Industry Wide Supply Constraint Risks to Fast Large Scale Carbon Capture and Storage Deployment 2010-2050

Master Thesis 45 ECTS

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Preface

This research has been carried out as a master thesis of the master Science and Innovation Management at Utrecht University. During six months it has taken place at Ecofys, a sustainable energy consultancy firm that is a full daughter of Eneco. It has been a contribution to the 2011 OECD International Energy Agency report on barriers to implementation of CCS - capacity constraints. However, the conclusions in this research are my own. They are not necessarily those of Ecofys or the IEA. I would like to thank Msc. Pieter van Breevoort, Dr. Joris Koornneef, Dr. Chris Hendriks, Msc. Paul Noothout and Msc. Erika de Visser (Ecofys) for their valuable input and the good time at Ecofys. Furthermore I would like to thank my academic supervisors of the Copernicus Institute for Sustainable Development and Innovation, Dr. Simona Negro and Dr. Robert Harmsen for their interest in the subject and approach and their valuable advice.

-Alexander Hulsman
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Summary

Fast large scale implementation of carbon (CO_2) capture and storage (CCS) in the period 2010-2050 as described by the OECD IEA BLUE Map scenario is 'ambitious' (IEA, 2009). As innovation is a dynamic process characterized by feedback mechanisms and interactions, an innovation system should be built up. This innovation system includes the function (activity) *resource mobilization* and the structural components *supply side* and *knowledge* infrastructure. Physical and human resources that cannot be supplied fast enough in the needed quantity or quality form supply constraints. Therefore the question is asked: *in what way industry wide supply constraints form a risk to the fast large scale deployment of CCS as described by the IEA Scenario and in what way can these be mitigated?* A first important methodological result is the success of the combination of a historical comparison and the assessment of supply constraints. A second methodological result is the clarifying effect of the distinction (based on innovation system theory) between current resource mobilization and the ability of the supply industry or knowledge infrastructure to increase. An empirical result is that the components that have been found to pose supply constraint risks have all a limited fulfillment of the quantitative resource mobilization in combination with unfavorable supply industry dimensions of exogenous demand growth or material availability. The combination of a qualitatively limited resource mobilization with the corresponding unfavorable supply industry dimension competition has occurred much less for physical resources. Especially the post-combustion capture option suffers from supply constraints but compression and transport do equally, notably in China and India. For human resources there is both a supply constraint of insufficient availability and supply constraints of insufficient performance. The successful large scale deployments of FGD and CCGT have been much less than what the IEA scenario describes for CCS, while not having had any supply constraints. Therefore it seems unlikely that large scale CCS deployment will go as fast as described by the IEA scenario. The gathered data about the specific resource mobilization and supply industry / knowledge infrastructure dimensions for different world regions could be further fine-tuned or confirmed by more thorough industry size and growth analyses. Gradual and long timeframe policies, in combination with early investments with public funds and a realistic view of a geographical distribution would be a possibility to decrease the identified supply constraint risks.

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Glossary

CCGT	Combined Cycle Gas Turbine
$DeNO_x$	$DeNO_x$ system
FGD	Flue Gas Desulfurization system
Industry	Industry supplying resources
OCGT	Open Cycle Combined Gas Turbine
Petroleum industry	'Petroleum industry' and 'oil and gas industry' are used as synonyms in this report

Figures with letter indications (such as Figure C-1 *can be found in the Appendix under the corresponding letter.*

1. Introduction

In order to limit the long term temperature rise to 2-2.4 degrees Celsius, anthropogenic CO_2 emissions should be reduced by at least 50 % by 2050 with respect to 2000 levels (IPCC, 2007). Wind, solar photovoltaic, biomass, hydro and nuclear energy production are today implemented and contribute to greenhouse gas emission abatement. Furthermore, in order to meet a 50% reduction in emissions, apart from a wider deployment of the modes of energy production mentioned above, carbon (CO_2) capture and storage (CCS) seems to be indispensable from an economically realistic perspective. To achieve this reduction without CCS would imply an increase in costs of 70% (IEA, 2010b). The International Energy Agency (IEA) of the Organization for Economic Co-operation and Development (OECD) has developed a scenario[1] for CCS, that describing the quantity of CO_2 has to be captured and stored annually until 2050 in order to meet this CO_2 reduction goal (see *Figure 1-1*). In this scenario, 19% of CO_2 emission abatement in 2050 is dependent on CCS (relative to the business as usual scenario). With currently only four commercial scale[2] CCS plants operational (Dooley et al. 2009), the IEA has described "this level of CCS deployment [… as] a tremendous global challenge" (IEA, 2009, p.6). The IEA has formulated the Roadmap (IEA, 2009) to specify how these goals can be met[3]. It assumes that 100 commercial scale CCS installations will be operational by 2020 and 3400 by 2050. These are (retrofitted) power plant CCS installations and industry site CCS installations, such as natural gas processing sites, biomass/natural gas based production of synfuel/hydrogen and production facilities in the cement, chemicals and iron and steel industry (IEA, 2009).

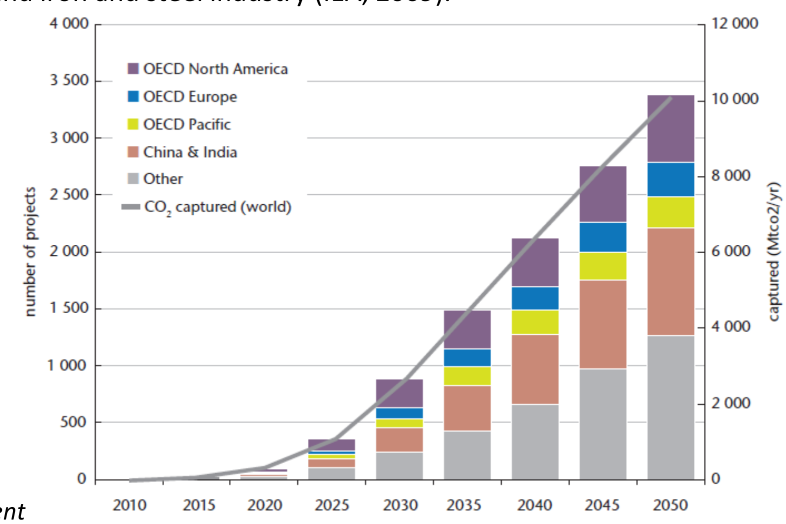

Figure 1-1 OECD IEA CCS deployment scenario (IEA, 2009).

[1] As a part (more than 20% in terms of CO_2 abatement) of the 2008 Energy Technology Perspectives BLUE Map scenario that describes which technologies can be deployed to what extent (bottom-up model optimizing cost) to reduce global CO_2 emissions by 2050 to half those of 2005, while assuming that "the energy sector CO_2 emissions will increase by 130% above 2005 levels by 2050 in the absence of new policies or from supply constraints" (IEA, 2009, p.5).

[2] Three natural gas treatment facilities and one coal gasificitation plant, all based on simpler processes that are unsuitable for most power generation applications.

[3] Addressing a deployment partitioning in the power sector and in the industry / upstream, actions in technology development, financing, legal, engagement and international collaboration. All is split up by 2010-2020 and 2020-2050.

The question rises if CCS can be deployed in the pace the IEA scenario suggests. The pace of deployment matters, as "delayed emission reductions [would] significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts" (IPCC, 2007, p.19). Needed finances and technological stand of affairs have been taken into account in the Roadmap and in more detail in the 'Energy Technology Perspectives' 2010 (IEA, 2010). Insight in the current development of the CCS innovation system ('orgware' as opposed to hardware and software, Hekkert et al. 2007) is provided by Van Alphen et al. (2010). It is striking that none of these researches (IPCC, 2007; IEA, 2010; Van Alphen et al. 2010), nor any other research that we know of, has *systematically* [1]looked into the availability of a great number of physical and human resources. To implement CCS on a large scale[2], these resources will be needed in large quantities, as described by the resource based view (e.g. Mahoney and Pandian, 1992). The physical and human resources need to be supplied by industries and educational programs which might currently be supplying not more than a fraction of the resources needed for CCS deployment. The incapability of a supply industry or an educational program to meet the CCS demand as it could become according to the IEA scenario would imply a supply constraint risk. To assess the capability of the supplying industries and educational programs to meet CCS demand as it could become according to the IEA scenario, the following research question has been formulated:

In what ways do industry wide supply constraints form a risk to the fast large scale deployment of carbon capture as and storage at the scale described by the OECD IEA BLUE Map scenario 2008 and how can these be mitigated?

In order to answer this question, a theoretical framework needs to be developed that describes which dimensions lead to supply constraints. A comparison with historical technology deployment can provide insight in the use of this framework and an idea of which speed of deployment acceleration is possible. The historical comparison is carried out with studies of the implementation of two technologies in the power sector: the flue gas desulfurization unit and the combined cycle gas turbine. These innovations are chosen because they are both power sector technology. There has been very rapid deployment of these technologies, i.e. there has been a high rise in number of desulfurization units and CCGT power plants (Graus and Worrel, 2007; Watson, 1997). Because obviously not all resources needed for CCS deployment can be extensively assessed, a selection is made of resources susceptible to supply constraints. Possible policy implications[3] to deal with supply constraint risks are formulated. This leads to the formulation of the following sub questions:

1. What have supply constraint risks at the introduction of flue gas desulfurization systems and combined cycle gas turbines been and what was the deployment rate of these fast large scale deployments?
2. What are critical physical and human resources that might cause supply constraints for CCS?

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[1] Innovation system assessments are in general descriptive per system function.

[2] 'Large scale' is used to indicate the deployment at a scale of $10GtCO_2$ capture and storage worldwide by 2050.

[3] Policy understood as actions of both government and firms, e.g. the term *firm policy*.

3. What is the risk of the occurrence of supply constraints for these resources?
4. How could the knowledge of these risks be used in order to mitigate supply constraints?

The implementation rate as described in the IEA scenario is compared to historical cases of technology implementation in order to verify whether the growth rates could be realized (*sub question 1*). In answering *sub question 2* an initial selection is formed of those resources that might form supply constraints. It results in a shortlist of critical physical[1] (e.g. components as absorption towers but also transport and storage services of CO_2) and human resources (e.g. a specific kind of engineer). *Sub question 3* assesses the supply constraint risk for the critical resources found at *sub question 2*. Finally (in answer to *sub question 4*) it is discussed how the identification of the supply constraint risks can avoid the actual occurrence of supply constraints.

The newsworthiness of this research lies in the focus on future constraints of mobilizing enough nonfinancial resources for large scale deployment of CCS. Energy technology analysis focuses on technological performance and costs (Blok, 2007). Normative scenarios take into account technology, economics and under the term 'problems, constraints, and opportunities' only legal and environmental issues (such as the over 1100 pages volume of Johansson, 1993). In these studies, resource mobilization is often only addressed in a subordinate clause stating there will be fierce competition with the oil and gas industry without further specification. The resource based view and Porter's industry analysis address resources extensively, but these theories focus on a firm level and are thus, at the least not integrally, useful for an assessment of the production capacity and production enlargement possibilities of a complete industry. Conceptualizations of *supply* and *resource mobilization* are for example used in innovation systems theory[2], but the availability of resources focuses mainly on the current mobilization of financial resources (e.g. Van Alphen et al. 2010), which is rather limited in our view. Furthermore, there has not yet been a focus on one part of the innovation system[3] with the development of a framework to systematically analyze this innovation system part. Mackaaij (2010) has previously added the notion of supply constraints (including nonfinancial ones) to innovation systems theory by case studies on offshore wind and geothermal energy in the Netherlands. The current research provides a new contribution to the innovation systems research tradition, because of a different case (global implementation of CCS), and its systematic assessment of supply constraints.

If the analysis of supply constraints proves useful for future CCS innovation system build-up, IS scholars with a focus on the future build-up of an IS might find it useful to equally include an assessment of supply constraints to large scale implementation and diffusion. For society, the usefulness of this research is that it will add the extra dimension of supply constraints to the Roadmap. Many studies have concentrated on the costs of CCS plants (e.g. Abu Zahra et al. 2007b; Dynamis, 2008) and even more on the technical performance of CCS plants (e.g. Abu Zahra et al.

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[1] The components broken down into the three main capture methods (post-, pre- and oxyfuel combustion) as it is to date not yet certain which capture technology, if any, will become the dominant one (IEA, 2009).

[2] 'Supply' as a structural component and 'resource mobilization' as a system function of an innovation system (see *Chapter 2*).

[3] Limited number of system functions and system structure components.

2007a; Singh et al. 2010). This study can be seen as a translation of the abstract Roadmap in more concrete industry terms. Supply constraints are the everyday reality of the industry in the form of lead times. According to Wu et al. (2005, p.126, emphasis original) “a firm’s ability to manage capacity is arguably *the* most critical factor for its long-term success”. In this way this study about the probability of supply constraints can be seen as a study about the probability of rapidly increasing lead times. This study on the likeliness of industry wide supply constraints hampering the deployment of CCS will provide policy makers with insights that are relevant when actively pursuing the realization of the IEA scenario. However serious these supply constraints, an early recognition helps to avoid them. For the large scale implementation of new technologies supply industry characteristics should be taken into account in a meaningful and systematic way. Orders for certain resources could be placed a long time in advance, for other resources there could be made use of conjectural low times. This would avoid supply constraints risks becoming supply constraints, which makes the Roadmap more realistic. For society at large, this implies an augmented probability[1] of execution of the CCS IEA scenario, and consequently an augmented probability of limiting long term global temperature rise to 2-2.4 degrees Celsius.

This study uses the same scope as the IEA scenario. The IEA scenario takes worldwide CCS applications to power plants (55% by 2050) and industry sites (45% by 2050) into account. The “optimistic view of technology development” employed by the IEA (IEA, 2010, p.166) is adopted. It implies that although some technologies are still in the demonstration phase, it can be assumed that they will be commercially available within five to ten years.[2] The focus is on the dimensions that might hamper the resources becoming commercially available within this timeframe and the dimensions that might hamper resources to become available in sufficient amounts.[3] The availability of finance or investment constraints, or the future development of yet non-existent technologies are not included as this would make the results of the results highly uncertain and cloud the specific supply constraint risk insights.

A theoretical delineation is given in *Chapter 2*. Dimensions are formulated on the basis of existing theories, and it is discussed how these dimensions lead to supply constraints. The research method is discussed in *Chapter 0*, in which the before mentioned dimensions are operationalized. Sub question 1 (historical comparison) is answered in *Chapter 4*: the occurrence of dimensions and the risk of supply constraints is investigated for the introduction of flue gas desulfurization systems and combined cycle gas turbines. Sub question 2 (selection of critical resources) is dealt with in *Chapter 6* (physical resources) and in *Chapter 7* (human resources). In the same chapters an assessment is made of the

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[1] The actual execution of the Roadmap will of course depend on many other factors, inter alia financial and political ones.

[2] The emergence of a dominant design is not subject of this thesis. Following the optimistic technological view, the technologies identified will all be deployed over time. In view of post-, pre- and oxycombustion this is not such an unrealistic view, because each method has its advantages for specific fuel types.

[3] Another approach could be to focus on what factors stimulate resources becoming commercially available within this timeframe, or which indicators stimulate the sufficient availability of resources within this timeframe. An increased or sudden interest of the oil and gas industry in an essential CCS component could in this view be beneficial. The additional investments that go with such an increased exogenous (seen from the CCS point of view) demand could accelerate technology development.

likeliness of the occurrence of supply constraints in the large scale deployment of CCS (sub question 3). Subsequently policy implications following the supply constraint risks (sub question 4) are treated in *Chapter 10*. This is done after the conclusions of the rest of the research.

2. Theory

Innovation is essential for economic growth and development (Alkemade et al. 2007). Currently the consensus concerning the correlation between CO_2 emission levels and climate change is growing. However, economic growth and development would be put to a risk if the world would be constrained to renewable energy sources on medium term (IEA, 2010b). CCS innovation is essential to economic growth and development in the sense that it allows economic growth and development to continue while limiting the dangerous side effect of accelerating climate change. As Alkemade et al. (2007) have pointed out, innovation is “characterized by uncertainties, huge investments and late returns on investment” (p.140) and a ‘particularly complex’ process in case of sustainable innovation. Negro (2007) stresses the issue of ‘carbon lock-in’. It is difficult for sustainable technologies to compete with fossil fuels, because the latter are to a great extent aligned to their clients and their suppliers, but also government regulations and knowledge infrastructure. Competition with such an incumbent regime is very hard because the new technology should construct these alignments (Geels, 2002). Because the practical implementation of CCS goes beyond the technological progress, it is relevant to look into the *innovative process*, a term that is referred to as ‘technological development in the wider sense’ by Hekkert et al. (2007, p.414).

Breaking in an incumbent regime and establishing a new regime goes through different phases. Bergek and Jacobsson (2003) have distinguished an *experimentation* phase and an *expansion, turbulence and growth* phase. See *Figure 2-1* for a representation of the diffusion over time and the different phases that can be distinguished. The experimentation phase corresponds to creation of possibilities as described by evolutionary economics, while phase 2 is more described by a neoclassical economical model where investments lead to rapid growth in economic activities (Kleinschmidt, 2004; Bergek et al. 2008). *Take-off* (Hekkert et al. 2010) demarcates the transition between both phases. During take-off, the slope of the diffusion curve increases (diffusion accelerates) so resource requirements are exponentially increasing. It follows that it is particularly during take-off that the resource supply should be ramped up[1] exponentially. The accelerating resource supply during take-off is indispensable to enter phase 2 with its high and continuous rate of diffusion.

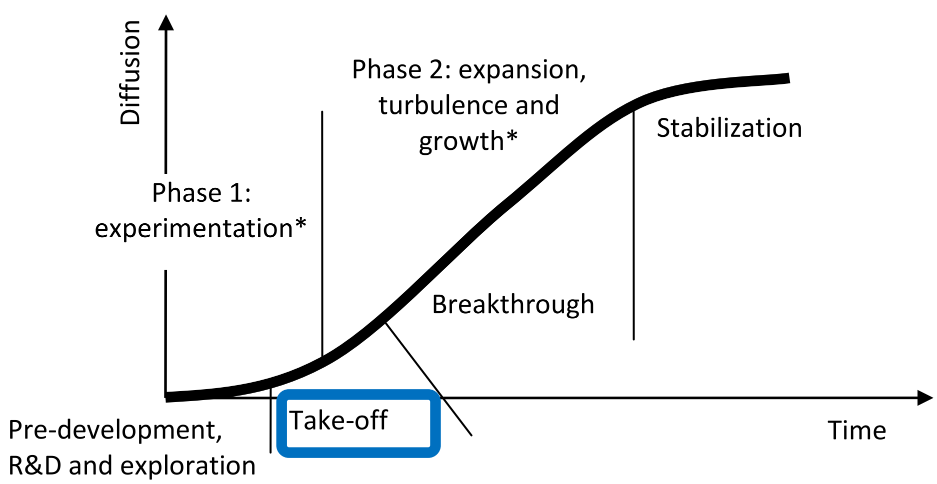

*Figure 2-1 Diffusion curve (adapted from Hekkert et al. 2010 and Suurs, 2009). This research focuses on supply chain constraints in the take-off and the acceleration phase. *’Phase 1’ and ‘Phase 2’ by Bergek and Jacobsson (2003)*

[1] ‘Ramping up production’ is the term commonly used to indicate production increase after a new product has developed, e.g. Terwiesch and Bohn (2001).

