropriate positions.

More students should be motivated to follow technical education programmes, particularly related to petroleum engineering or geo-engineering. Petroleum engineering is associated by some young people with unsustainability: a new type of student might be attracted to these programmes if CCS establishes itself as a pivotal technology to mitigate carbon emissions. This requires a broader effort to gain public support and a focused effort on high school pupils/students to make them aware of carriers and challenges in CCS.

Investigate in detailed knowledge and expertise need for storage assessment
What knowledge and expertise and how much, is required for the assessment of reservoirs has not been studied. It is recommended to assess in detail, what critical skills are needed and how many FTEs should be employed in the near future that will create an optimal deployment of CO_2 storage capacity. This should be combined with a detailed assessment of skills and capacity requirements in oil and gas exploration.

Promote international data exchange
Oil companies and/or national institutes have already gathered data on many (depleted) hydrocarbon fields. This data is rather diffuse and often not consistent. Sharing of data (international, intercompany) would allow research by third parties and a better overview of the quality of the existing data on possible CO_2 storage locations. Consistent and accurate estimates of storage capacity are needed in most world regions in an early phase of the CCS deployment to prevent the storage part of the chain becoming a constraint.

9.2 Capture

Recommendations to mitigate supply chain risks for: Solvents, hydrogen gas turbines and advanced flue gas treatment

How to prevent supplier concentration?
To encourage the R&D by different companies, it is recommended to stimulate diversity of suppliers in the different demonstration and pilot projects. This includes stimulating diversity in the development of different capture options and suppliers, for example.

9.3 Other points of attention

Material availability will become an important issue in the near future, not specifically for CCS, but for the large scale deployment of advanced technologies in general. For CCS, catalysts use critical materials, particularly titanium oxide, vanadium, tungsten, cobalt, copper and platinum. Although not a direct, short-term, risk, but of high general economic importance, is chromium, which is applied in stainless steel. Recycling and optimising material efficiency are therefore important in realising the BLUE Map scenario at the lowest possible (environmental) costs. Stainless steel might encounter temporal shortages in supply in times of economic growth.

The **build up of institutional knowledge** is very important. The supply chain analysis in this report shows that whether or not supply constraints appear, depends on a range of complex technological and economical factors. Specialised knowledge will, in a tight job market, often be pulled towards the industry where higher salaries are paid. However, technological knowledge is needed in other institutions to coordinate and design national and international CCS deployment. It is important that relevant knowledge (technological, but also on the market) is present in regulatory markets, competent authorities and other institutions that are involved in the rollout of CCS. This helps to design optimal implementation plans that take into consideration the supply chains necessary for a successful deployment of CCS (for example, by preventing sudden demand increases in a specific year).

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[45] The views expressed in this report do not necessarily represent the views of the people mentioned here.

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Appendix A Capture equipment considered

The table below shows the long list of the components that were considered, the first column indicates the type of CCS (Pre=Pre-combustion, Post=Post-combustion, Oxy=Oxyfuel-combustion). The middle column gives main process steps, or main components and the right column indicators subcomponents of those process step/main components. The process steps that are studied in more detail are indicated in black. If this process step is only studied on the level of the main component (i.e. not on a sub-component level), the subcomponents are shown in gray. The last four columns indicate the reasons for including the process step in the short list. This assessment is based on in-house knowledge and a literature scan. Based on this preliminary assessment we have selected the final short list of process steps from the list of processes that scored more than one possible supply chain constraint, indicated by an 'x' in the last four columns.

Capture technology	**Component/Process step**	**Sub-component**	**Reason to include in shortlist**			
			Immature	**Niche market**	**Severe demand competition expected**	**Containing potentially rare materials**
Pre	ASU	Destillation column			x	x
Pre	ASU	Heat exchanger			x	x
Pre	ASU	Booster compressor				
Pre	Gasifier	Gasifier				
Pre	Gasifier	Feeding system	x[1]			
Pre	Gasifier	Syngas filters				
Pre	Shift	Shift reactor				
Pre	Syngas Gas Treatment	Catalysys	x[2]		x	x
Pre	CO_2 compression	CO_2 compressor		x	x	
Pre	Sulphur recovery	Sulphur recovery unit				
Pre	Conversion	Gas Turbine	x	x		
Oxy	ASU	Distillation column			x	x
Oxy	ASU	Heat exchanger			x	x
Oxy	ASU	Booster compressor				
Oxy	CO2 compression	CO2 compressor	x[3]	x	x	
Oxy	Combustion	Heat Recovery Steam Generator (superheater/heat exchangers)				x