2.1 Technological innovation system

A new technology breaking into an incumbent regime and establishing a new regime is a dynamic process. This dynamic process is not linear, i.e. from fundamental research to applied research to product development. Instead, it is “characterized by complicated feedback mechanisms and mutual interactions involving science, technology, learning, production, policy and demand” (Negro, 2007, p.25). According to Lundvall (1988) innovations are very limited in ‘pure markets’ or ‘pure organizations’, while innovations often occur when there are ‘relationships of an organization type’, i.e. when there is information exchange and cooperation. The technological change is thus next to hardware and software dependent on ‘orgware’, that is, its *innovation system* (TIS, Hekkert et al. 2007). This concept of an innovation system is based on organizational economics and interactive learning. Hekkert et al. have pointed out that currently the relevant knowledge base for most technologies is not limited to a country, region or industry sector. Therefore the technological innovation system can be often be used instead of a national, regional or sectoral one. This technological innovation system consists of the actors that are involved with or should be involved with developing and implementing a specific technology. Or, as Carlsson and Stankiewicz (1991) have put it this technological system is “as a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology”. It is a network of public and private institutions “involved in the production, diffusion and use of knowledge relevant to technological development, the linkages and interactions between these institutions, and the resulting flows of knowledge, technology, financing and other resources” (Sagar and Holdren, 2002, p.468). These institutions can be universities, governments, NGO’s, new entrant en incumbent firms, and research consortia, but institutions can also be more abstract, for example laws (Suurs, 2009). By theoretically grouping all actors in system components, a system structure emerges (see *Figure 2-2*) of which every component has to be properly developed to make the innovation (innovative process) a success. It distinguishes between a governmental/political subsystem, a supply side, a demand side, a knowledge infrastructure in the middle and an intermediary infrastructure (Suurs, 2009). The governmental/political subsystem consists of the governments and ministries issuing policy. The supply side consists of those actors producing technological artefacts, such as suppliers and manufacturers (Alkemade et al. 2007). The demand side consists of firms and governments that use the technology. The knowledge infrastructure creates, assesses and diffuses knowledge. It encompasses actors such as research institutes and educational institutions. The intermediary structure consist of those actors that exchange knowledge between the supply and demand side, such as project developers (Alkemade, 2007).

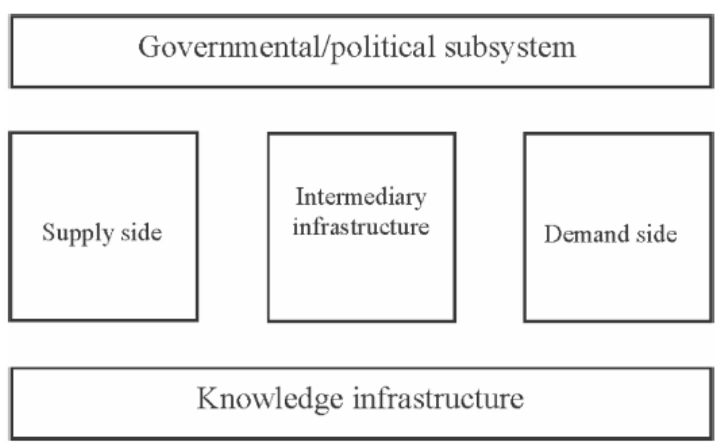

Figure 2-2 System structure (Alkemade et al. 2007)

While the structure of the innovation system helps conceptualizing the innovation by grouping the different actors, on itself it does not describe the innovative *process*. The factors influencing development and diffusion are the activities carried out by the actors (Edquist, 2004). These activities are an integral part of the innovation system. The activities are therefore functional (or *functions*) of the innovation system.

2.1.1 Innovation system dynamics

Especially the understanding of the dynamics of an innovation system provides handholds to boost the innovative process and build up a non-existing or partially existing innovation system. Therefore, much innovation system research has focused on system functions. Several descriptions of the innovation system exist that have used a different clustering of functions (Suurs, 2009). Based on different sets of system functions that have been used in literature (e.g. Liu and White, 2001; Johnson, 2001), Hekkert et al. (2007) have proposed seven system functions (the descriptions below are also based on those of Negro, 2007).

1. *Entrepreneurial activity.* First of all it is recognized that entrepreneurial activity is essential for the innovation system, as without the entrepreneur innovation would not take place. Entrepreneurs use the potential of new knowledge, networks and markets to set up new projects and experiments. By experimenting learning takes place. Entrepreneurs are not necessarily new entrants, but can equally be incumbent firms. The fulfillment of this function is dependent on the number of new entrants, the number of diversification of activities and the number of experiments with the new technology.
2. *Knowledge development* is the most basic function of the innovation system. It consists of the creation of new knowledge, either fundamental or of a more practical nature. Knowledge should be developed if encountered problems in the innovation process require so. Besides the development of strictly new knowledge, it is also the combination of new and old knowledge and the reuse of old knowledge by imitation. The knowledge can be developed by universities, corporate R&D departments, but equally important in an innovation context is ‘learning by doing’, ‘learning by searching’ (i.e. demonstration) and ‘learning by using’ and ‘learning by interacting’.
3. *Knowledge diffusion through networks.* Networks determine the structure of the innovation system. Knowledge diffusion passes through networks. This is important in a strict R&D setting, but especially in a heterogeneous context where researchers meet government representatives, competitors and the market. It is essential for a government to be aware of the latest technological possibilities, norms and values when setting standards. ‘Learning by using’ is the form that is in place in user-producer networks.
4. *Guidance of the search* provides a possibility to focus and thus prevent the scattering of efforts. Where entrepreneurial activity and knowledge development can be seen as ‘creating’ in evolutionary economics sense of the word, there is also a selection needed. Due to limited resources naturally not all options can be pursued. The search for a successful innovation path can be guided by “those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users” (Hekkert et al. 2007, p.423).
5. *Market formation.* At the same time, the new technology needs a niche market to be given a temporary (financial) competitive advantage. These activities can be brought together under the term market formation. When a product is finally ready to be put on the market, the

market might not be ready for it because previous technologies are embedded in several ways. This makes it difficult for a new product to enter, especially because at the same time it is often still struggling with teething troubles.

6. *Resource mobilization.* Entrepreneurial activities, the creation of knowledge and other activities that are described here and needed for innovation are difficult to execute without any resources (both financial and human[1] according to Hekkert et al. 2007, p.425). Jacobsson et al. (2004, p.7) define supply of resources as “capital, competence and input materials”[2]. Resources need to be allocated in sufficient degree as they are the basic input to all activities in the innovation system. This activity is designated resource mobilization[3].
7. *Creation of legitimacy/counteract resistance to change.* Parties that believe in the ultimate success of the innovation can play a role by convincing the numerous actors needed that this is ‘right horse to bet on’. This is an essential activity, as actors with interests in the incumbent system might see a new innovation system as a threat, with a result that they might counteract the build-up of a new innovation system.

Experimental studies have validated that these seven system functions describe the relevant activities of an innovation system (Suurs, 2009). “[T]he way in which the system is structured, is an important determinant for facilitation of the functions” (Kleinschmidt, 2004, p.73). There is a feedback relation between the system structure and system functionality (Alkemade et al. 2007). ‘[E]conomic competence’ as part of the system structure (differing per country according to Carlsson and Stankiewicz, 1991) influences the rate of fulfillment of the system function *entrepreneurial activities*. Present *knowledge infrastructure* influences the fulfillment of the system function *knowledge diffusion*. The current research focuses on the *supply side* as it influences the fulfillment of the system function *resource mobilization*.

2.1.2 Porter and industry structure

Porter has described how a structural analysis of industries can be performed (Porter, 1980). He has defined industry as “the group of firms producing products that are close substitutes for each other” (p.5). According to this definition firms are often part of more than one industry. It resembles the system structure as described by innovation system theory as it also includes interaction with suppliers and buyers. It describes the creation of competitive advantage for an individual firm by increasing its bargaining power with respect to its buyers and suppliers, and its defense with respect to new entrants, substitute products and competitive rivalry. There are two reasons why it is difficult to use this industrial analysis to identify possible supply constraints. Firstly, as is indicated by the focus on bargaining power, financial considerations play a main role in competitive advantage. The end goal is to increase and to assure profits for long term firm viability. Secondly, as it describes how a firm can

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[1] Several experimental studies have also looked into the availability of other resources, such as biomass for biomass energy (Negro, 2007).

[2] However in the rest of this article the focus is on capital whenever supply of resources is discussed.

[3] Liu and White (2001) have instead used ‘Manufacturing’ as a system function. It is predominantly concentrated on organization and invention in manufacturing.

obtain an advantage over new entrants, substitute products and direct competitors, it is difficult to use Porter to analyze total industry capacity. However, its definition of an 'industry' can of course be used.

2.1.3 Resource based view

A defining framework for resources can be found in the extensive resource based view literature. The resource based view has a broad definition of resources. According to Mahoney and Pandian (1992), possible resource constraints include the availability of labor and physical input, the availability of finance, the availability of suitable investment options and the availability of skilled managerial capacity. The resource based view focuses on a firm perspective where the availability of distinctive resources defines the competitiveness of the firm (Wernerfelt, 1989; Hewitt-Dundas, 2006). For supply constraints the aim is to focus on a global perspective where the central point is not competitiveness of a firm but the ability of an industry to meet a specified production target. As Mahoney and Pandian have written from a resource based view (the article is titled 'The resource-based view within the conversation of strategic management') these resource constraints apply to a specific firm.

2.2 Supply constraints framework

Mahoney and Pandian's definition of supply (resource) constraints could be grouped into physical and human resources (if financial resources and suitable investment options are left out because of the current study's delineation). The notion of constraints of physical resources, labor and competent managerial capacity for a specific firm is transposed to use them in an industry perspective. Labor and managerial capacity are then both human resources, while physical resources consist of the 'physical input' (this term is also used by Jacobsson et al. 2004). Physical 'input' is a clear definition as it limits the research domain to the first tier level; those resources that are directly delivered to the project developers. Suppliers of those resources are themselves dependent on other semi-manufactured goods, but those are not independently included in 'physical input'. The most intuitive supply constraint for physical resources is insufficient production. It can lead to long lead times or the inability to serve new clients. Next to this as the supply constraint risk of *insufficient production*, another situation could keep resources from being available. If adaptation to the new technology of a physical resource takes too much time, well performing resources will be unavailable (insufficient product innovation). Alternatively well performing resources might be available in a very limited amount because manufacturing takes too much time (insufficient process innovation). These last two causes both lead to insufficient availability of well performing physical resources. This will be denoted as the supply constraint risk of *insufficient performance*[1]. To develop an innovation system there is a need for a "supply of qualified people from the educational system and a thorough industrial training system for a variety of craft and technical skills" (Freeman, 1992, p.178). There is the risk of insufficient availability of personnel (merely not enough personnel available, comparable to the risk of

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[1] 'Insufficient' in the expressions *insufficient production* and *insufficient performance* should be understood as a synonym of 'constraint' in 'supply constraint'. 'Insufficient' indicates that the production / performance is a bottleneck during CCS deployment. Furthermore a *dimension of the risk of insufficient production* / *performance* is in general noted shorter as a *dimension of insufficient production* / *performance.*

insufficient production for physical resources), but there can also be the issue of insufficient performance.[1] Whereas the insufficient availability of personnel can be resolved by the introduction of educational programs and retraining programs in the industry as Van Alphen et al. (2007) have indicated, familiarity with a system can often only be acquired by years of experience.

The quantitative and qualitative fulfillment of the system function resource mobilization (excluding financial resources) with respect to the demand (as described by the IEA scenario[2]) determines the extent to which of the system structure components 'supply side' (for physical resources) and 'knowledge infrastructure' (for human resources) need to be further developed. The supply side (supplier/manufacturer industries) and the knowledge infrastructure (educational institutions) of the system structure, determine the possibility of the speed of the future quantitative and qualitative fulfillment of *resource mobilization*. More precisely, the supplier/manufacturer industries determine the possible future quantitative and qualitative mobilization of physical resources. Educational institutions (including firms providing on the job training) determine the possible speed of the future quantitative and qualitative mobilization of human resources (see *Figure 2-3*). For example Alkemade et al. (2007, p.164) have found "Whenever there was an imbalance between the supply and demand sides or when the interaction between these subsystems became blocked, system functionality declined and wind energy development collapsed."

Several dimensions are developed to structure the factors influencing supply constraints risks. As the future fulfillment of the function resource mobilization of physical resources depends on the supply side and the future fulfillment for human resources depends on the knowledge infrastructure, the relevant dimensions are described separately: physical resources in *Section 2.2.1* and human resources in *2.2.3*.

[1] Experts interviewed by Van Alphen et al. (2010) have for example suggested the creation of specific CCS masters to solve this problem.

[2] Fulfillment of the function resource mobilization is taken with respect to the IEA scenario. If resources are mobilized in a sufficient rate to meet the IEA scenario demand, the function is fulfilled.

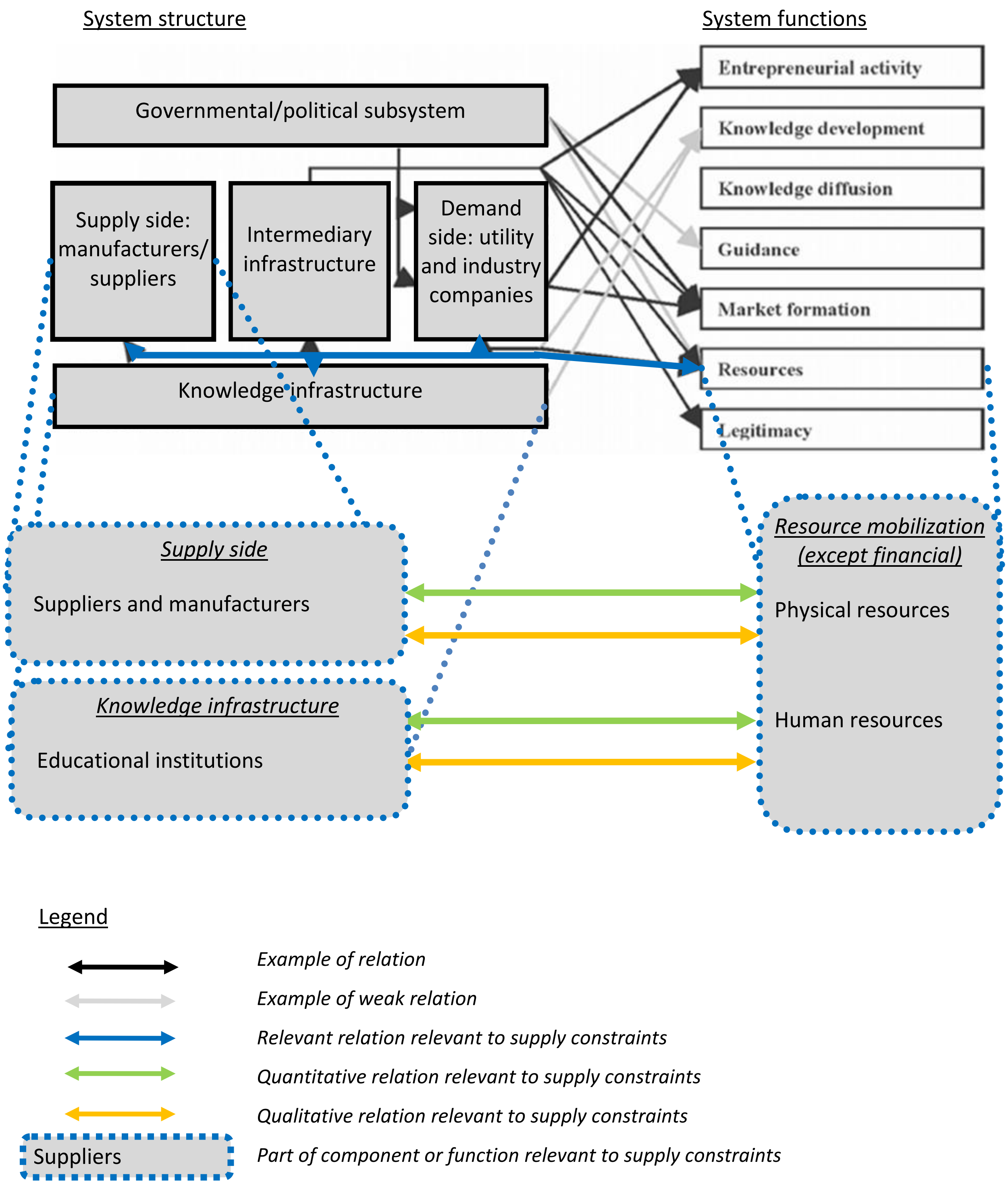

Figure 2-3 Interaction between components of the system structure and the seven system functions. Adapted from Alkemade et al. (2007). The supply side, the knowledge infrastructure and selected parts of resource mobilization are crucial for the occurrence of supply constraints.

2.2.1 Risk of insufficient production of physical resources

A supply constraint risk for a resource will depend on the necessity and the difficulty of a production increase of the resource. The necessity depends on the current *industry size* with respect to future demand. If in addition to a limited supply industry size (i.e. a limited resource mobilization), other sectors increase their demand (*a demand that is exogenous* to the deployment studied) simultaneously; this is likely to cause additional difficulties. If in addition to a limited supply industry size the production of physical resources is dependent on *scarce materials*, this would equally form a supply constraint risk. Therefore three dimensions have been distinguished for insufficient production of a physical resource: *industry size*, *exogenous demand* and *material availability*[1]. It should be noted that if the necessity of a production increase is absent, a difficulty to increase the production does not pose a supply constraint risk. Similarly, the if there is a necessity to increase production, but there is no difficulty to do this (i.e. exogenous demand and material availability are not problematic), this does not pose a supply constraint risk.

Resource mobilization: industry size

Radical enlargement will be needed when a physical resource is currently used to a limited extent. In that case the industry would need to expand significantly, i.e. it would need to increase its scale (Porter, 1980). Although industries can in general, using current capacity, still meet a somewhat fluctuating demand, it might cause problems when a high market growth needs to be in place for an extended period of time, because stocks are exhausted and manufacturing can often not continue on peak capacity for long periods. On the other hand, when physical resources that are needed are currently widely used in other applications, the industry would only need to grow modestly. In this case industry size would not be problematic.

Supply side: exogenous demand

If another sector increases its demand for a resource significantly, this diminishes the availability of the resource for the technology under study. If the exogenous demand for a resource is constant or only growing a little, it is not a problematic dimension of insufficient production. If the exogenous demand is expected to decrease the excess capacity could be used to fulfill the future demand of the technology. In addition, if another sector is financially very strong, a growing exogenous demand will be more problematic because competition for limited resources will become harder. Miller et al. (1999) have pointed out that this could lead to a decrease in future output.

Supply side: material availability

Suppliers of physical resources are in most cases relying on suppliers themselves, and that second tier suppliers might be relying on third suppliers (Sutton, 2004). In order to avoid an extensive study of all the tier levels suppliers, only the upstream limits are taken into account, i.e. the availability of scarce materials. These materials are for example alloys based on rare earth materials, or raw base chemicals needed for the production of solvents. The availability of scarce materials consequently can impede the ramping up of the production of a resource.

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[1] As a new framework is developed, it is tried to only use the most unambiguous dimensions, to leave less room for disputation. The theoretical framework may be extended with more dimensions of an unfavorable supply side for physical resources or knowledge infrastructure for human resources.

2.2.2 Risk of insufficient performance of physical resources

The risk of the supply constraint of insufficient performance depends on the engineering needed to adapt the physical resource.[1] The speed and the success of an engineering process depend, within the focus of this research, on the degree of competition within the industry. When significant innovation is needed, a larger degree of competition and low supplier concentration is beneficial (Belleflamme and Vergari, 2011).[2] Therefore there are two dimensions of insufficient performance of a physical resource: *engineering* and *competition*. It should be noted that if engineering is not problematic, a problematic competition cannot pose a supply constraint risk. Similarly, when engineering is problematic, but competition is not, it is assumed[3] that the engineering will take place under pressure of the competition. In that case there is no supply constraint risk.

Resource mobilization: engineering

Adaptation might take a long time and influence the supply. This has for example been foreseen in the case of the implementation of solar photovoltaics (Hubbard, 1989). If significant engineering work is needed, this is a dimension for the supply risk of insufficient performance. In this case it might take an extended period to fulfill the engineering process, or the engineering might not result in the expected level of performance.

Supply side: competition

An oligopoly, i.e. a significant industry concentration, can be seen as a market of imperfect competition. Industry concentration depends on the degree of oligopoly (Thépot, 2008). A monopoly as an extreme value because in that case 'the number of oligopolists is 1'. Furthermore, if a physical resource would be heavily patented, this might impede other firms to participate in competition[4] (Cohen, 2004; Laginier, 2004). This would result in a significant industry concentration, while a low industry concentration is more effective during the take-off phase (see the beginning of this section, *2.2.2*) in which CCS finds itself currently.

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[1] Although in this research the optimistic assumptions of the IEA regarding technology development are followed, this research does not ignore the fact that CCS technology is not mature yet and that technological development will play a major role in the performance of CCS installations.

[2] When innovation would be taking place in smaller steps (i.e. incrementally),a larger degree of supplier concentration would stimulate innovation (Belleflamme and Vergari, 2011).

[3] Because of the optimistic technological view we have assumed in this research.

[4]In some cases a firm will not even "commercialise the patent but use it to prevent that a competitor can patent and use it." (Kleinknecht et al. 2002).

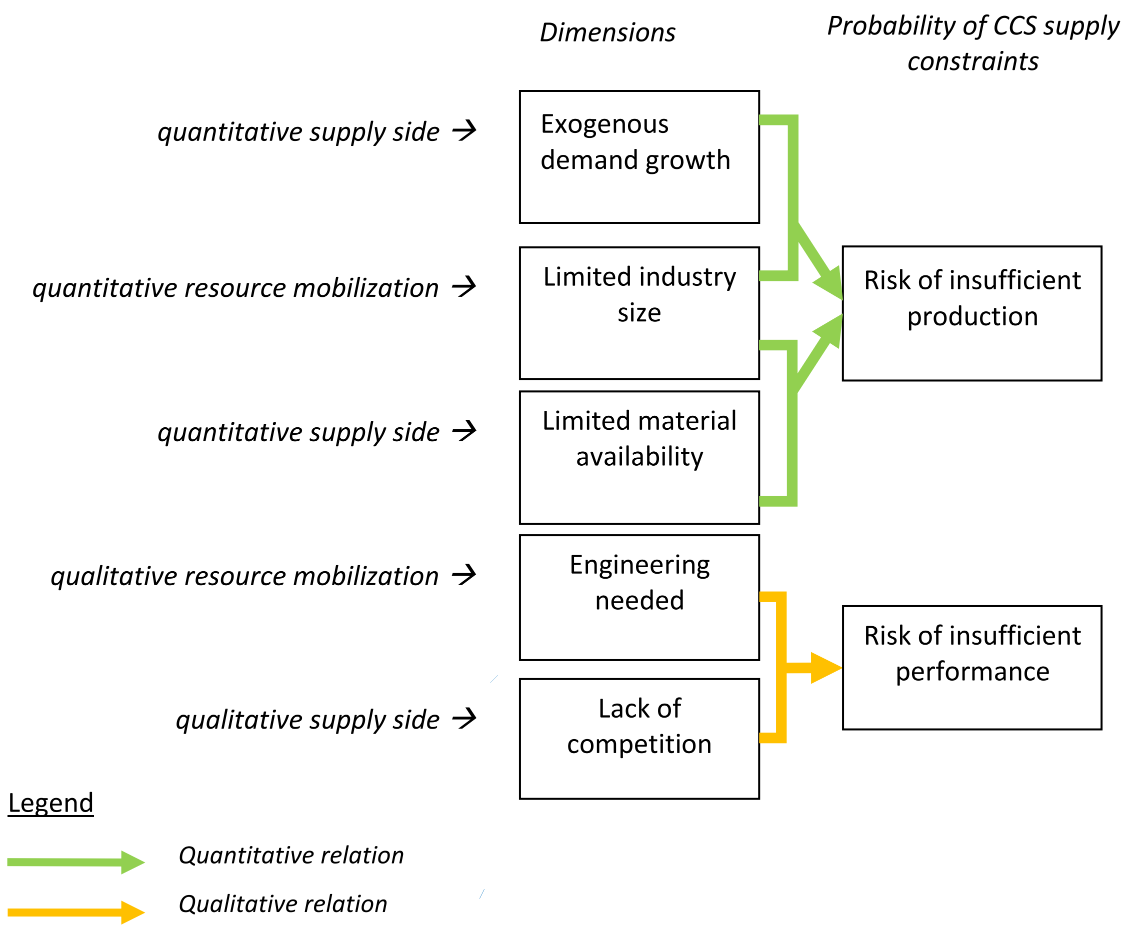

Figure 2-4 Proposed framework for components and services: the presence of a combination of dimensions results in supply constraint risks.

2.2.3 Risk of insufficient availability of human resources

The availability of personnel depends, next to the obvious HR supply size and growth[1] and exogenous demand (both similar to the dimensions developed for physical resources), also on education. If education takes a long time, this influences the rate with which HR supply can grow. Therefore are

[1] While for components and services industry growth is not included in the first indicator, it is for human resources. This is because industry growth is (even more so than industry size) sensitive information that is not freely available. For human resources this kind of information is freely available on medium term, e.g. US Bureau of Labor Statistics (2010).

three dimensions of insufficient availability of personnel: *HR supply size and growth*, *exogenous demand* and *education*. It should be noted that if the necessity of a HR supply increase is absent, a difficulty to increase HR supply size (i.e. a problematic exogenous demand or education) does not pose a supply constraint risk. Similarly, if there is a necessity to increase HR supply size, but there is no difficulty to do this, this does not pose a supply constraint risk.

Resource mobilization: HR supply size

The extent of the needed growth differs per location. The importance of spatial differences with respect to the availability of skilled personnel has been recognized by Freeman in his analysis of national innovation systems: "Nowhere could industry develop and use the new technologies without a national system of innovation to provide supporting services and skilled people even when technology was mainly imported." (Freeman, 1992, p.178).

Supply side: exogenous demand

Similar to the dimension for physical resources, exogenous demand growth of the same human resources will determine the availability of these human resources. Van Alphen et al. (2010, p.405) have for example found that the "concern" about "increasing scarcity of skilled (technical) personnel […] is compounded by reports that petroleum-engineering departments are already operating up or above capacity and that there is competition for qualified personnel within the energy industry".

Supply side: education

A long education time will make it difficult to rapidly increase the availability of personnel. If expert demand increases, the expert supply cannot readily provide the needed people. Even if the needed number of people would directly enroll for the needed disciplines in university (which is unlikely) at the moment the demand has increased, there would be a significant time lag due to the education time. Next to education at universities or schools, to develop a installation experienced personnel is often needed. This personnel needs to have gathered sufficient experience at another site. However education on the job is generally less capable of providing large numbers of personnel. The HR supply education on the job can provide depends on the availability of the kind of jobs that can provide this experience.

2.2.4 Risk of insufficient performance of human resources

In their study of the Swedish security industry, Oltlander and Perez (2005) have found that there has been a radar and sonar personnel shortage because there have been no university education programs for these fields. This illustrates the difficulties that can arise if the needed expertise differs from current expertise. Therefore the dimension of insufficient performance of personnel is *novelty*.

Resource mobilization: novelty

If the assembly of the different physical resources and the operation of the plant is a process that differs significantly from any current practice, educational programs and retraining will take more time and pose more difficulties than if it is relatively similar to current practice. The need for a specific type of engineer that does not as yet graduate from universities might form supply restrictions for firms in an industry (Carlsson and Jacobsson, 1995). In this case it is likely that it will be difficult to quickly dispose of an adequately performing staff for the assembly and the operations of installations. As this problem might be resolved by the introduction of education problems as referred to by Van Alphen et al. (2010), the time needed 'on the job' to become experienced might equally be important here.

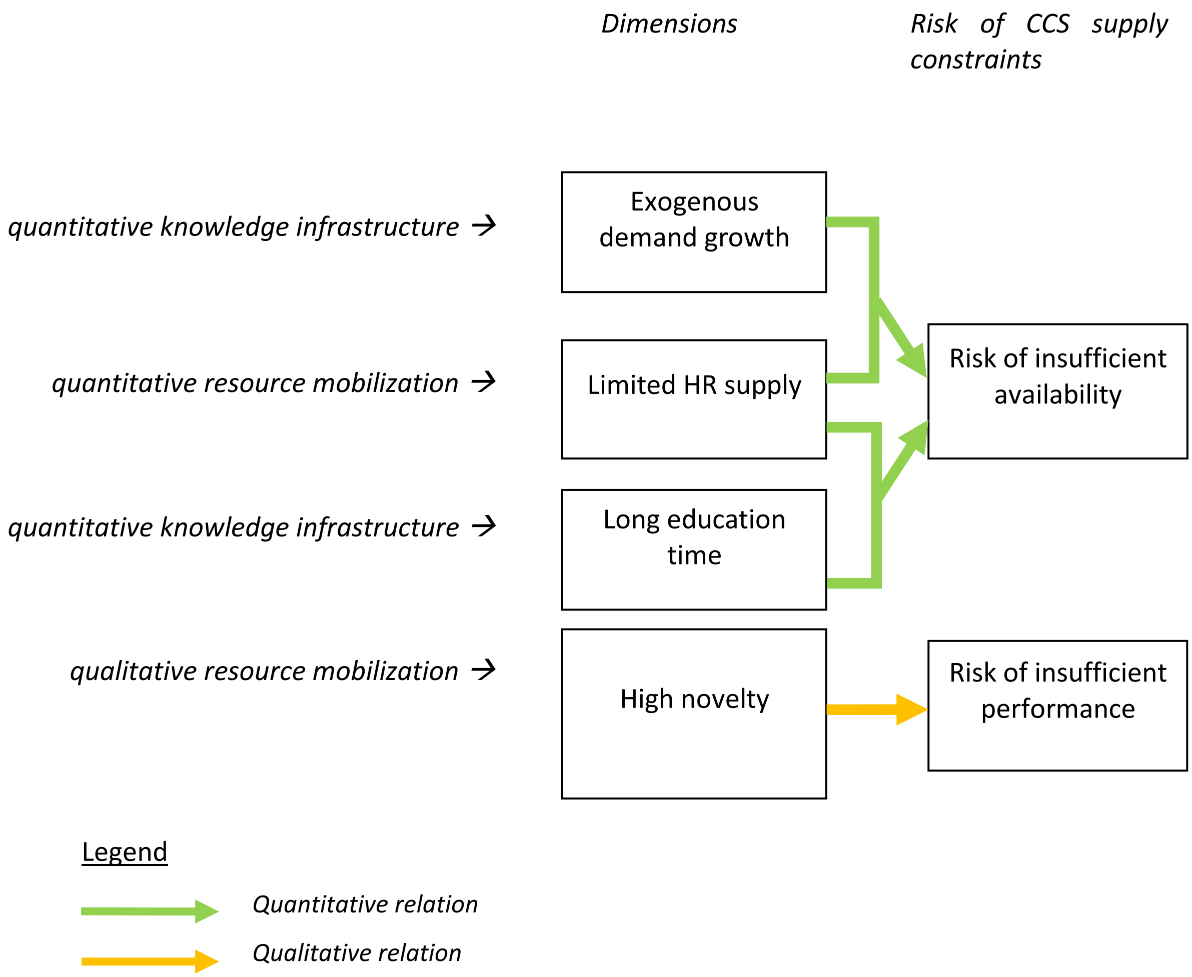

Figure 2-5 Proposed framework for human resources: the presence of a combination of dimensions results in supply constraint risks.

3. Carbon capture and storage technology

Carbon capture consists of the separation of CO_2 and other gases. There are currently three main capture technologies; post-, pre- and oxyfuel combustion. The difference between the three capture technologies lies in the point of the energy generation or industrial process where the capture takes place. The main industrial CCS applications are natural gas reforming, refinery operations, the production of cement, chemicals (e.g. ammonia) and iron/steel production (IEA, 2009). Natural gas reforming, refinery operations, the production of and ammonia produce a concentrated CO_2 stream (currently often vented into the open air) that renders additional capture installations redundant to a large degree. During many of these processes CO_2 is extracted to purify other gas streams, so capture is actually already incorporated in often a technologically simpler way (Dooley et al. 2009). The four CCS installations that are currently operating on a commercial scale are of this kind (one coal gasification plant and three natural gas treatment plants; Dooley et al. 2009). In this chapter the principle of the three capture technologies is described, as is the further process of compression, transport and storage, based on the description of Meerman et al. (2010).

Post-combustion capture separates CO_2 from the rest of the flue gas (mainly water vapor and nitrogen) of an energy generation or industrial process. After advanced flue gas cleaning has eliminated inter alia NO_x and SO_2 and the flue gas is cooled, the CO_2 is eliminated by a solvent, a sorbent or a membrane in an absorber tower. This part of the process is called scrubbing. Subsequently the CO_2 is separated from the solvent, sorbent or membrane in a so-called 'stripper'. The solvent / sorbent can then be re-used. Post-combustion is regarded as the most mature technology that can be used to capture CO_2[1]. Of the three capture technologies, it has been demonstrated nearest to commercial scale (see *Figure H-1*).

Pre-combustion is based on H_2 production. While for post-combustion the actual fuel combustion process does not have to be altered, pre-combustion requires that the fuel is first used to generate H_2. This requires almost pure oxygen, which is produced by an air separation unit. This oxygen is used to reform (gasify) the fuel into 'syngas' (H_2 + CO + CO_2) in a gasifier. Subsequently, by adding steam (H_2O) to this so-called syngas the carbon-mono-oxide (CO) is transformed to H_2 and CO_2 (water gas shift). A membrane, solvent or sorbent in the water gas shift reactor permits the separation between the H_2 gas and the CO_2. The pure CO_2 stream is then ready for compression. The separation and compression take less energy than with post-combustion (Metz et al. 2005). The H_2 gas can subsequently be combusted in a H_2 turbine. Pre-combustion has been proven in industrial applications (such as H_2 production for the production of ammonia and for petroleum refining). For energy production an integrated gasification combined cycle power plant has been designed, but not yet commercially proven (Koornneef, 2010). Pre-combustion is still in the pilot phase, although several commercial scale projects have been announced (e.g. BP, 2011).

For oxyfuel combustion an air separation unit produces almost pure oxygen. This oxygen is directly led into the boiler where it is used to combust the fuel (oxyfuel is a contraction of the words 'oxygen' and 'fuel'). This reaction leads to a flue gas that consists of almost exclusively CO_2 and water vapor. After removal of impurities and water the CO_2 is ready for compression. Alternatively, the water can be

[1] The UK government has for example decided to limit its 2010 funding competition to post-combustion bids (Lund et al. 2010).

removed during compression. Oxyfuel combustion has been proven at a 30MW pilot plant scale (Kluger et al. 2010).

Compression is needed after all three capture technologies, because the CO_2 has to be transported (at about and stored. This compression is performed by large compressors, often installed in series called stages (Holcomb et al 2007; Griffiths, 2009; Siemens, 2009). Compression is a mature technology for natural gas. Compression is slightly less of an issue after pre-combustion than after post- or oxyfuel combustion because it produces CO_2 under pressure (Koornneef, 2010). Pipeline transport is the mode of transport studied in this report as it is the currently the predominant mode of transport (IEA, 2009) and the most cost-effective one for distances under 1000 km (Metz et al. 2005). Pipeline transport requires in general a pressure between 80 and 150 bar (Aspelund and Jordal, 2007). Offshore pipelines require an elevated pressure of up to 200 bar or just over (interview Neele). CO_2 can be stored in saline aquifers and depleted gas fields. CO_3 can in general be injected at the same pressure as transport.

3.1.1 CCS system functions as described by Van Alphen et al. (2010)

Van Alphen et al. (2010) have analyzed the CCS innovation system by mapping the seven system functions described above. The research maps to which extent the seven functions of the CCS innovation system are fulfilled in the Netherlands, Canada, Australia, Norway and the US. The averages for each function are depicted in Figure 3-1. This is done by interviewing "the main actors" (p.397) in the innovation system, and scoring the results on a Likert scale of 1 (very weak) to 5 (very good).

1. While a "rapidly increasing amount of (industrial) organizations [are] involved" (p.398), *entrepreneurial activity* is not regarded as well fulfilled (2.9 of 5) because especially on the capture side a lot of work remains to be done.
2. The function *knowledge development* has been well fulfilled (3.9 of 5), as the actors interviewed "are satisfied with the knowledge base that has been accumulated over the past decade" (p.399).
3. Because there are strong international CCS consortia and an increasing number of conferences, the function *knowledge diffusion* is regarded as being pretty good fulfilled (3.7 of 5).
4. The function *guidance of the search* is "sufficiently" fulfilled (3 of 5). Scientific research organizations perceive clear signals about the knowledge voids that need to be filled, and policy makers formulate the direction of CCS innovation in roadmaps.
5. Simultaneously, the lack of regulative clarity with respect to storage possibilities and liabilities is hampering innovation here. While there are niche markets for CCS technologies (Enhanced Oil Recovery in the US, and Norway where CO_2 is captured from natural gas processing because of a carbon tax), "it is unlikely that utilities will adopt CCS on a large scale until sound climate policies make CO_2 financially worth capturing and storing" (p.403). *Market formation* is consequently rated lowest of all scores: 2.2. of 5.
6. As for *resource mobilization*, financial resources are regarded to be insufficient for commercial-scale CCS deployment. As for human resources, there is an "increasing scarcity of skilled (technical) personnel in CCS" (p.405). This results in a score of 2.8 of 5.

7. With respect to *the creation of legitimacy*, two observations are relevant. On one side, in all countries industrial lobby groups are influential when political decisions regarding CCS are being taken. On the other side, there are 'not-in-my-backyard' arguments of local communities and environmental action groups that fear that CCS deployment will extend the legitimacy of fossil based energy production and will at the same time limit the development of renewable energy production.

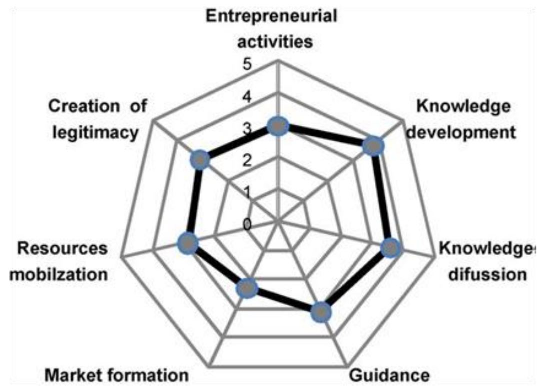

Figure 3-1 Spider diagram depicting CCS function fulfillment (5 = very good, 1 is very weak, Van Alphen et al. 2010).

Van Alphen et al. (2010) have mainly mapped resource mobilization regarding the availability of financial resources[1] while these are not the only resources that are likely to form a constraint to large scale deployment. In Van Alphen et al. (2010), there is also a paragraph briefly discussing the need for skilled personnel, but this takes up less than 10% of the results section about resource mobilization in the article, while it does seem to be a serious constraint.

[1] As is common practice while mapping innovation systems' functions (e.g. Bergek and Jacobsson, 2003).

4. Method

To answer the sub questions and finally the main research question of this case study, the following course of action has been taken. Subsequently this framework has been operationalized (indicators are developed to the dimensions), applied to the historical cases of flue gas desulfurization and combined cycle gas turbines. Finally it is applied to the case of CCS to obtain an idea of the most important supply constraint risks.