Capture technology *(continued)*	**Component/Process step** *(continued)*	**Sub-component** *(continued)*	**Immature**	**Niche market**	**Severe demand competition**	**Containing potentially rare materials**
Oxy	Combustion	Boiler/burner/combustor	x	x		x
Oxy	Combustion	Acid condenser[7]	x	x		
Oxy	Combustion	Steam turbines	x[4]			
Oxy	Combustion	steam condensor				x
Oxy	Combustion	Gas turbines	x	x		
Oxy	Combustion	advanced flue gas treatment oxyfuel	x	x		
Post	DeNox	Catalysts			x	x
Post	Scrubber/absorber	Pumps for direct contact coolers				
Post	Scrubber/absorber	Flue gas cooler				
Post	Scrubber/absorber	Flue gas fan				
Post	Scrubber/absorber	Amine pumps				
Post	Scrubber/absorber	Absorption towers	(x)[5]	(x)[5]	x[5]	
Post	Scrubber/absorber	Heat exchangers				
Post	Scrubber/absorber	Solvents (e.g Amines)	(x)[6]	x	x	
Post	Stripper	Stripper				
Post	CO2 capture - other	Filters				
Post	CO2 compression	CO2 compressors (multistage)		x	x	
Post	CO2 compression	Heat exchangers				x
Post	CO2 compression	Dehydration				
Post	CO2 compression	CO2 pumps				

[1] Optimizing fuel feeding systems, especially for biomass, is still an area of development for gasification systems.

[2] This score only applies to advanced hot flue gas cleaning technology development for IGCC configurations.

[3] Integrated purification and compression in coal fired oxyfuel cycle is currently being tested and is not mature.

[4] Only for steam turbines in gas fired oxyfuel cycles maybe immature. For coal fired concepts, existing and mature steam turbines can be deployed.

[5] Rated for large scale scrubbers/absorption towers

[6] Immature for solvents optimized for CO_2 capture from power plants with low energy demand

[7] Included in the component advanced flue gas treatment (section 5.2.2)

Appendix B Description of CCS technologies

There are three categories of capture technologies that are studied in this project: post combustion, pre combustion and oxyfuel combustion. In this section, the three capture technologies are shortly introduced. We describe here the most important technology blocks of selected power generating concepts (PC, NGCC and IGCC) and the application of one of the three capture principles within these concepts. The maturity of the individual technology blocks within each power generation technology including capture is scored using the color signs shown at the right side of this page. This assessment of the maturity is largely based on information provided by the Zero Emission Platform (ZEP, 2008)