4.1 Operationalization

In *Chapter 2* a number of dimensions is identified that can lead to supply constraint risks for physical resources and a number dimensions is identified that can lead to supply constraint risks for human resources. In this chapter, indicators are introduced that are used to assess whether these dimensions are problematic for a given resource. For each dimension a (number of) indicator(s) is developed. These indicators often depend on the needed quantity of a resource for certain deployment of the technology. For the case of CCS, the unit of deployment used is (like the IEA scenario), Mt CO_2 captured / stored ($MtCO_2$/yr CS). Furthermore, in this chapter it is specified how the outcomes of the indicators are interpreted in terms of a dimension being problematic. For the operationalization of the dimensions of insufficient production of physical resources and insufficient availability of human resources predominantly quantitative indicators have been developed. With respect to the dimensions of insufficient performance of physical and human resources the indicators are qualitative.

4.1.1 Risk of insufficient production of physical resources

Risk of insufficient production of physical resources is formed by the dimensions *industry size*, *exogenous demand* and *material availability*, as described in the previous chapter. The indicators and classification can be found in *Table 1* and are described below per dimension.

Industry size

The *amount of a physical resource needed per $MtCO_2$/yr CS* installed must be identified. The *current production capacity* depends on how widely the physical resource is currently used. This can be measured by identification of the main sector(s) in which the physical resource are used, and the amount of the physical resource that is currently used in these sector(s). Together with the outcome of the first indicator it leads to the needed *industry size* growth to accommodate CCS demand as described by *Equation 1* and *2*.

Equation 1

$$needed\ production\ capacity\ per\ \frac{MtCCS}{yr} \times targeted\ amount^1\ of\ \frac{CO_2}{yr} = needed\ production\ capacity$$

Equation 2

$$\frac{current\ production\ capacity}{needed\ production\ capacity^1} = needed\ industry\ size\ growth$$

[1] This is by 2035, because by then the increase in production capacity is negligible. The speed of deployment is constant after 2035 (see *Figure 1-1*).

If this results in a growth of less than 1% annually, the industry size is not problematic. If it results in a growth of 1-5% annually, industry size is problematic. A growth above 5% makes the industry size very problematic (Ecofys estimate[1]), especially because such a growth should be maintained over a long period of time[2] to meet the IEA scenario goals[3].

Exogenous demand

As described in the *Theory* chapter, exogenous demand is taken into account as a dimension when it is expected to increase. Exogenous demand growth can be measured by the forecasted growth of the demand of the other main sector(s) (as they have been identified for the assessment of the industry size dimension) using the physical resource. The classification of the exogenous demand growth is logically the same as that of the industry size. A growth of less than 1% annually (including negative growth[4]) implies that exogenous demand is 'not problematic', a growth of 1-5% annually implies that exogenous demand is 'problematic' and a growth of more than 5% annually makes exogenous demand 'very problematic'.[5] As exogenous demand is created by a financially very strong sector, a growing exogenous demand will become more problematic because in the competition for the resource the financially very strong sector is likely to win and leave very little for the technology under study. If this is the case 'not problematic' becomes 'problematic' and 'problematic' becomes 'very problematic'.

Material availability

This dimension could be assessed quantitatively by comparing the amount of scarce material needed to the current and forecasted availability of these materials. Due to time constraints it has been chosen to only assess *if* scarce materials are needed for a resource. If there are no scarce materials needed, material availability is 'not problematic'. If there are scarce materials needed, material availability is 'problematic' but if very scarce materials are needed, this makes material availability 'very problematic'.

[1] This has been checked by multiple Ecofys experts for reliability.

[2] This does not imply that production capacity increase to meet Roadmap goals is constant over the decennia.

[3] It often difficult to measure the first indicator *needed amount per* $MtCO_2$ */yr CS installed* because of continuing technical uncertainty. It is difficult to measure the second indicator *current capacity* because industrial data (including an industry size) is often exclusively available on a commercial basis. An alternative to the explicit measurement of both indicators is to use an expert judgment of the needed capacity growth. This is done for most of the components.

[4] Exogenous demand growth can also be negative, if the main buying sector is expected to decrease their demand over the next forty years.

[5] These sector growth forecasts are likely to be unavailable for the majority of components. In those cases expert estimations are being used.

Table 1 Operationalization of the dimensions of sufficient production of physical resources. An interpretation is given to the outcomes, by assigning 'A' when the dimension is not problematic, 'B' when the dimension is problematic or 'C' when the dimension is very problematic.

Dimension	Indicator	Scale		Classification	
Industry size	Needed amount per $MtCO_2$/yr CS installed	Annual capacity	results in	needed annual growth <1%	A
				1% < needed annual growth < 5%	B
	Current capacity	Annual capacity		5%< needed annual growth	C
Exogenous demand	Prospective exogenous demand growth from main sector(s) in which this physical resource is applied	Total prospective exogenous market growth (%)		annual growth <0%*	A
				1%< annual growth <5 %*	B
				5%< annual growth*	C
Material availability	Need for scarce materials	Qualitative		no scarce materials	A
				scarce materials	B
				very scarce materials	C

* If the exogenous demand creating sector is financially very strong, 'not problematic' becomes 'problematic' and 'problematic' becomes 'very problematic'.

4.1.2 Risk of insufficient performance of physical resources

The risk of insufficient performance of physical resources depends, as described in the previous chapter on the dimensions *engineering* and *competition*. The indicators and classification to assess these two dimensions is described below and can be found in *Table 2*.

Engineering

The degree of engineering needed is measured by the extent to which the technology needs to be adapted to be applied in the new setting. The indicator is the phase of the maturity of the technology with respect to the application in the new setting. If the physical resource performs such that it can be used in this form to meet IEA goals of CCS, it is regarded as mature and consequently engineering is 'not problematic'. A physical resource that is in the demonstration phase results in engineering being qualified as 'problematic'. Technology that, for the new technology, has only been applied in R&D, can be seen as very immature with respect to CCS application. In this case engineering is 'very problematic'.

Competition

Bauer (1963, p.90) has elaborated on the criteria and characteristics of industry concentration:

"The essence of monopoly is the absence of alternatives or a severe restriction on their number. Monopoly is present where those dealing either as buyers or (as sellers) with a firm or a concerted group of firms cannot obtain the same commodity or service from other independent sources (or where such sources are quantitatively unimportant) and where there are no close substitutes for the commodity or service [and] when there is a distinct gap in the chain of substitutes or the range of alternatives […] An important and distinctive characteristic of oligopoly is the realization by each firm that its fortunes depend very closely upon the actions of the others in the same market."

The average market share of today's major oligopolies in the US is 75% (Hannaford, 2007). In practice, domination is often understood as the oligopoly having 50-75% of the whole market. There is no consensus about a definition of a specific market share dominated by a specific number of firms that determines a strict line between 'oligopoly' and 'competitive market'. The recurring definition is that oligopoly firms must have complete information and they must choose their prices simultaneously (Bardsley, 2010; Bauer, 1963). Due to time constraints, this definition of implies that the competitiveness of an industry will be assessed qualitatively.

Patent dependence is not necessarily a function of the number of patents on a physical resource, but on the importance of the possession of patents to produce a physical resource. According to Smith (2005, p.160), "[m]any patents refer to inventions that are intrinsically of little technological or economic innovation". Some patents may not be very critical because they address only one of the many possible ways of producing a physical resource. Other patents might entail a production process that is far superior to other production processes for this physical resource. Therefore patent dependence is assessed qualitatively. The classification consists of the indication 'industry not competitive' in case only one supplier dominates the market and/or there is a high patent dependence, 'moderately competitive industry' in case few suppliers dominate the market and/or moderate patent dependence is in place and 'competitive market' otherwise.

Table 2 *Operationalization of the dimensions of insufficient performance of physical resources. An interpretation is given to the outcomes, by assigning 'A' when the dimension is not problematic, 'B' when the dimension is problematic or 'C' when the dimension is very problematic.*

Dimension	Indicator	Scale		Classification	
Engineering	Maturity of the technology	Qualitative		commercially proven	A
				demonstration phase	B
				R&D phase	C
Competition	Industry concentration	Qualitative	results in	competitive industry	A
				moderately competitive industry	B
	Patent dependence	Qualitative		industry not competitive	C

4.1.3 Risk of insufficient availability of human resources

The risk of insufficient availability of human resources depends, as described in the previous chapter, on the dimensions, *HR supply size and growth*, *exogenous demand* and *education*. The indicators and classification of these dimensions is described below and can be found in *Table 3*.

.

HR supply size

In order to be able to derive the needed growth of the availability of a class of human resources, first the *numbers of such personnel needed for each MtCO$_2$/yr CS* are identified. The current availability of this class of personnel can be measured by the number of, for example, chemical engineers annually graduating from technical universities and schools. The current availability of, for example, chemical engineers (on the job training) can be measured by the number of projects executed times the average amount of chemical engineers on a project. Whereas for physical resources the current production capacity is calculated by the current demand of the other main sectors using this physical resource, for human resources the *number of personnel annually graduating* (or obtaining enough experience to do the job) can directly be used. The needed *HR supply size* growth is obtained *Equations 3* and *4* below.

Equation 3

$$numbers\ of\ such\ personnel\ needed\ per\ \frac{MtCCS}{yr} \times targeted\ amount^{1}\ of\ \frac{CO_2}{yr} = number\ of\ these\ employees\ needed$$

Equation 4

$$\frac{number\ of\ personnel\ annually\ graduating}{number\ of\ these\ employees\ needed} = needed\ HR\ supply\ size\ growth$$

The classification is similar to that of the needed growth of physical resources.

Exogenous demand

Exogenous demand growth for human resources can be measured in a similar way as exogenous demand for physical resources. Therefore, firstly the main sector(s) in which similar human resources are required must be identified. Secondly, the demand forecast of these sector(s) is needed. The classification is similar to that for exogenous demand for physical resources.

Education

Education time is measured from high school onwards, and includes education at universities and schools but also on site experience. For managerial engineers for example, who can fulfill the function of project developer, a university education will not suffice as a preparation. On site experience at a CCS installation will be needed before they can fulfill the function of project developer.

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[1] This is by 2035, because by then the increase in production capacity is negligible. The speed of deployment is constant after 2035 (see *Figure 1-1*).

Table 3 *Operationalization of the dimensions of insufficient supply of human resources. An interpretation is given to the outcomes, by assigning 'A' when the dimension is not problematic, 'B' when the dimension is problematic or 'C' when the dimension is very problematic.*

Dimension	Indicator	Scale		Classification	
HR supply size	Number of these employees per $MtCO_2$/yr CS annually installed according to the scenario	Number	results in	< 1% annual growth	A
	Number annually graduating / obtaining enough experience to do the job	Number		1%< <5% annual growth	B
				5%< annual growth	C
Exogenous demand	Prospective demand growth from main sector(s) in which this human resource is needed	Annual growth (%)		< 1% annual growth	A
				1%< <5% annual growth	B
				5%< annual growth	C
Education	Time to educate people, measured from high school onwards	In years		less than or equal to 3 years	A
				between 3 and 5 years	B
				more than 5 years	C

4.1.4 Risk of insufficient performance human resources

The risk of insufficient performance of personnel is, as described in the previous chapter, dependent on the dimension *novelty*. The indicator and classification of this dimension is described below and can be found in *Table 4*.

Novelty

The novelty of technology can be measured by the degree an employee needs to obtain CCS specific training. If there is a great resemblance to other industries, it will be possible to work on CCS without much CCS specific training. When there is only some, or virtually no resemblance, CCS specific training will be needed to an (extended) degree.

Table 4 *Operationalization of the dimension of insufficient performance of personnel. An interpretation is given to the outcomes, by assigning 'A' when the dimension is not problematic, 'B' when the dimension is problematic or 'C' when the dimension is very problematic.*

Dimension	Indicator	Scale	Classification	
Novelty	Difference to most similar industries	Qualitative	great resemblance	A
			some resemblance	B
			virtually no resemblance	C

Combinations of problematic dimensions lead to supply constraint risks

The supply constraint risk of insufficient production and the supply constraint of insufficient performance can be constructed as a function of the outcomes (*not problematic*, *problematic* or *very problematic*) for each dimension. Graphically, the dimensions form the axes of a spider diagram, such as in *Figure 4-1*. Filling the outcomes on the axes spans a surface on the spider diagram, such as in *Figure 6-1*. This way, the visibility of the fields named *high risk* or *risk* determines the risk level of either insufficient production (upper fields in the spider diagram) or insufficient performance (lower fields in the spider diagram). If a field named *risk* at the lower part of the spider diagram is still entirely visible (as is the case in *Figure 6-3*), this is because both the dimensions competition and engineering are at the least problematic (i.e. B or C). As explained in the previous chapter (see *Section 2.2.2*), this results in a supply constraint risk. If a field named *risk* at the upper part of the spider diagram is still entirely visible (as is the case in *Figure 6-1*), this is because *industry size* and *exogenous demand* and/or *material availability* are at the least problematic. As explained in the previous chapter (see *Section 2.2.1*), this results in a supply constraint risk. If a field named *high risk* is visible, both the adjacent dimensions should be very problematic.

It should be noted that the axes are deliberately chosen in this configuration. To start with the upper part of the spider graph, the dimension *industry size* is placed in the middle because it is key to the risk of insufficient production. If this dimension is problematic in combination with any of the two other dimensions of insufficient production being problematic, it results in a supply constraint risk. A problematic *exogenous demand* in combination with a problematic *material availability* does not lead to a supply constraint risk if industry size is sufficient, as is explained in the previous chapter (*Section 2.2.1*).

Legend

A not problematic
B problematic
C very problematic

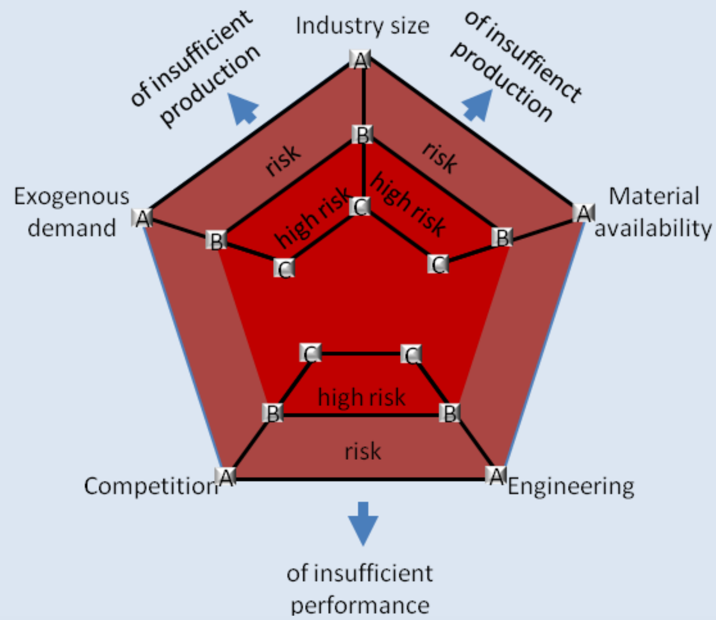


Figure 4-1 The supply constraint risk of insufficient production capacity and insufficient performance can be constructed with the values of the dimensions.

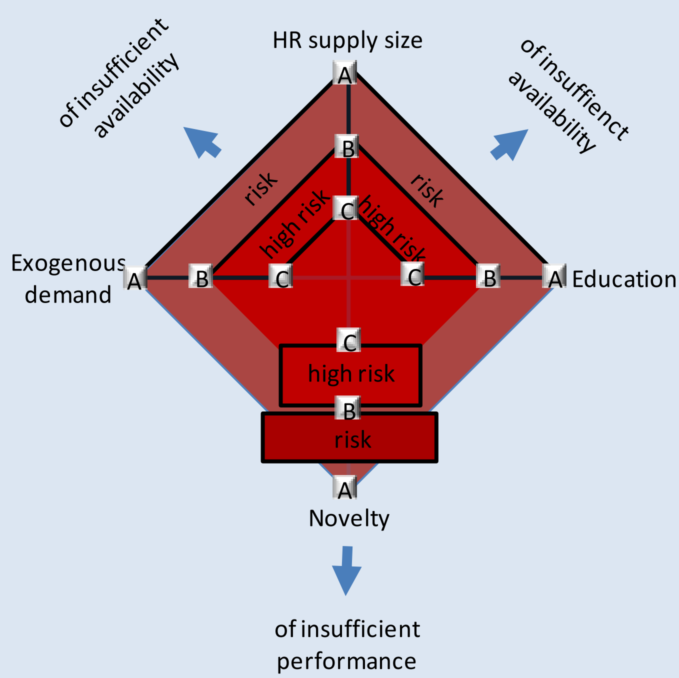


Figure 4-1 Spider diagram. The human resource supply constraint risks of production capacity and equipment performance can be constructed with the values of the dimensions.

4.2 Data collection

Different sources of data are used to be able to assess if a dimension is 'not problematic', 'problematic' or 'very problematic' for a specific resource. The indicators are assessed for the historical cases to obtain their supply constraint risk. For a complete historical comparison, deployment and deployment rate data are also gathered. Subsequently, data has to be collected to make an initial selection of physical and human resources that might cause supply constraints. Finally, the indicators are assessed for the physical and human resources to obtain their supply constraint risk.

4.2.1 Historical cases (sub question 1)

Flue gas desulfurization systems and combined cycle gas turbines are regarded on an aggregate level. The introduction of these technologies has been accompanied by two innovation systems that have been built up and the mobilization of many resources. However, due to time constraints an aggregate level approach (no distinction between the different resources) is chosen with a distinction between countries. Precise data on the speed of the deployment will be derived from the Platts (2006) World Electric Power Plant database in combination with scientific articles that have assessed the introduction of these technologies (such as Graus and Worrel, 2007; Watson, 1997).

4.2.2 Selection of critical physical and human resources (sub question 2)

For the physical resources this is done by literature study and expert judgment. The literature study will consist of the assessment studies performed by the industry, utilities (such as Dynamis, 2008) and international institutions (such as the IEA) and scientific literature on the functioning of the three CCS technologies. The expert judgment will be obtained by interviews with experts in the industry and utility firms that are involved in CCS projects. The resources that are needed for the construction and operation of CCS installations are selected on the basis of an estimation of the dimensions being problematic or not. For human resources, the primary source of information is expert interviews, as there has been written little about which human resources are essential to install CCS.

4.2.3 Supply constraint risk dimensions CCS resources (sub question 3)

Information about the dimensions is searched in grey (such as trade association reports) and scientific papers on the functioning of the CCS technologies. Subsequently, this data is used to formulate semi-structured interviews with both industry/power sector experts and trade experts affiliated to consultancy agencies and governments to have as many different sources and actors included, for validation of data. Furthermore distance does matter in some cases, as regional innovation system literature has stressed (Suurs, 2009). Van Alphen et al. (2010) have assessed the fulfillment of the system functions of the CCS TIS while stressing national differences for the system function knowledge development. Within the current research it is similarly useful to stress regional differences for some resources. Large physical resources will be dependent on different industry structures in different regions of the world. In choosing the regions IEA (2009) has been followed: *1. OECD countries*, *2. China and India* and *3. other non-OECD countries*[1].

4.2.4 Interviews

Summarizing, the semi-structured interviews are set up to find the critical physical and human resources that might cause supply constraints, and assess the indicators for these resources.

4.3 Data analysis

The historical cases provide an independent source for comparison of a fast deployment acceleration and a high rate in case of the absence or presence of supply constraints. If the deployment of CCS installations as described in the IEA scenario is similar to historically known rapid deployments, this proves that it is in theory possible to deploy a technology this fast. After data collection an assessment of the dimensions is obtained. How this exactly leads to supply constraint risk statements as described in *Chapter 4.1*. The results are linked to the findings of Van Alphen et al. (2010) to the resource mobilization function of the CCS innovation system. An analysis is given of the success of this approach and what its policy implications are.

[1] OECD NA = USA, Canada, Mexico; OECD Europe = Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, UK; OECD Pacific = Australia, Japan, New Zealand, South Korea; Non-OECD = the rest of the world. China and India are taken as one world region, i.e. the industry sizes and growths are added.

5. Historical deployment cases

To put the IEA scenario implementation of CCS in a context, it is compared to the deployment of flue gas desulfurization systems (FGDs) and combined cycle gas turbines (CCGTs) by an analysis of the dimensions that have played a role at the time of the take-off of FGDs and CCGTs. As introduced in *Section* Historical cases (sub question 1)*4.2.1*, the dimensions and supply constraints are regarded on an aggregate level for this historical comparison, i.e. not split up in components and human resources. The governmental push-factors are included in the discussion of the deployment speed.

5.1 Flue gas desulfurization

Sulfur dioxide is seen as dangerous for human health in large concentrations and as dangerous for the environment, predominantly through acidification of surface water and precipitation. SO_2 emissions can be reduced in three ways; similarly to CO_2 capture pre- and post-combustion are options. Because SO_2 is not inherent to fossil fuel combustion, it can alternatively be reduced by changing the combustion to alternatives such as using fluidized bed combustion or changing the combustion fuel (e.g. to synthetic fuels). In this comparison the focus is on post-combustion flue gas desulfurization (scrubbers), because most research has focused on it and consequently suitable data is available. This in turn is because no pre-combustion technology "removes as much SO_2 as post-combustion control technologies" (Taylor, 2001). Of the post-combustion technologies, the "so-called 'wet' FGD systems employing limestone or lime as chemical reagent" are used in more than 86% of the worldwide installed scrubbers (Rubin et al. 2004). These are similar to full scale chemical plants (CAPEX of about 100 million dollars in the early 1980s, see *Figure C-3*, and at that time using 3 to 6% of the energy generated by the power plant; Taylor, 2001), and therefore comparable to CO_2 capture installations. Furthermore FGD systems can be retrofitted to existing power plants, similarly to CO_2 capture retrofit.

5.1.1 Risk of insufficient production

Industry size was significant at take-off (high acceleration around 1976, see *Figure 5-1.a*). Ten firms stated they could deliver scrubbers (a main component of a FGD unit) in 1973 (Taylor, 2001). Industry size can however be considered to have been limited until the 1990s for other components, as concerns about the capacity of suppliers of components such as "slurry pumps, centrifuges and vacuum filters" but equally for "large" compressors and gas flow modeling have been expressed in 1991 (Smock, 1991).

Exogenous demand. We have no indication that exogenous demand has been increasing for FGD systems. Instead of exogenous demand forming a problematic dimension of insufficient production, rather the inverse, a decrease of demand of the primary customers seems to have been case. Taylor notes that "[t]he volatility of the FGD equipment and services industry (…)ultimately caused Riley, American Air Filter, and Combustion Equipment Associates to drop out of the business" (p.41, referencing McIlvaine, 1990).

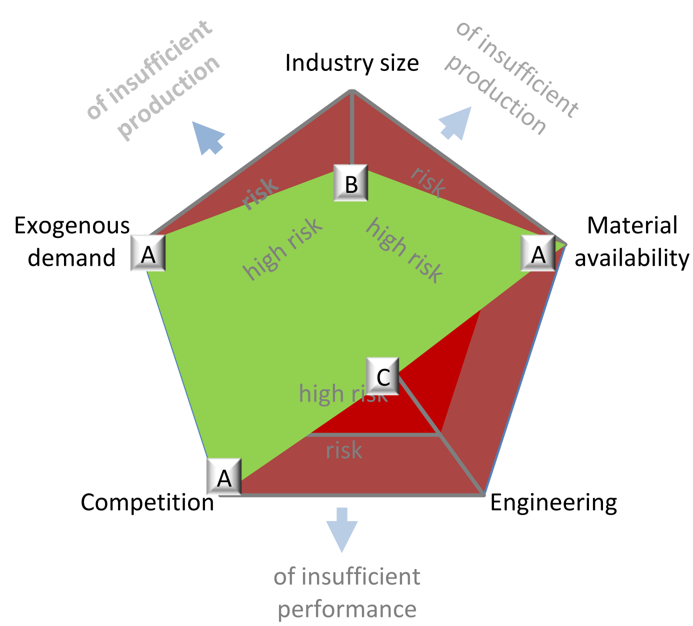
Material availability. Due to corrosion issues, large quantities of exotic alloys are needed (Smock, 1991). However in practice alloys are based on Fe, Ni, Cr and Mo (Agarwal, 1996). Material availability has consequently not been an issue.

5.1.2 Risk of insufficient performance

Engineering has been a very problematic dimension. The first application of a FGD system on a boiler of over 100 MW has been as late as 1968 (Taylor, 2001, p.30). During the first two decades of the large scale deployment of FGD systems (1975-1995), the price of FGD systems has decreased by half (see *Figure C-3*). Although the average FGD system has a lower removal grade in the early decades, reliability was a much bigger issue. I.a. the underestimation of corrosion issues resulted in reliability problems. Also design changes were needed (Taylor, 2001, p.30). "Maintenance costs and just keeping these FGDs became an operational nightmare." (Agarwal, p.447/2). In search for a basic understanding and answers to the problems being experienced, utilities turned to their vendors (alloys and non-metallic suppliers), architect/engineering firms, fabricators, corrosion institutions, such as Battelle, EPRI, and universities, and to whatever other source of information, which was available to them." (Agarwal, 1996, p.447/2). Better performing alloys were found during the late 1970s and 1980s. Next to the widespread corrosion problems, equally fitting ("pluggage") of different components and mechanical problems were an issue of concern (Taylor, 2001, table 2.5, p.43).

Competition. A large number of smaller firms and departments of larger firms were involved in US FGD competition during the development phase in the 1970s. The smaller firms were in general bought by larger firms during the following years, as the FGD market was thought to become a very profitable one (Taylor, 2001, p.40). This resulted in the top five FGD suppliers making up for almost 73% of the FGD market in the 1980s in the US. As this is as after the development phase, this industry concentration should not be regarded as a problematic dimension of insufficient performance (see *Chapter 2.2.2*). During the years 1974-1993 several competing FGD technologies were developed (see Taylor, 2001, Table 3.14, p.135).

5.1.3 Graphical representation of FGD supply constraint risks



Legend

A not problematic
B problematic
C very problematic

Figure 5-1 FGD: risk of insufficient production

5.1.4 Deployment of FGD

The deployment in the US, Germany and Japan, the three main deployment countries of FGD units (FGD deployment until 1999; Rubin, 2004) are depicted in *Figure 5-3*. Total deployment in the US between 1970 and 1999 was 82GWe, in Germany 47GWe and in Japan 17GWe. Maximum deployment rate of the US was 6GWe/yr, of Germany 14GWe/yr and for Japan 1GWe/yr. Worldwide FGD deployment for the period 1972-1999 has been 189GWe, with a maximum deployment rate of 18GWe/yr (*Figure 5-5.a*). It shows not more than an approximately five-year period of acceleration (see *Figure 5-3.a*, *b* and *c*). After this period the US and Japan have known a relatively stable rate of deployment (constant slope US 1976-1986 and Japan 1980-1999). The US deployment rate was lower between 1986 and 1993, after which retrofit became more important and the slope increased again. While the total power plant construction has decreased between 1975 and 1999 in the US, absolute FGD deployment has not decreased (*Figure C-1.b* and *Figure C-2.b*). In Japan the context was totally different, as the total power plant construction has increased in the 1990s, but the FGD deployment rate has stayed constant (*Figure C-1.d* and *Figure C-2.d*). Germany has known a very high deployment rate by retrofit. It has installed FGD for more than 28GWe of power plant capacity in two year (between 1985 and 1987, *Figure 5-3.b*), which is more than half of its coal fired power plant capacity at that time. After 1987 the country has known a relatively steady deployment although total power plant construction has decreased from 1987 on (*Figure C-2.c*). While worldwide FGD deployment for the period 1970-1999 was 189GWe, there has been built 559Gwe of new coal fired power plants that have never been retrofitted (*Figure C-1.b*). This results in a limited relative deployment of less than 20% (*Figure C-2.b*).

Since the 1960s coal fired power plants have been the primary emitter (Taylor, 2001 for the US, but most likely all around the world, compare “[u]nabated SO_2 emissions are particularly high for coal combustion” (Graus and Worrell, 2007, p.2). SO_2 emissions for natural gas fired power plants are less than 1% percent of coal fired power plants (Veltman et al.2010). SO_2 emissions for oil fired power plants are equally non-negligible, but worldwide oil-fired capacity is limited (IEA, 2010a). Sulfur dioxide was during the 1950s seen as primarily a risk for human health. This has lead to more stringent regulations in for example 1970 US regulation (Taylor, 2001, p.31). In the same regulation (‘National Ambient Air Quality Standards’), a distinction has been made between sources that are yet to be built and existing sources (Taylor, 2001), which are obviously less stringent. This distinction, that has been followed for decades (for example in the acid rain program of 1990; Rubin, 2004) has been the outset for an introduction of the new technology on new power plants, and a later retrofit on existing plants[1]. Regulations became more stringent in the US in 1977. This is reflected in the larger share of new built plants with wet FGD[2] (*Figure C-1.b*). In different parts of the world regulative requirements on sulfur dioxide emissions forced many new and existing power plants to adopt flue gas desulfurization units.

Germany has introduced radical stringent regulation in 1983. As this was almost a decade after the take-off in the US, a rapid acceleration has been possible. Taylor (2001) mentioned explicitly that,

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[1] Only power plants with more than 70 MWt were subject of this first regulation (Taylor, 2001).

[2] Next to mere FGD / CCGT / CCS introduction also the total newly installed power plant capacity is relevant because “this is the market background for new-FGD units” (Taylor, 2001, who has taken a similar approach). See *Appendices C* and *D*.

notwithstanding the rapid decrease after 1983 of the new coal-fired power plants built, the American FGD industry was able to keep production up by supplying one-third of the FGD units deployed in Germany. China has begun to implement FGD systems on a larger scale in the 2000s. Although in 2006 no more than 22% of the thermal power plants that have been installed during that year were equipped with FGD systems, there is a steep rise in FGD installations. In 2006 only 14% of the installed capacity was equipped with a FGD system whereas this was only 2% in 2000[1] (Gao et al. 2009).

5.1.5 Lessons learned and conclusions from FGD deployment

While there have been problematic dimensions of insufficient production and insufficient performance of FGD, take-off has still taken place in a relatively short period of time. In *Chapter 2* it has been argued that individual problematic dimensions can be overcome; that only certain combinations of problematic dimensions lead to supply constraints. The history of FGD consequently strengthens this theory. The FGD figures for the US and Japan suggest that a significant FGD building capacity (short take-off/acceleration phase) has been established early on, which then remained relatively constant (constant slope in *Figure 5-3.a* and *c*) for the rest of the implementation period.

5.2 Combined cycle gas turbines

Combined cycle gas turbine power plants are gas fired power plants that are primarily based on gas turbines. Furthermore, they are equipped with a second power generating mechanism which uses the flue gas heat of the gas turbine in a steam turbine. The technology stems in jet engine technology developed during the Second World War (Watson, 1997).

CCGT power plants combines steam turbine and gas turbine technology, which made it difficult to guarantee high availability figures in the seventies. However, in the mid-seventies they started to show "techno-economic characteristics which were revolutionary in comparison with the steam turbine" (Islas, 1997 p.62). CCS also combines different existing technologies, and as did CCGT, requires further development of some the components. The use of and the learning by doing with the gas turbine has proven necessary before the more complex CCGT would be sufficiently reliable to be commercially applied.

5.2.1 Risk of insufficient production

Industry size has not been a problematic dimension, because both gas turbines and steam turbines were already produced in large amounts at the time of introduction (see *Figure D-2)*. Installation of non-CCGT gas turbines has not risen during the time of the first commercial scale deployment of CCGTs (see *Figure D-1.b*), so *exogenous demand* has not been a problematic dimension. We have no indications that CCGTs are dependent on scarce materials, so there is no indication for *material availability* as a problematic dimension.

[1] These percentages include gas fired capacity, but coal fired capacity is largely dominant in China (97% of the incremental thermal capacity in 2006; IEA, 2006).

5.2.2 Risk of insufficient performance

Engineering has been a problematic dimension, as there have been considerable problems with CCGT reliability (no higher availability than 80% in the early 1970s; Watson, 1997). Technological maturity was limited at first commercial scale introduction, but has improved significantly later.

C*ompetition.* During the development of CCGTs limited experience with power plant gas turbines was available. Only companies who had access to jet engine expertise managed to develop and produce successfully large scale CCGTs. There was competition between four groups of companies (GE, Siemens/Pratt and Whitney, MHI/Westinghouse/Rolls Royce and ABB). The (four) groups of companies with jet engine experience partly licensed their technology to other manufacturers, so that CCGTs could be built all over the world. Apart of licensing, some critical parts of technology were strategically kept in house, so that industry stayed divided in a constant number of four competing groups. Over the years, GE gradually developed a dominance with a market share of 50% during 1999 - 2003 (see *Figure D-3*).

5.2.3 Graphical representation of CCGT supply constraint risks

Legend

A not problematic
B problematic
C very problematic

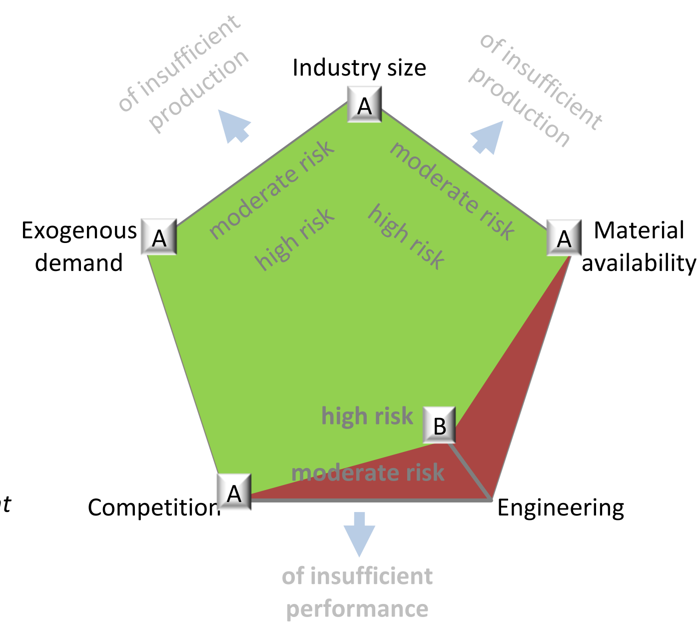

Figure 5-2 CCGT: risk of insufficient performance

5.2.4 Deployment of CCGT

The deployment in the US, the UK and Germany, three main deployers of CCGT[1] (CCGT deployment until 2005; Platts, 2006) show different initial deployment acceleration (see *Figure 5-4.a*, *b* and *c*). Where the US shows a very smooth exponential increase (and Germany a similar one), the UK shows a

[1] The Netherlands, much smaller in terms of total electricity generation, have also deployed significant CCGT capacity. More than half the electricity generation (7GWe) of the Netherlands was 1998 generated by CCGTs (Hofman, 2002).

deployment with a very high rate that has known almost instantaneous acceleration starting much later (1990 instead of the early 1970s). While the exponential increase in the US holds on for a long time (until 2001), the acceleration in Germany becomes a steady deployment as early as 1993, almost simultaneously with the UK (1992). In the US, total gas fired power plant construction has increased from the 1980s on and CCGT construction similarly (*Figure D-1.c* and *Figure D-2.c*), in the UK and Germany CCGT construction became unambiguously the principal gas fired power plant (*Figure D-1.d*, *e* and *Figure D-2.d*, *e*). In the UK the natural gas fired power plant was a relatively new phenomenon (*Figure D-2.d*). Total deployment in the US between 1970 and 2005 was 118GWe, in Germany 5GWe and in the UK 18GWe. Maximum deployment rate of the US was 24GWe/yr, of Germany 0,5GWe/yr and for the UK 3GWe/yr. Worldwide CCGT deployment for the period 1970-2005 has been 260GWe, with a maximum deployment rate of 45GWe/yr between 2001 and 2003 (*Figure 5-5.b*). This reflects a relative deployment of 40% by 2005 of all the new built gas fired power plants (*Figure D-2.b*).

CCGT has known a long experimentation phase. Although CCGT configurations have functioned as early as the 1970s, the total system remained unreliable due to gas turbine immaturity (strictly seen, an external hampering factor), i.e. too much downtime to be commercially interesting (Watson, 1997). Small applications of CCGT in the oil and gas industry had to be scaled up to power plant sizes (*sic*; CCS technology is currently on small scale applied for enhanced oil/gas recovery). through advances in jet engine technology that provided a possibility to scale up gas turbines to power plant size. As for government involvement, CCGT has benefitted mainly from government funded defense R&D programs instead of direct funding. After power blackouts in several industrialized countries in the 1960s, gas turbines were scaled up to serve as peak load power plants. This pushed the development of and utility experience with large gas turbines, and CCGTs came into the picture for base load purposes.

CCGT has enjoyed the absence of industry size as a problematic dimension. In the early decades (1970s / 1980s) of commercial scale deployment, CCGTs have been applied in limited numbers (see *Figure 5-5.b*). The oil crisis was part of this, but also the fact that CCGTs experienced significant performance problems (Watson, 1997) played an important role. But it has had the possibility to enjoy the advances through high defense spending on jet engines in the US, and boosts due to the discovery of a North American gas field, which assured some of the first CCGT orders in the 1970s. The symmetry with jet engines allowed industry to shift the allocation of personnel and equipment between military and civil divisions, instead of losing the developed knowledge because of inevitable firing of critical personnel and decommissioning of production sites. In the UK there has been a very fast deployment of CCGTs. This is not unrelated to the closing of domestic coal mines under the Thatcher governments, leaving a change to CCGT power plants as the only option.

5.2.5 Lessons learned and conclusions from CCGT deployment

CCGT has not been troubled by many problematic dimensions, although deployment has for a long time been hampered by an external factor; the development of a gas turbine. The CCGT world deployment graph shows a remarkable exponential deployment until 2001, i.e. long take-off/acceleration phase (*Figure 5-5.b*). This is mainly caused by the prime (both in time as in quantity) deployer of CCGT: the US. Deployment graphs for Germany and the UK do not show the same form (compare *Figure 5-4.b* and *c* with *Figure 5-4.a*). From a supply constraints point of view this form is a logical one, because the first deployer has to deal with the supply constraints. Because markets are coupled over the world, Germany and the UK could deploy CCGT with a very high deployment acceleration because the US having dealt with the main problematic dimension for CCGT (engineering).

5.3 Deployment of CCS

CCS deployment according to the IEA scenario (*Figure 1-1*) involves acceleration until 2030 and a constant deployment until 2050. Total power plant deployment in the first 27 years (2010-2037) is 523GWe, in the first 35 years (2010-2045) 904GWe[1] and 2010-2050 is 1159GWe, with a maximum constant deployment rate of 42GWe/yr before 2037 and 51GWe/yr between 2040 and 2050 (*Figure 5-5.c*). CCS deployment including industrial application would be almost twice as high. According to the IEA CCS scenario power plants account for 55% of the deployment and industry applications for 45%. Industry applications have a slightly higher rate of deployment in the first decades because some of these applications are significantly easier to realize than carbon capture from power plants (IEA, 2009). The industry CCS installations should be kept in mind while assessing the comparison in *Section 5.4*. The industrial application has not been quantitatively taken into account in this comparison as FGD industry application deployment figures are not readily available.

Coal fired power plants should play a major part in CCS deployment according to the IEA scenario. On the other side, forecasted evolution according to the BLUE Map scenario (IEA, 2010a) of the worldwide total coal fired power plant capacity indicates that total capacity will decrease significantly until 2050 (*Figure C-2.a*). According to the BLUE Map scenario there will especially be very few new coal fired power plants. The moderate CCS deployment up until 2030 in absolute numbers implies consequently that all new built coal fired power plants in the 2020s need to be equipped with CCS. In addition, some of the non-CCS coal fired power plants constructed in the 2010s need to be retrofitted during this period (*Figure C-1.a*). This will result in a relative deployment of 32% by 2037, 82% by 2045 and 95% by 2050 (*Figure C-2.a*).