🟩 Mature

🟨 Proven but may require changes due to capture

🟧 Requires further research, development and demonstration

B 1 Post combustion

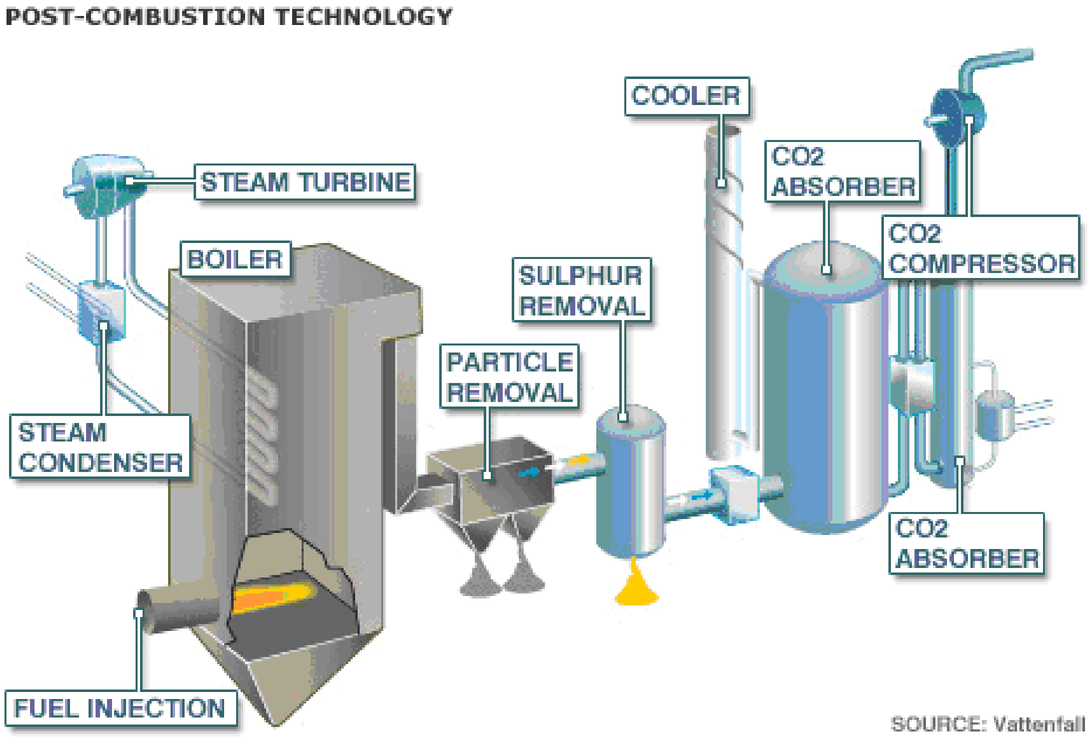
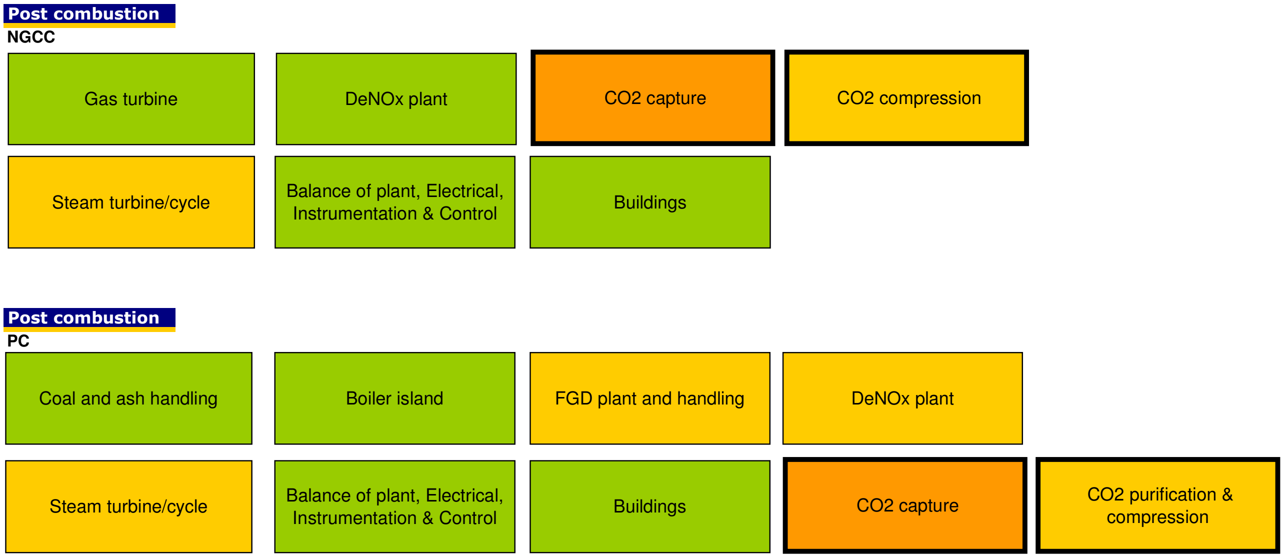


Figure B - 1 Schematic overview of post combustion technology. Source: Vattenfall

Carbon capture using post combustion technology means that CO_2 is removed from the flue gasses after the combustion of the fuel. The first step is combustion of fuel and air in a *boiler* (or gas turbine) producing steam and flue gases. The steam powers a *steam turbine* that generates electricity. The flue gases, containing predominantly CO_2, N_2 and H_2O, are led to the flue gas cleaning section that typically includes removal facilities for particulate matter, sulfur oxides and NOx. Advanced flue gas cleaning is often required to allow for a proper operation of the CO_2 capture facility that is places behind the flue gas cleaning section. After flue gas cooling the CO_2 can be removed with the use of solvents. Examples of currently used and studied solvents are MEA (mono-ethanol-amine), MDEA (methyl-di-ethyl-amine), ammonia based solvents, potassium carbonate and amino acid salts. The CO_2 is removed from the flue gas and absorbed by the solvent in the CO_2 absorber; typically a large steel or concrete structure that contains *packing material* to allow for a large contact area between the flue gas and the solvent. The CO_2 is removed again from the solvent by the addition of heat and/or lowering the pressure, this is done in the desorber. The almost pure CO_2 is then compressed and dehydrated and can subsequently be transported and stored.

Post combustion can be used in combination with both coal, biomass and natural gas fired power plants or can be used to scrub CO_2 from flue gases from industrial facilities, such as cement or steel manufacturing. The description above is based on using coal as fuel. Flue gas cleaning facilities prior to the CO_2 capture step may have different configurations and requirements when applying post combustion on flue gases from other sources. When firing natural gas, for instance, particulate matter and sulfur oxides are generally very low or absent.

In Figure B - 2 we score the maturity of several technology blocks in the concepts using post combustion capture. We see that the CO_2 capture block in the NGCC and PC concepts require RD&D and the most other blocks are mature. Points of attention within the PC concept are the changes in the steam cycle and turbine section and adaptations in flue gas cleaning/cooling equipment. CO_2 compression is considered mature, but should be able to cope with some impurities still present in the captured CO_2 stream.



Post combustion
NGCC

Gas turbine	DeNOx plant	CO2 capture	CO2 compression
Steam turbine/cycle	Balance of plant, Electrical, Instrumentation & Control	Buildings	

Post combustion
PC

Coal and ash handling	Boiler island	FGD plant and handling	DeNOx plant	
Steam turbine/cycle	Balance of plant, Electrical, Instrumentation & Control	Buildings	CO2 capture	CO2 purification & compression

Figure B - 2 Maturity of technology blocks for power generation concepts NGCC and PC including post combustion capture. Bold frames indicate a new technology block that is added due to CO_2 capture. Based on ZEP (2008).

B 2 Pre-combustion

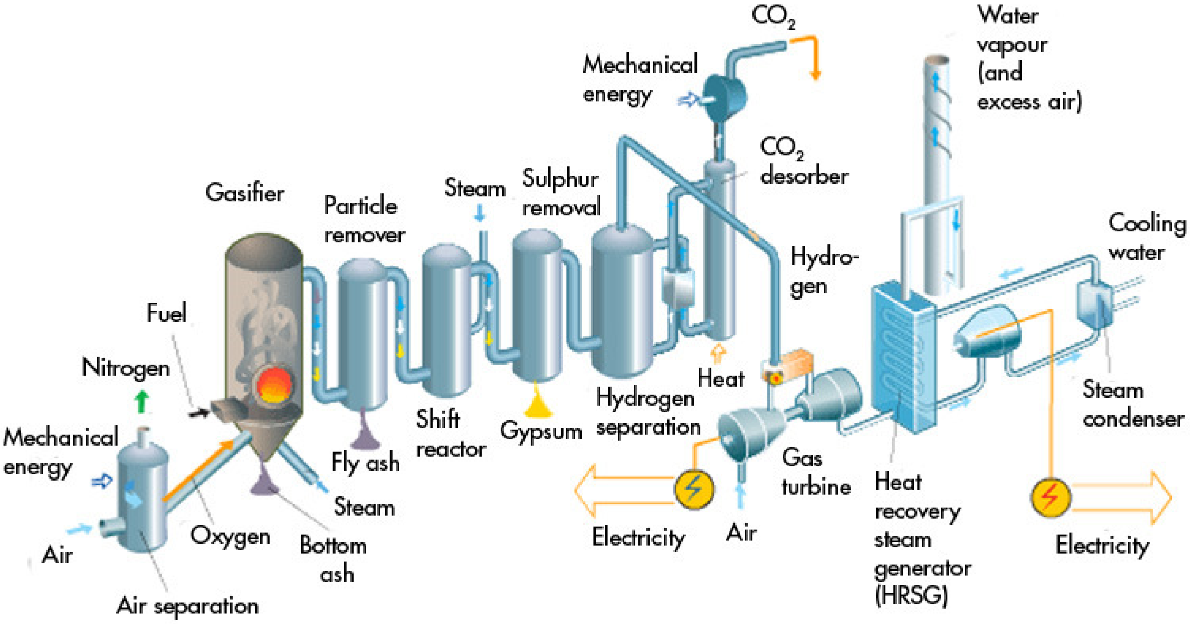
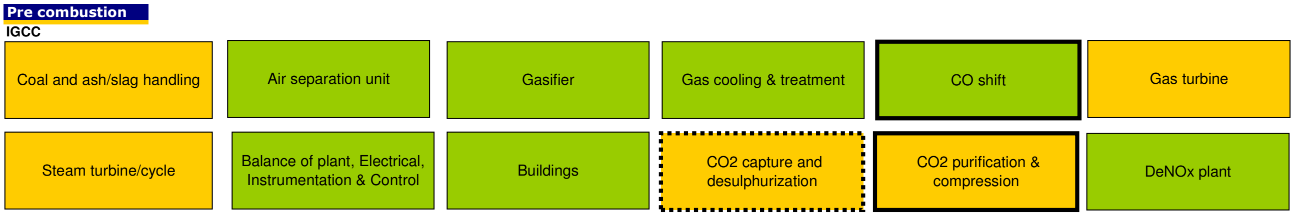