5.4 Deployment of CCS compared to FGD and CCGT deployment

Worldwide FGD deployment in the first 27 years of deployment (1972-1999) has been more than three times less than the IEA scenario world deployment in the first 27 years of deployment (2010-2037, compare *Figure 5-5.a* and *Figure 5-5.c*). The maximum deployment rate of FGD in the first 27 years of deployment is less than half of maximum deployment rate of CCS in the first 27 years of deployment. Relative to the total capacity of power plants already installed the worldwide CCS deployment is less ambitious than FGD deployment in at least one country; Germany (compare *Figure C-2.a* and *d*). Worldwide relative CCS deployment is however much more ambitious than worldwide relative FGD deployment (compare *Figure C-2.a* and *b*).

The total CCGT deployment in the first 35 years of deployment (1970-2005) has also been more than three times less than the IEA CCS scenario world deployment during the first 35 years of deployment (2010-2045). Even the impressive CCGT deployment rate between 2001 and 2003 is only half of that of CCS between 2040 and 2045.

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[1] This is relevant for a comparison with FGD and CCGT, as we have no deployment data of the first 40 years of deployment of FGD and CCGT, see *Section 5.4*.

The CSS scenario describes a relative deployment that is more than 50% more than FDG deployment (32% vs. 20% of total power plant capacity after 27 years) and more than double (82% vs. 40% after 35 years).

The form of the deployment (determined by the length of the take-off phase, i.e. the length of the period of acceleration until deployment has a constant rate) of the historical cases can also be compared to the CCS deployment curve. While CCGT deployment has been driven by financial arguments (cheap gas and load factor flexibility), FGD deployment has been driven by regulations. This could explain why the FGD world graph does not show such a smooth acceleration as CCGT deployment (*Figure 5-5.a* and *Figure 5-5.b*). If the FGD deployment in the US and Japan will be exemplary for the CCS deployment (and thus possibly[1] regulations a principal push factor), there will be a short take-off phase, i.e. a significant CCS building capacity will be established early on (in the first five years) which would subsequently remain relatively constant (constant slope in *Figure 5-5.a* and *c.*) for the next 22 years. If CCGT deployment will be exemplary for CCS deployment (and thus possibly financial arguments a principal CCS push factor) there will be a long take-off (acceleration) phase of about 30 years.

[1] The inference that the differences between FGD and CCGT deployment are due to a different push factor should be handled with care as this is based on only two cases (FGD and CCGT).

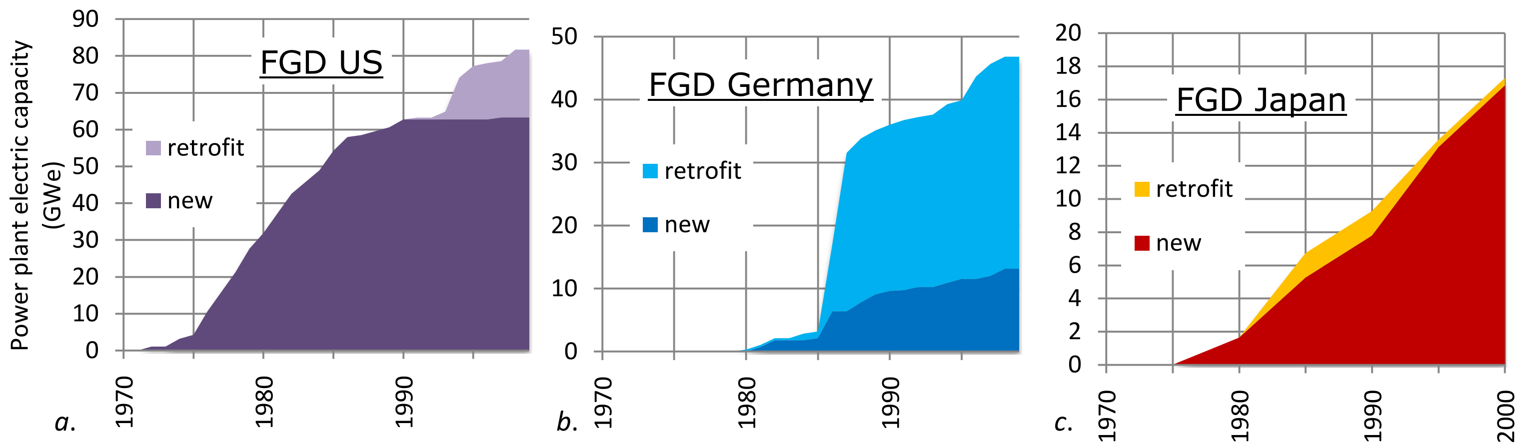


Figure 5-3 FGD deployment. Based on data extracted from Rubin et al. (2004).

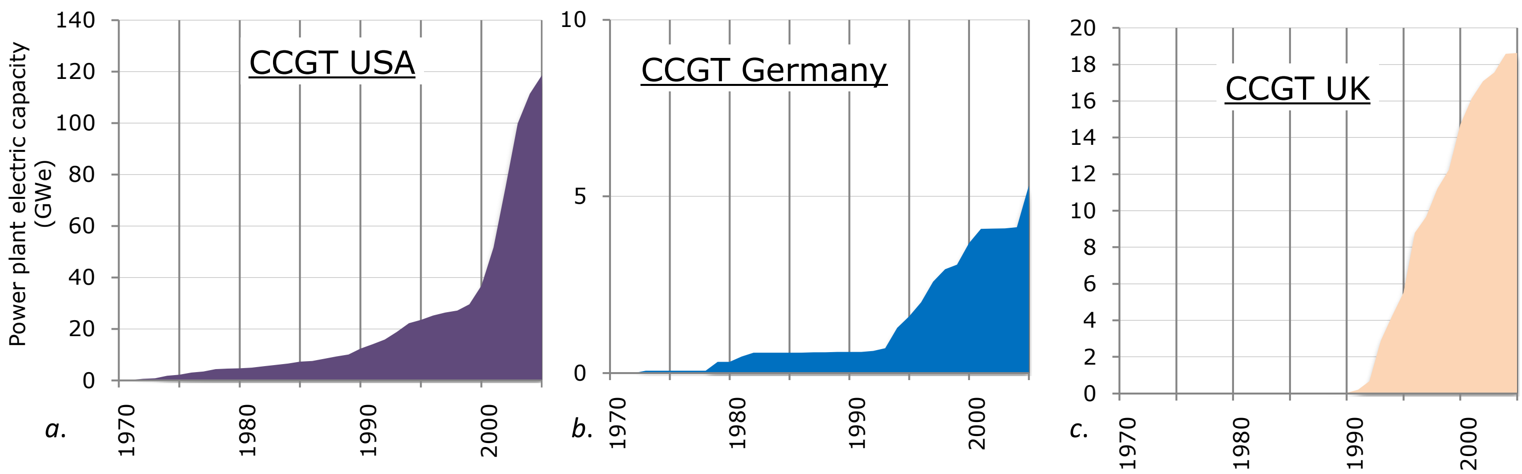


Figure 5-4 CCGT deployment. Based on data extracted from Platts (2006)

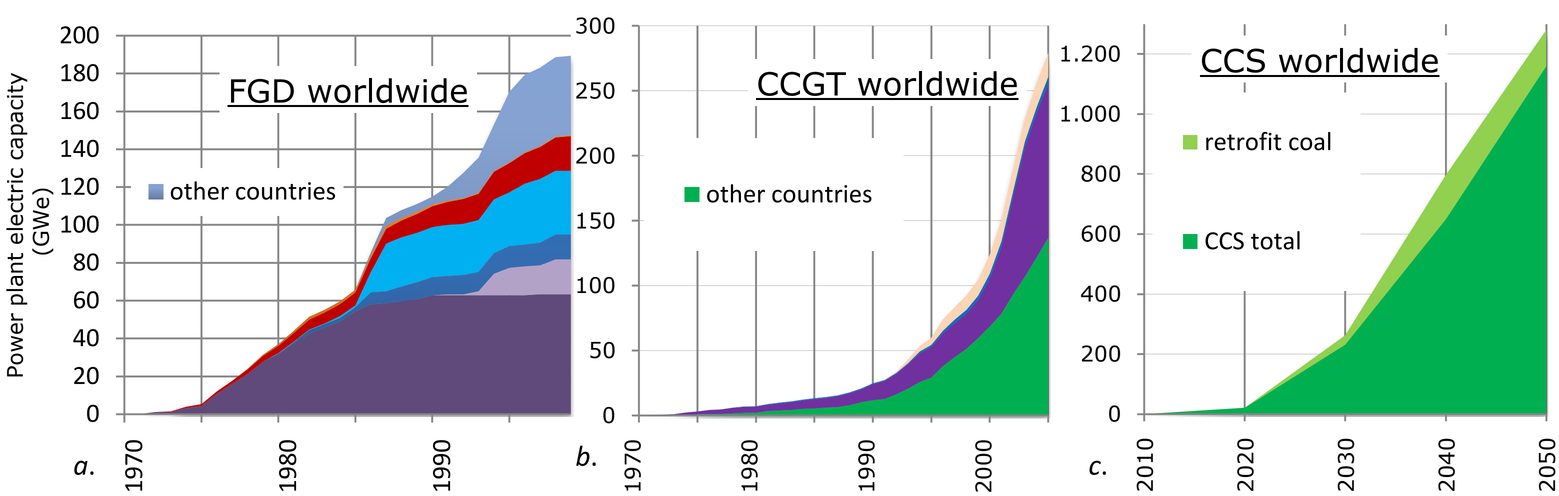


Figure 5-5 See Appendix C—3 *for a description of the modeling for a and c*

a. FGD worldwide deployment. Colors correspond to FGD graphs above

b. CCGT worldwide deployment. Colors correspond to CCGT graphs above. Based on data extracted from Platts (2006)

c. CCS deployment (all fuels)

6. Physical resources

In the beginning of each of the four paragraphs of this chapter the critical components are identified for post-combustion, pre-combustion, oxyfuel combustion and compression. An initial selection of components and their functionality can be found in *Appendix E*. Subsequently the supply constraint risk is assessed for each of the selected components.

6.1 Post-combustion

The post-combustion components of the initial selection in *Appendix E* that seem to have one or more problematic dimensions are:

Catalysts for deNO$_x$ systems. Estimated problematic dimensions: *industry size* and *material availability*. DeNO$_x$ systems are currently often used in power plants, but for post-combustion CCS power plants deNO$_x$ systems will be indispensable because a “low NO$_x$ level [is] required for amine based solvents” (Koornneef, 2010 p.121). Catalysts needed in these deNO$_x$ systems are in general dependent on scarce materials (Cavezzali et al. 2009).

Absorption towers. Estimated problematic dimensions: *industry size* and *material availability*. Because of its impressive size of up to 60 meters (TCM, 2010) in height significant amounts of construction capacity and materials will be needed. The materials might be scarce because they have to be corrosivity issues with CO_2.

Solvents. Estimated problematic dimension: *competition*. Solvents seem be heavily patented which can lead to monopoly positions (e.g. Tatsumi et al. 2010; Freeman and Rochelle, 2010; Vitse et al. 2010).

6.1.1 Risk of insufficient production

Industry size. Although deNO$_x$ systems are used at power plants worldwide, it is estimated that industry size of deNO$_x$ production will have to grow by 1 to 5% annually to meet CCS demand (personal communication Koornneef, 2010). So for deNO$_x$ catalysts, the current industry size is a problematic dimension. Special coating or packing techniques are needed on the inside of the absorption tower, which are almost exclusively used in some petrochemical industries (interview Billingham). The size of absorption towers needed for CCS is such (10m x 15m x 50m) that the production could use the “the entire global production capacity” of a certain packing supplier (Simmonds et al. 2010 p.25). Only three producers are currently involved in the manufacturing of these claddings (interview Billingham). Industry size is can thus be regarded as a very problematic dimension of insufficient production of absorption towers. An overview of the literature on solvent consumption given by Koornneef (2010, table 6-5, p.175) shows that the most common solvent, mono-ethanol-amine (MEA) , is on average used by a rate of 1.5g MEA / kg CO_2 captured. This would result in an MEA consumption of 7,5 Mt per year if half of the 10 Gt CO_2 per year[1] would be captured

[1] 10 Gt CO_2 per year is the amount that should be captured annually by 2050 according to the IEA Roadmap.

using MEA or a comparable solvent. Because the total world production is currently[1] 1,5 Mt of MEA, the industry would have to multiply its production by a factor six. While other solvents are in general less consumed than MEA (Koornneef, 2010, table 6-5, p.175), these solvents are in many cases especially developed for CCS and therefore their industry capacity has yet to be built up. Combined with the needed ramp up for MEA production this leads to the conclusion that the industry size is a very problematic dimension for solvents.

Exogenous demand. “Solvent production is assumed to increase with the expected increase in industrial activities and natural gas cleaning”, so exogenous demand is expected to grow between 1 and 5% (personal communication Koornneef, 2010). There is no indication that the supply of absorption towers or catalysts for $deNO_x$ units will have to deal with an exogenous demand growth.

Material availability. Solvents are in general made with basic chemicals such as ammonia, hydrogen and nitrogen (personal communication Koornneef, 2010), so material availability is not expected to become a problematic dimension. While exogenous demand is not expected to be a problematic dimension for absorption towers and $deNO_x$ catalysts, material availability is. Absorption towers need stainless steel, which is clad onto the main structure of carbon steel (interview Billingham). $DeNO_x$ catalysts need titanium dioxide (~90%), vanadium pentoxide (0.5% to 5%), and tungsten trioxide (10%) (Röder et al. 2004). Of these, tungsten is assessed by the European Commission as forming a possible supply constraint for economically important industries (EC, 2006).

This results in a risk of insufficient production of solvents catalysts for $deNO_x$ systems, absorption towers and for post-combustion (see also *Section 6.1.3*).

6.1.2 Risk of insufficient performance

Engineering. $DeNo_x$ catalysts have been applied for decades (Rubin, 2004) and absorption towers are technically simple (interview Billingham), so *engineering* is not a problematic dimension for these two components. Current day solvents such as MEA on the other hand are very energy intensive (Knuutila et al. 2009) and are furthermore subject to further research, development and demonstration on solvent CO_2, thermal and bio degradation (Eide-Haugmo et al. 2010 and Freeman and Rochelle, 2010). Engineering of solvents is thus a problematic dimension of insufficient performance of these solvents.

Competition. For $deNO_x$ catalysts competition is in place (CESI, 2006). There is a large number of manufacturers of absorption towers, some 100 in the UK alone (Simmonds et al. 2010), so competition is unlikely to become a problematic dimension of insufficient performance for either $deNO_x$ catalysts or absorption towers. Only for solvents there is a problematic dimension of insufficient competition. Competition can be hampered because of the highly proprietary character of certain solvents, such as Alstoms chilled ammonia. Drawing conclusions based upon Statoil experience and considerations at the start up of the large demonstration site ‘Technology Center Mongstad’ in southern Norway, there seems to be limited competition and innovative drive in the amine market (interview Berger).

[1] The most recent number found was 2004: Goliath, 2006. There is no reason to assume that this has changed significantly during the last decade.

This leads to the conclusion that there is a risk of insufficient performance of solvents for post-combustion (see also Section 6.1.3).

6.1.3 Graphical representation of post combustion supply constraint risks

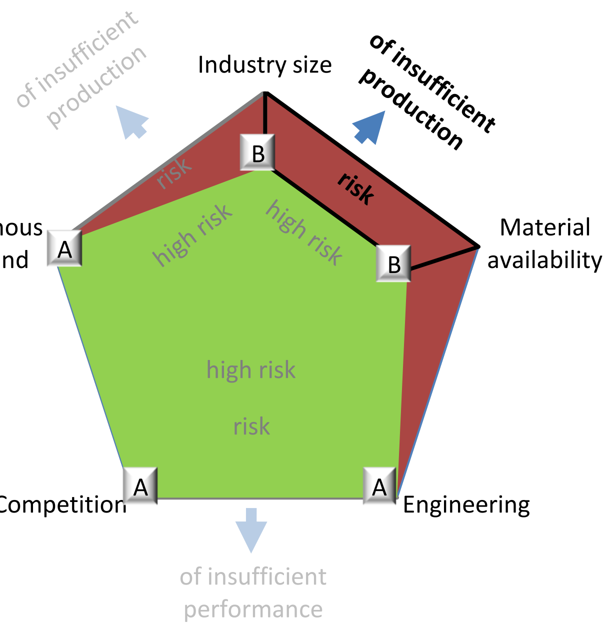


Figure 6-1 Catalysts for deNO$_x$: risk of insufficient production

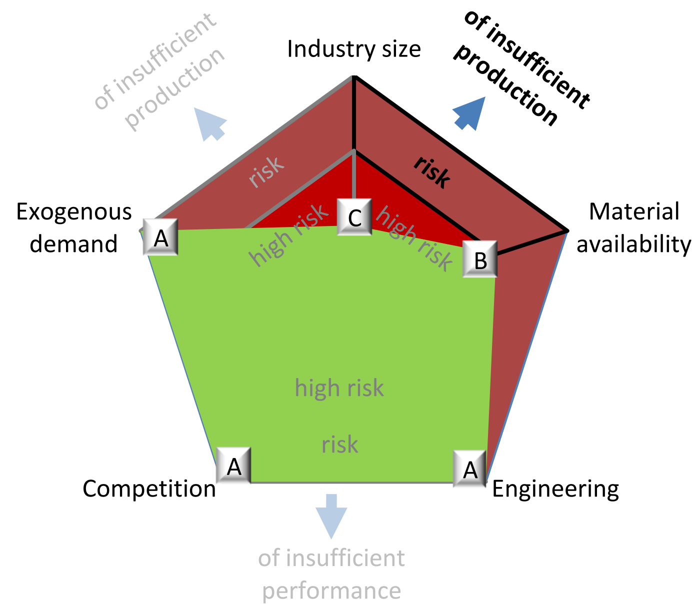
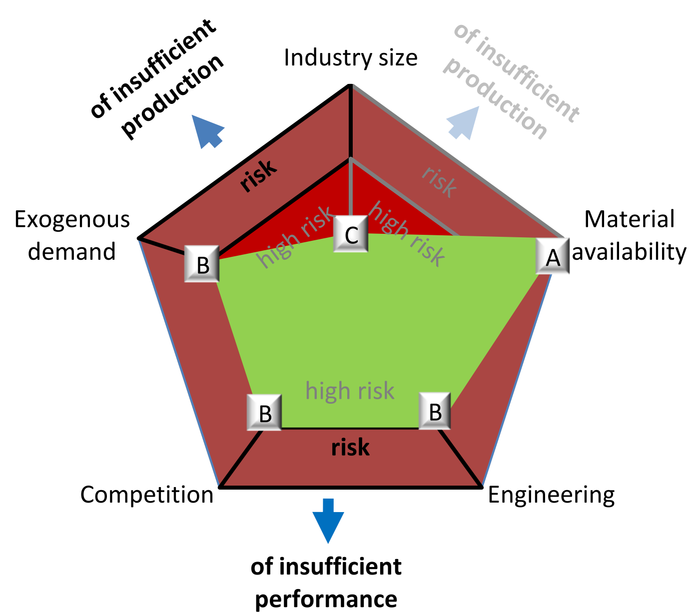


Figure 6-2 Absorption towers: risk of insufficient production

<u>Legend</u>

A not problematic
B problematic
C very problematic

Figure 6-3 Solvents: risk of insufficient production and performance



6.2 Pre-combustion

The pre-combustion components of the initial selection in *Appendix E* that seem to have one or more problematic dimensions are:

Air separation units. As air separation units are equally used for oxyfuel combustion, see *Section 6.3*.