Figure B - 3 Schematic overview of pre-combustion technology. Source: Vattenfall

In pre-combustion capture, the CO_2 is removed or separated before the combustion process. Instead of combusting the fuel directly, in pre combustion the fuel is first gasified or reformed into syngas containing predominantly hydrogen and CO_2. The CO_2 is being captured and the hydrogen rich gas is used to generate power.

One configuration that uses the pre combustion capture option is shown in the figure above. This figure shows an IGCC with CO_2 capture. The first step in pre-combustion is producing an almost pure O_2 stream by separating air in an *Air Separation Unit*. The O_2 is led to a *gasifier* where it reacts with the fuel to form syngas. This syngas is a mixture of H_2, CO, CO_2 and H_2O. The syngas is cleaned to remove trace substances and particute matter. Then, in the *water gas shift reactor*, steam is added to the syngas, converting the CO to H_2 and CO_2. The CO_2 can then be removed with chemical and physical solvents, adsorbents and membranes. The CO_2 is then captured from the stream and after compression and dehydration it can be transported to a storage location. The H_2 rich stream is led to a *gas turbine* to produce electricity. Heat is recovered from the gasifier and flue gas exiting the gas turbine and is used to produce steam that powers a *steam turbine* for additional electricity generation, increasing the efficiency of the plant.

In Figure B - 4 we score the maturity of several technology blocks in the concepts using pre combustion capture. We see that all technology blocks are considered (almost) mature. Added blocks needed for CO_2 capture are the Water gas shift (CO shift) reactor and the CO_2 purification and compression block. The CO_2 capture block is typically sour gas separation block very much similar to already used H_2S removal technology. Adaptations are necessary in the gas turbine block and steam cycle. The latter deals with the optimal syngas cooling after gasification and steam requirements for the WGS reaction.



Pre combustion

IGCC

Coal and ash/slag handling

Air separation unit

Gasifier

Gas cooling & treatment

CO shift

Gas turbine

Steam turbine/cycle

Balance of plant, Electrical, Instrumentation & Control

Buildings

CO2 capture and desulphurization

CO2 purification & compression

DeNOx plant

Figure B - 4 Maturity of technology blocks for power generation with an IGCC including pre combustion capture. Bold frames indicate a new technology block that is added due to CO_2 capture. Note that the CO_2 capture block is dashed as CO_2 capture is very similar to already existing syngas desulphirization sections within an IGCC. Based on ZEP (2008).

B 3 Oxyfuel

Oxyfuel combustion uses almost pure O_2 instead of air for combusting fuel. The air is first led into an *Air Separation Unit* removing the O_2 from the air. The oxygen and the fuel are then together led into a *boiler* where the fuel is combusted. The steam that is generated is led to a *steam generator* producing electricity. The flue gas from the combustion process is first treated by removing particulates and sulphur. Part of the flue gas is recycled into the combustion process to control the temperature in the boiler. The result is a flue gas containing mainly CO_2, water and some impurities. The CO_2 is purified by removing water and impurities. Then the CO_2 that is compressed and ready for transport.