Catalysts for acid gas recovery and water gas shift reactions. Estimated problematic dimension: *material availability*. These catalysts depend on scarce materials (personal communication, Koornneef 2010).

Hydrogen turbines. Estimated problematic dimension: *engineering*. Hydrogen turbines are needed to combust the produced hydrogen. Although several manufacturers claim to have developed a hydrogen turbine, none are currently operational (personal communication Hendriks, 2010).

6.2.1 Risk of insufficient production

Industry size. Currently catalysts for acid gas recovery and the water gas shift can be delivered without significant lead times (interview Burdock). Given this information and the fact that water gas shift reactors and acid gas recovery are currently widely applied, it is estimated that industry size is sufficient for CCS deployment (personal communication Koornneef, 2010), i.e. industry size is not a problematic dimension for these catalysts. H_2 turbines are being developed by the same manufacturers who are currently producing large industrial gas turbines (Hendriks, 2010). The industrial gas turbine industry is significant in size, and is used to deal with demand fluctuations (see *Section 5.2.4*), so H_2 turbine industry size is unlikely to become a problematic dimension.

Exogenous demand (for catalysts) for acid gas recovery and the water gas shift is expected to increase from the iron and steel industry, the chemical industry, the coal-, gas- and biomass-to-liquids processing industries (personal communication Koornneef, 2010). The demand for gas turbines has increased significantly during the last decade (see *Figure D-1*), so exogenous demand is likely to become a problematic dimension for both catalysts as H_2 turbines.

Material availability. For acid gas recovery, catalysts based on cobalt are in general needed (Kohl and Nielsen, 1997). Cobalt is economically important and it is labeled as posing a supply risk and a critical material by the European Commission (EC, 2010), therefore material availability is classed as a very problematic dimension of insufficient production of these catalysts. There is no indication that H_2 turbines will need significant amounts of scarce materials, so material availability is not a problematic dimension here.

There is a low risk of insufficient production for air separation units (see s*ection 6.3*). Because industry size is estimated to be sufficient for both components treated here, the conclusion is that there is a *low risk of insufficient production of catalysts for acid gas recovery units / water gas shift reactors and H_2 turbines* for pre-combustion (see also *Section 6.2.3*).

6.2.2 Risk of insufficient performance

Engineering. Catalysts are a mature technology as they have been used in both acid gas recovery as in water gas shift industrial applications for decades (personal communication Koornneef, 2010), so engineering is not a problematic dimension. Pure hydrogen turbines are not yet in the demonstration phase, but several producers claim to have developed one (personal communication Hendriks, 2010). This justifies the classification of the engineering dimension as 'problematic' for hydrogen turbines.

Competition. Catalysts for acid gas recovery and water gas shift have a wide supplier base (interview Burdock), so a lack of competition cannot be seen as a problematic dimension. The four large manufacturers who have been active in the development of combined cycle gas turbines are involved in competition (see *Section 5.2.2*, so competition is not a problematic dimension.

There is a low risk of insufficient performance for air separation units (see *section 6.3*). There is a *low risk of insufficient performance of H_2 turbines* for pre-combustion (see also *Section 6.2.3*).

6.2.3 Graphical representation of pre-combustion supply constraint risks

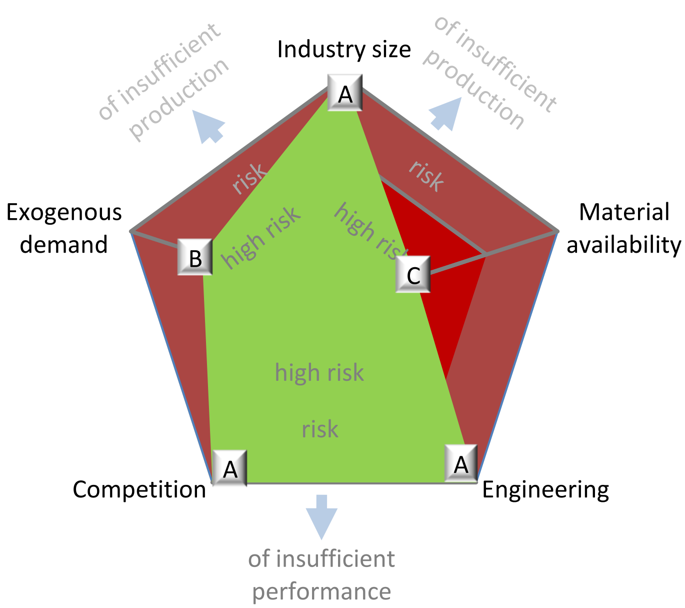


Figure 6-4 Catalysts for water gas shift reactors and acid gas recovery units: low risk of supply constraints

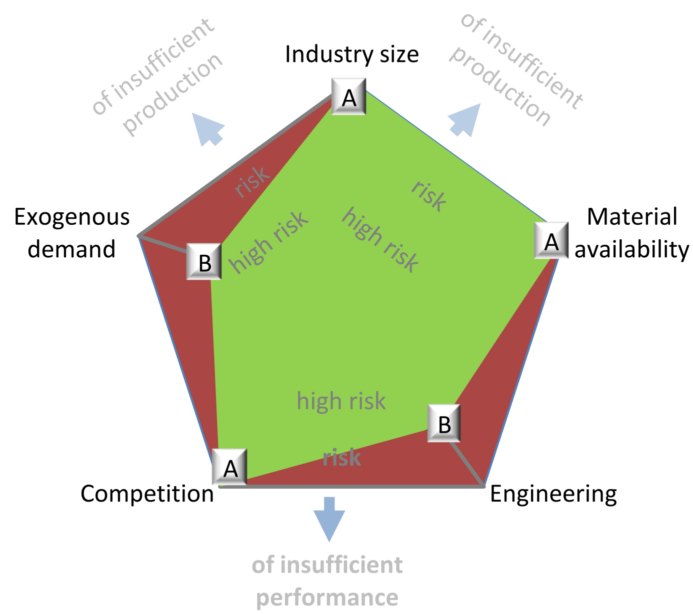


Figure 6-5 H_2 turbines: low risk of insufficient performance

Legend

A not problematic
B problematic
C very problematic

6.3 *Oxyfuel combustion*

The pre-combustion components of the initial selection in *Appendix E* that seem to have one or more problematic dimensions are:

Air separation units. Estimated problematic dimension: *exogenous demand*. Air separation units are increasingly used in a variety of industrial applications (Koornneef, 2010), so the market might be tight.

Advanced flue gas treatment systems. Estimated problematic dimension: *engineering*. Advanced flue gas treatment is still in the R&D phase (White et al. 2010).

6.3.1 Risk of insufficient production

Industry size. The air separation industry size needs a ramp up of 5% annually to meet CCS demand (personal communication Koornneef, 2010). The desulphurization and $deNO_x$ industry, on which advanced flue gas treatment is based, is applied on a significant share of worldwide power plants (see *Chapter 5*, *Appendix C* and *Figure F-1*). However, if oxyfuel combustion becomes the dominant technology and most of the coal fired power plants will be equipped with CCS (see *Figure 5-5.a*), the industry will have to increase its size and growth.

Exogenous demand. The air separation unit industry has been growing with an average 20% annually during the past decade, because of an increased demand from the iron and steel industry, the chemical industry, the coal-, gas- and biomass-to-liquids processing industries (Suresh et al. 2008). An additional ramp up of more than 5% might be difficult, because the 20% annual growth must have put significant stress on the industry, with the result that it is difficult for the industry to meet additional demand coming from CCS. In any case, exogenous demand will be a problematic dimension for air separation units. Advanced flue gas treatment is based on $deSO_2$ and $deNO_x$ technology. It is not expected that there will be an increase in installation of $deSO_2$ and $deNO_x$ systems on non-CCS power plants (i.a. because acid rain is not an urgent problem anymore) so exogenous demand growth is not a problematic dimension for advanced flue gas treatment.

Material availability. There is no indication that scarce materials are needed for air separation units or advanced flue gas treatment systems, so material availability is not regarded as a problematic dimension. Because industry size is only a problematic dimension for air separation units, there is a *risk of insufficient production of air separation units* for oxyfuel combustion (see also *Section 6.3.3*).

6.3.2 Risk of insufficient performance

Engineering. Air separation units are a mature technology, so engineering is not a problematic dimension. Advanced flue gas treatment for oxyfuel on the other hand is currently not yet demonstrated, and White et al. (2010, p.138, 142) indicate that they only "aim to show that this is not required and that oxyfuel combustion opens the way for innovative solutions to traditional problems". Furthermore, although they have more modeled than experimental results, it is "clear that the [chemical] reactions as posed seem to be producing the desired results." This shows that re-engineering is still in its early stages, and can thus be regarded as a very problematic dimension.

Competition. The air separation industry has consolidated significantly over the last decade (Suresh et al. 2008). Improvements are expected with respect to economies of scale, efficiency, and with respect to the use of membranes, but *competition* will be limited (i.e. a problematic dimension). However, air separation units are a mature technology, so there is a low risk of insufficient performance. While advanced flue gas treatment is still in the R&D phase, the technologies on which it is based are mature. There is a large number of competitors active in the FGD and $deNO_x$ market (Platts, 2006), which have the knowledge and skills to develop advanced flue gas treatment for oxyfuel combustion. The competition dimension for advanced flue gas treatment is thus not significant.

This results in a *low risk of insufficient performance* of the selected components for oxy-fuel combustion (see *Section 6.2.3*).

6.3.3 Graphical representation of oxyfuel combustion supply constraint risks

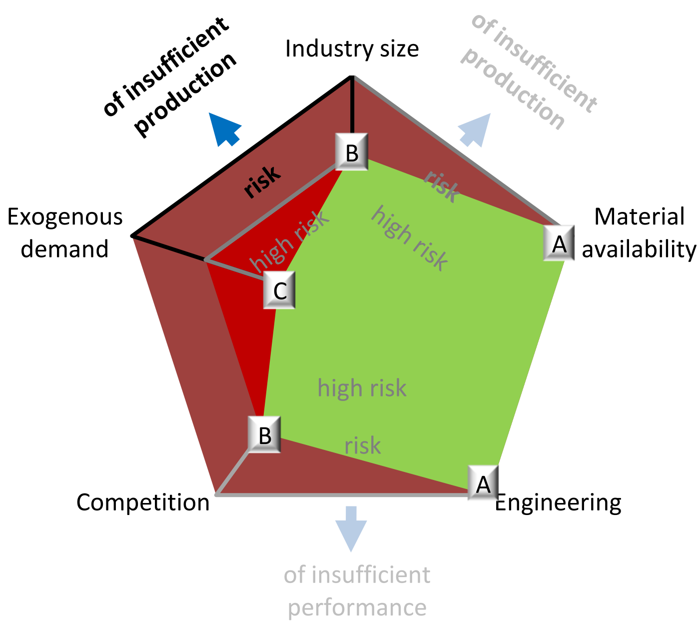


Figure 6-6 Air separation units: risk of insufficient production

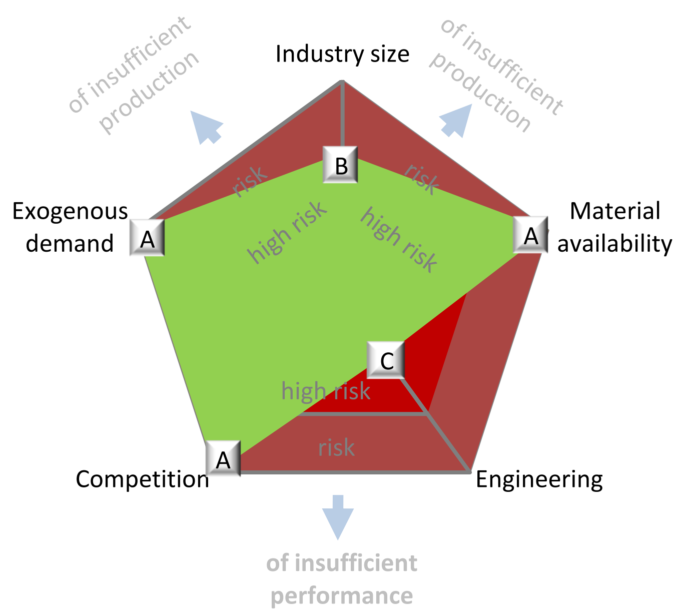


Figure 6-7 Advanced flue gas treatment for oxyfuel combustion: low risk of supply constraints

<u>Legend</u>

A not problematic
B problematic
C very problematic

6.4 Compression

The compression components of the initial selection in *Appendix E* that seem to have one or more problematic dimensions are:

Compressors. Estimated problematic dimension: *industry size* and *engineering*. The number of compressors needed to compress 1,800 Mt CO_2 annually in North America by 2050 (IEA, 2009) is ambitious with respect to a total gas use of less than 450 Mt natural gas in the US in 2004 (ICF, 2009a). Adjustments include both material choice because of corrosivity of CO_2 and size of the compressors because of a more elevated pressure in CO_2 transport than in natural gas transport (interview Billingham). As the compressors that are needed for CCS are very large and thus costly to transport in large numbers across the world, it is useful to make an assessment for three world regions separately.

6.4.1 Risk of insufficient production

The needed capacity for compression is much larger than the current annually produced compression capacity for natural gas, especially for the OECD countries, China and India (*Figure G-4*). This is partly due to a high pressure needed for CO_2 transport. A pressure up to 230 - 260 bars can be used (Barrie et al., 2004, Berger et al., 2004). As a consequence, the *industry size* needs to increase with more than 5% annually (*Figure G-1*). In the China and India world region a significant increase in natural gas infrastructure is forecasted (IEA, 2010; *Figure G-2*). This results in a *high risk of insufficient production in China and India and a risk for other non-OECD countries* (see *Figure 6-8,* and *Appendix G—2*).

6.4.2 Risk of insufficient performance

CO_2 compressors are in principle similar to those used for natural gas compression. However, due to higher corrosivity of CO_2, *engineering* of the alloys used might be needed. As these alloys will not be very complex by themselves, but the manufacturing of large compressors with these alloys might pose some problems (interview Billingham). For oxyfuel combustion, water removal could be integrated (personal communication Koornneef, 2011). The size of the compressors needed for CCS also has to be increased, which is a technological challenge as well. Per world region there are only one or two manufacturers. This combination results in *a risk of insufficient performance for all world regions* (see *Figure 6-8,* and *Appendix G—2*).

6.4.3 Graphical representation of supply constraint risks for compression

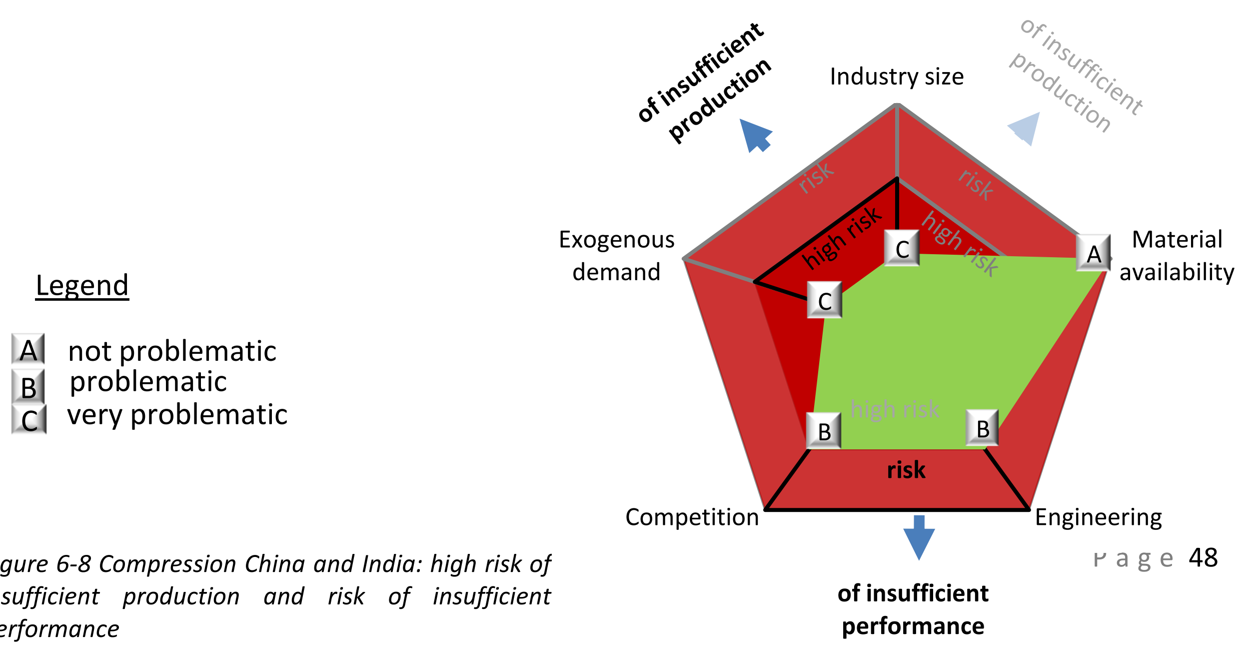


Figure 6-8 Compression China and India: high risk of insufficient production and risk of insufficient performance

6.5 Transport

CO_2 transport entails the pipeline transport from the capture location to the storage location. Alternatively, CO_2 could be transported by ship. Neele et al. (2010) suggest this as inter alia a temporary solution during construction of CO_2 pipelines. CO_2 transport resembles natural gas transport (Neele et al. 2010). Transport is currently performed for Enhanced Oil (or gas) Recovery (EOR) operations, notably in the US (Wilson et al. 2003). According to Metz et al. (2005, p.5) "pipeline transport of CO_2 operates as a mature market technology". As there is consequently no need for innovation on a component level, the assessment of CO_2 transport will have a different character than that of the capture and compression parts of CCS. Therefore transport services are studied on the aggregate level of the service, i.e. one supply constraint assessment for the transport service provided by the pipelaying industry that currently serves the oil and gas industry.

6.5.1 Risk of insufficient production

Industry size. Onshore pipelaying seems sufficient, but for offshore there is a shortage particularly known for pipelaying ships (interview Neele, 2010). In order to determine the supply constraint risks with respect to offshore pipelaying, the offshore part of the CO_2 network needed to execute the IEA scenario is estimated. For North Western Europe it is estimated (based on maps of Neele et al. 2010, app. D) that the offshore pipeline needed for CO_2 (4,400 to 9,100 km) is smaller than the current pipeline for natural gas (14,500 km under the North Sea). It is estimated that (including offshore pipelines in southern Europe) this will probably be one third of the total pipeline needed in Europe. If it is estimated that worldwide one quarter of the CO_2 pipeline will need to be laid offshore, this would not be a very conservative guess in view of the distribution of storage reservoirs (Pershad et al. 2010, p.32,33, figures 6,7). Furthermore, in other parts of the world, there is relatively more onshore storage capacity available than in Europe (e.g. ICF, 2009a). Taking into account that offshore storage is in all world regions relatively close to the coast, there is less demand for offshore transport . Based on a total of 200,000 to 361,000 km according to the IEA scenario, an offshore length of 50,000 to 90,000 km should be laid by 2050. A pipe laying vessel can lay 2 km of pipe per day on average, which will add up to about 500 km a year, depending on effective planning. This results in the need for four vessels. Even if as much as half the total pipeline length will be offshore, only eight pipelaying vessels will be needed, which seems feasible (but not negligible) with respect to the total number of currently operational pipelaying vessels. There are currently 40 pipelaying vessels worldwide, of which 29 are capable of laying pipe in deep water (Quest Offshore, 2010). Therefore it can be concluded that the dimension industry size is not problematic for offshore. Looking closer (quantitatively) to onshore availability, in order to meet CCS demand, pipeline construction needs almost to double with respect to current construction for natural gas. For the China and India world region the industry size is extremely limited, it needs to more than quadruple with respect to current construction for natural gas (see *Figure I-2*). This leads to high growth percentages in the pipeline construction market (see *Figure I-1*). Therefore it can be concluded that industry size is problematic for OECD countries and very problematic for China and India.