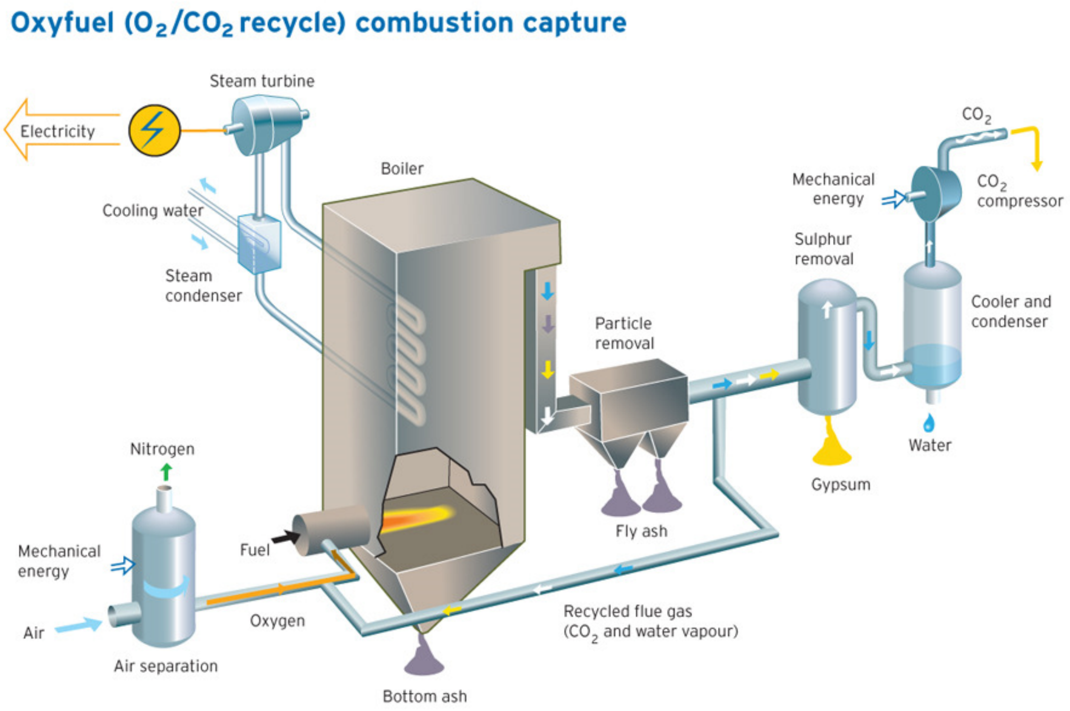


Figure B - 5 Schematic overview of oxyfuel combustion technology. Source: Vattenfall

In Figure B - 6 we score the maturity of several technology blocks in the concepts using oxyfuel combustion concept with CO_2 capture. For the NGCC concept we see that the gas turbine and burners is the least mature technology block. This type of turbine has not yet been proven or demonstrated. For the PC concept we see that most of the technology blocks need to be adapted when using the oxyfuel technology. The steam cycle and boiler island (configuration/design of burners and heat exchangers), the removal of impurtities from the CO_2 stream and compression of (wet) CO_2 is the subject of recent and ongoing RD&D efforts and is considerably different compared to PC concept without capture and the PC concept with post combustion capture. The least mature block is considered to be the advanced treatment of the flue gas where CO_2 stream is compressed and integrated with the removal of impurities such as SOx and NOx.

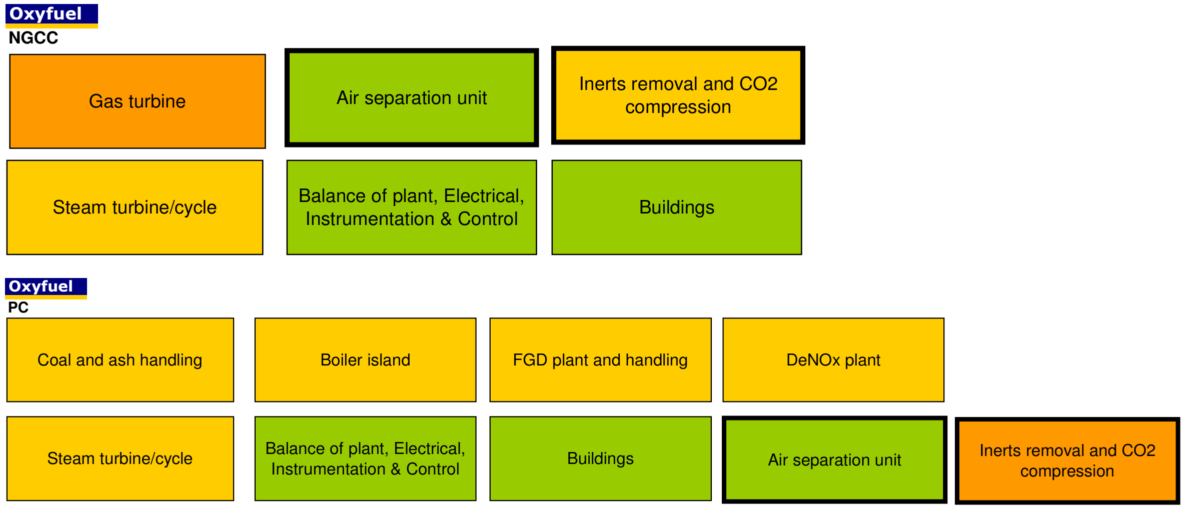


Figure B - 6 Maturity of technology blocks for power generation concepts NGCC and PC including post combustion capture. Bold frames indicate a new technology block that is added due to CO_2 capture. Based on ZEP (2008).

Appendix C Technology providers vs. service providers

In section 2.3 we emphasize that we consider the full CCS chain when analysing possible supply chain constraints. We distinguished constraints regarding Equipment & Materials and Services & Skills related constraints in the supply chain of CCS projects.

In CCS projects, Engineering Procurement and Construction (EPC) (sub)contractors or consortia will most likely design and deliver the main technology blocks (i.e. components) for the power plant, including the components needed for CO2 capture. The scope of such EPC contracts includes for instance project management, engineering, procurement of sub-components from the boiler islands to the fans and pipes, construction of the technology blocks and commissioning. This holds for the energy conversion and CO2 capture part of the CCS chain, but also for the transport and storage part.

This implicates that a large amount of companies will contribute to delivering parts of the CCS chain. For simplification, we can divide these companies into engineering companies and engineering contractors or consultants. The first group of companies constitutes technology providers and contains companies that deliver the actual hardware, i.e. technology blocks, for CCS chains. The second group consists of more service-oriented companies that may not deliver the hardware themselves but are responsible for amongst others: design, procurement, project management, legal and financial services. Note that these groups are not mutually exclusive and companies may thus be present in both groups, i.e. most technology providers also offer engineering and contracting services.

Examples of the first group are: UOP, General Electric, Babcock and Wilcox, ALSTOM, GDF-Suez, Siemens, Mitsubushi Heavy Industries (MHI), Hitachi, Cansolv, Xebec-Questair, HTC Purenergy, Doosan-Babcock, Linde-BOC, Air Products, Praxair, Air Liquide, KBR, Aker Clean Carbon, Fluor and many others.

Examples of the second group are: Fluor, Foster Wheeler, Lurgi, Technip, JGC, Aker Solutions, WorleyParsson, MMI Engineering, Jacobs Engineering, TetraTech, ARUP, AMEC, Wood Group, AspenTech, Ingen, Schlumberger and many more.

A recent trend that may be discerned is that technology and service providers join forces in cooperative agreements or through licensing contracts. Through these co-operations, companies or consortia can now deliver the full CCS chain package to the market integrating both services for design and engineering of power plants, transport and storage sites, and delivering the hardware.

The advantage of these cooperative agreements is that consortia can link services to enhance for instance project management. This will result in less bottlenecks when designing, constructing and operating the CCS chain, i.e. ease implementing CCS projects. However, it is not incongruous to suggest that this also links possible supply chain constraints for both Equipment & Materials and Services & Skills. Or in other words, if only a few worldwide consortia can deliver the necessary services and equipment for CCS projects, this would render the market more susceptible to capacity limits and thus supply chain constraints.