Exogenous demand growth. The world wide pipeline interregional natural gas trade by pipeline is expected to increase with 1.8% annually to 2030 (based on IEA, 2010, fig.5.7). In addition, many pipelines are built to replace rather than to complement current pipelines, for example the new pipelines from Russia to Europe (IEA, 2010, p.195 footnote). For North America the natural gas infrastructure will be built in about the same pace in the next two decades (possible arctic projects included) as has been the case during the last decade (ICF, 2009b). The costs of pipeline building are composed of roughly one third labor in the US (ICF, 2009b). Especially for China and India and the OECD pacific the exogenous (natural gas) market growth seems significant in view of the current small natural gas market in these countries (*Figure I-3*). For the other non-OECD countries and OECD Europe, the proportions between the current natural gas markets, the projected natural gas investments and the needed CO_2 investments are comparable to those of North America, i.e. it is rrom a growth point of view only a problematic dimension for China and India. However, the petroleum industry is financially very strong, and large sums equally go round in their supplying service industries for transport and storage (55 USD billion for the US and Canada alone until 2020; ICF, 2009b). Competing with the oil and gas industry for the same services seems financially difficult in view of the limited 14.9 USD billion until 2020 (IEA, 2009) that is associated with pipeline construction for large scale CCS deployment. "it has to be recognized that the investment needed to support a national CO2 transportation network will require significant capital and may entail competition for the same material and manpower resources as that of the natural gas and oil pipeline industries." (ICF, 2009a). For this financial reason, it will be problematic to obtain access to these services for CCS purposes in all world regions.

Material availability is an issue as the construction of pipes is dependent on the world steel price. Even in the US, where labor is relatively expensive compared to the rest of the world, the steel prices makes up about one third of the pipeline construction price (ICF, 2009b). Therefore material availability is a problematic dimension for all regions.

6.5.2 Risk of insufficient performance

Engineering is not expected to be a problematic dimension, as technically natural gas pipelines that are out of service could be used to transport without significant changes (Neele et al., 2010). However pressure is generally higher for CO_2 transport, so that thicker pipeline walls are more suitable for CO_2 transport (ICF, 2009a).

Competition For the transport part, the pipelines up to 16-20" will probably not cause any supply constraints. The larger pipelines, those serving several carbon emitting sites / several sequestration sites, are a different case. Mr. Billingham has been involved in the commissioning of a large pipeline from North Africa to Italy. In this process the longlist was limited to 6/7 contractors, of which on closer investigation only 3 appeared to be actually able to construct this pipeline. So according to Mr. Billingham especially marine pipelines might cause difficulties. Currently the North Stream Pipeline is being constructed from Russia to Western Europe. This keeps one of these few companies busy for 2/3 years. Furthermore, as there is a very limited number of companies capable of constructing these pipelines, also on land commissioning of the larger pipelines is equally problematic. The conclusion is that competition is a problematic dimension for all world regions.

6.5.3 Graphical representation of supply constraint risks for transport

Legend

A not problematic
B problematic
C very problematic

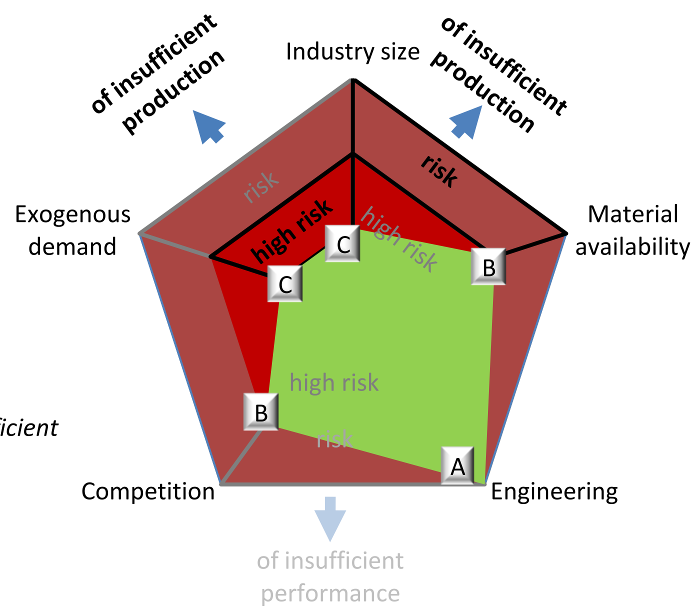


Figure 6-9Transport China and India: risk of insufficient production

6.6 Storage

Natural gas injection (used for natural gas storage) is very similar to CO_2 injection (Metz et al. 2005). CO_2 injection is currently performed for Enhanced Oil (or gas) Recovery (EOR) operations, notably in the US (Wilson et al. 2003). As there is consequently no need for innovation on a component level, the assessment of CO_2 storage will have a different character than that of the capture and compression parts of CCS, but similar to that of CO_2 transport. Storage services are studied on the aggregate level of the service, i.e. one supply constraint assessment for the storage service provided by the pipelaying industry that currently serves the oil and gas industry.

6.6.1 Risk of insufficient production

Industry size. According to ICF (2009a) the average number of wells per $MTCO_2$/yr is more than 40. Although this number seems small in comparison to numbers of natural gas wells, it is not so when compared to current case studies. While storage (Sleipner, 1 $MtCO_2$/y) in the North Sea operates with only one well, the In-Salah project in Algeria needs three wells because of a lower permeability (Benson and Cook, 2005). Also in the GESTCO case studies performed by Ecofys (confidential, but IPCC refers to GHGT-7 proceedings of Larsen et al. 2005) well numbers beneath the 40 / $MtCO_2$/y are mentioned. It is very difficult to estimate the number of wells needed per $MtCO_2$ stored, because of geological differences, and differences between onshore / offshore storage (interview Prelicz, 2010).

More than 25% of the world's active oil rigs is drilling for oil or natural gas in the US (Schlumberger, 2010). Although OECD Europe has roughly half the US NG and oil production (IEA, 2010a), it has ten times less active rigs (Schlumberger, 2010)[1]. This can be (partly) understood by the extreme low

[1] However, drilling rigs can be transported between adjacent regions.

reserve-to-production ratio in North America (BP, 2010). Because of their low reserve-to-production ratio, the US are obliged to drill for fossil fuels that are more difficult to recover. For example, the production of an average natural gas well in the early to mid-1970s was three times that of an average natural gas well in the US (USGS, 2002). The increase of active rigs in the 2000s inactive rigs have first been brought back into service (based on databases of Baker Hughes[1], 2010, see *Figure J-1*). After all the available active rigs been brought back into service, new active rigs have been manufactured in high rate. This rig manufacturing has been started up rapidly when the need occurred. A split up of the non-US rig numbers shows that there is a significant change in rig activity over the years in all regions of the world[2] (*Figure J-2*). The current number for rigs used for natural gas drilling can be extended quickly if needed as shown by US experience (Berkman and Stokes, 2009). Therefore industry size is not a problematic dimension.

Exogenous demand. The exogenous demand growth for drilling rigs will depend on the natural gas and oil market growth. The world gas production is forecasted to grow between 1 and 5% per year until 2035 (which is more than the world oil production). The growth will especially take place in non-OECD countries (IEA, 2010a)[3]. Worldwide storage capacity will grow from 0.014 bcm in 2009 to 0.015 bcm, while China's annual growth rate of natural gas storage is as high as 16% (PennEnergy, 2010), so this is very problematic. For the rest of the world, the natural gas exploration and development investments are significantly less than those for the US (IEA, 2010a, p. 197 table 5-7). However, the petroleum industry is financially very strong, and large sums equally go round in their supplying service industries for transport and storage (55 USD billion for the US and Canada alone until 2020; ICF, 2009b). Competing with the oil and gas industry for the same services seems financially difficult in view of the limited 14.9 USD billion until 2020 (IEA, 2009) that is associated with pipeline construction for large scale CCS deployment. For this financial reason, it will be problematic to obtain access to these services for CCS purposes in all world regions.

Material availability is a problematic dimension, the construction of drilling rigs is dependent on the steel price (e.g. Greenberg, 1965). When retired, drilling rig steel is reused (Kaiser and Pulsipher, 2007).

6.6.2 Risk of insufficient performance

Engineering. By September 2010 a quantity of 0.01 bcm of natural gas was stored in the US (EIAb, 2010). "Fortunately, recent advances in well technology, such as horizontal drilling, massive hydraulic fracturing, and multi-

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[1] The Baker Hughes census has used a different method than Schlumberger. As a result, the U.S. dominance in numbers of active rigs is even more striking. However the Baker Hughes census is useful because extended time series are available.

[2] These Baker Hughes world regions do not correspond to the world regions used in this report (IEA Roadmap world regions).

[3] Even with equal production, an ever increasing number of new wells would need to be built because of the decreasing productivity per well.

lateral wells will enhance the potential for individual well injectivity, and reduce the number of wells required to inject a volume of CO_2 compared with traditional drilling techniques common in early CO_2 EOR projects." Cooper (2009)

The application of injection technology on this scale is not new (Wilson et al. 2003). The technologies are similar to conventional natural gas drilling, but need extra engineering capacity because new technology adjustments are needed. The current total annual US injection of wastewater with an injection of approximately 2 $GtCO_2$/y corresponds to the needed injection in 2050 as described in the IEA scenario. The current "experience gained from existing deep-fluid-injection projects is relevant in terms of style of operation" (Metz et al. 2005, p.212). According to Metz et al. (2005, p.230) the injection technology can be considered relatively mature:

"Drilling and completion technology for injection wells in the oil and gas industry has evolved to a highly sophisticated state, such that it is now possible to drill and complete vertical and extended reach wells (including horizontal wells) in deep formations, wells with multiple completions and wells able to handle corrosive fluids. On the basis of extensive oil industry experience, the technologies for drilling, injection, stimulations and completions for CO_2 injection wells exist and are being practised with some adaptations in current CO_2 storage projects."

However, the experience with storage projects as such is unequally distributed over the world. In non-OECD countries there is very limited storage experience (IEA, 2009). Therefore the technology can be seen as less mature in non-OECD countries.

Competition is not a problematic dimension. In the US alone there are more than 300 rig owners[1] (Berkman and Stokes, 2009).

6.6.3 Graphical representation of supply constraint risks for storage

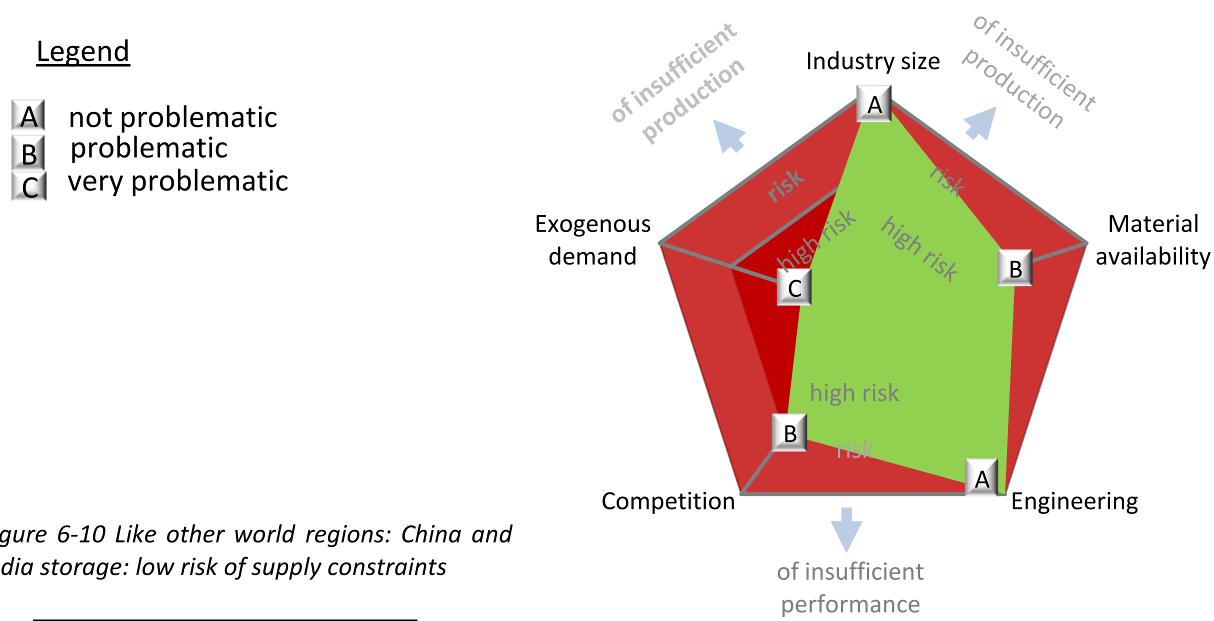

Figure 6-10 Like other world regions: China and India storage: low risk of supply constraints

[1] Drilling rigs are large platforms and consequently not constructed in a indicatory. Rig owners are thus likely to coordinate the construction of their own rigs.

7. Human resources

For the CCS innovation system:

"the increasing scarcity of skilled (technical) personnel in CCS may cause problems, as CCS has the potential to become an industrial sector that is comparable to the current oil and gas industry […] the solution for this potential problem [is] introducing educational programs at universities to get future engineers acquainted with specific CCS knowledge [and] the need to retrain current managers and technicians in the industry" (Van Alphen et al. 2010, p.405)

Technological problems are mainly encountered in the capture part, as the transportation and storage part are to a high degree similar to enhanced oil recovery technology. As a result, mainly the capture part will still have a need for highly skilled engineers (Koperna, personal communication, 2010). Chemical and petroleum engineers are critical here because CCS capture is effectuated by installations that resemble large chemical plants. Large flows of gases and liquids can in particular be found at the manufacturing sites of basic chemicals, petroleum and coal products, while this is much less the case in other places where chemical engineers are employed. As far as petroleum engineers are concerned, they are indispensable for CO_2 storage[1] next to their involvement in capture installations.

Next to engineers the professions that might become critical for the technical part are operators. More than 13,500 'operators of natural gas plants'[2] and 22,250 'chemical plant and system operators' are working in the manufacturing sites of basic chemicals, petroleum and coal products in the US[3]. These numbers are of the same order of magnitude as the number of power plant operators: more than 35,000 (US Bureau of Labor Statistics, 2009). This number of operators is likely to form a large enough experience reservoir with respect to the 590 CCS installations needed in the US by 2050. The total employment of chemical plant operators in the US is expected to decline with more than 1% (US Bureau of Labor Statistics, 2010). The same is the case for 'petroleum pump system operators, refinery operators, and gaugers', whose job numbers will equally 'decline rapidly' from 47,100 in the next decade. Both are typically educated by 'long term on the job training'. This indicates that there will most likely be no problems with the availability of adequate operators. The numbers of petroleum and chemical engineers working in the manufacturing of basic chemicals, petroleum and coal products are of a much lower order.

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[1] While in *Chapter 2* we have stated that we would not include professions on the basis of their involvement in one specific component or service, we now make an exception for the involvement of petroleum engineers in CO_2 storage. There seems to have been an almost continuous severe shortage of petroleum engineers. This shortage is much more serious than supply shortages in other professions in the oil and gas industry such as geologists and pipelayers (interview Prelicz, 2010).

[2] Professions as defined by the U.S Standard Occupational Code.

[3] For lack of information on this profession for other parts of the world, we extrapolate the conclusions for the US.

For project implementation, environmental scientists and specialized lawyers seem to be the most logical specialized professions to look into[1]. There are currently 85,900 environmental scientist jobs in the US. This number is expected to grow with 2,5% annually in the next decade. However, the number of job openings is expected to be 'roughly in balance' with the number of job seekers (US Bureau of Labor Statistics, 2010). In view of the high number, it should be possible to find enough environmental scientists for CCS projects. However, no more than 500 lawyers are currently working in the oil and gas extraction industry (US Bureau of Labor Statistics, 2009).

Concluding, the human resources that might become critical for CCS implementation are the following three ones. The dimension that has been decisive to include the human resource as critical is also mentioned.

> *Chemical engineers.* Decisive dimension: *HR supply size*. Chemical engineering is not a an engineering specialism that is widespread, and the labor market is traditionally tight (interview Midgley, 2010).
> *Petroleum engineers.* Decisive dimension: *HR supply size*. There is a severe shortage of petroleum engineers (interview Prelicz, 2010).
> *Specialized lawyers.* Decisive dimension: *education* (interview Hughes, 2010).

7.1.1 Risk of insufficient availability

Chemical engineers

If it would be assumed that all chemical engineers (irrespective of their previous professional experience) are capable of building and operating CCS installations, the HR supply size is large. In 1999 there were 183,500 chemically educated engineers in the US. In the same year not more than 79,900 graduated engineers were employed in chemical engineering (NSF, 1999). This implies that the stress on the labor market for chemical engineers is limited. According to another source (US Bureau of Labor Statistics, 2010; different numbers due to the use of a different classification and survey approach) 31,700 chemical engineers were employed in the US in 2008. This source expects the employment of chemical engineers to diminish slightly over the coming decade, which equally leads to the conclusion that there will be sufficient chemical engineers without specific experience available.

For other world regions than North America, conclusions are drawn on the basis of indirect information, as detailed statistics on the number and the employment of chemical engineers are not available. *Figure H-4* shows that the share of engineering degrees among all university degrees is in general significantly higher in Europe and than in the US. This implies that if there is no problematic HR supply size and growth dimension for chemical engineering in the US, the same could be said for Europe.

Notably in China the chemical industry is expanding quickly (Cefic, 2010; *Figure H-7*). However, the increase in number of engineers exceeds the growth of the chemical industry in China (comparison

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[1] Next to these specialized professions, every project will need experienced business people in order to make implementation a success. As these business professions are not very specific for CCS projects, we will not consider those.

NSB, 2005; *Figure H-6*, and Cefic, 2010; *Figure H-7*). So if it is assume that in China and in the US very roughly the same share of all engineers are chemical engineers, it can be deducted that the number of chemical engineers will not be a major problem for China.

Currently CCS needs the most upscaling in the power sector. Installations in the oil, gas and coal processing are demonstrated on a commercial scale, while this is not yet the case for installations in the power sector (McConnell et al. 2009; *Figure H-1*). The capabilities needed for CCS are in particular strong in the oil and gas industry according to the top 5 patent holders for CCS capture development (Lee et al. 2009; *Figure H-2*). 1330 chemical engineers are currently employed in US petroleum and coal products[1] (US Bureau of Labor Statistics, 2009), which makes these chemical engineers the best suited to the construction of CCS installations. Like manufacturing of petroleum and coal products, the manufacturing of basic chemicals[1] is done in large chemical plants with large flows of gases and liquids. Because of the comparability of skills, next to the chemical engineers employed in the petroleum industry particularly these chemical engineers which have this specific on the job training are needed for the development of CCS capture plants. If manufacturing of basic chemicals is included, the total number of chemical engineers with the right on the job training is limited to 5010.

In general chemical engineers, like other engineers, are needed to build new chemical plants, and less to operate them which is done by chemical plant operators (US Bureau of Labor Statistics, 2010). So if it is estimated that for the construction (assumed to take four years) of a CCS installation approximately ten chemical engineers are needed, and during the operation of a CCS installation one chemical engineer will suffice, the number of chemical engineers needed for North America alone is more than 1500 by the year 2050 (see *Figure H-3*). This number is relatively high (30%) in comparison to the 5010 chemical engineers currently employed in US basic chemicals, petroleum and coal manufacturing. Although these sectors are significant in size, the relatively low number of 5010 is comprehensible in the light of the limited number of new plants being built, and thus the limited engineerial capacity needed.

In conclusion of the dimensions of the insufficient supply of chemical engineers, the number of skilled chemical engineers is likely to be limited by the lack of specific professional experience (on the job education), and not in the number of chemical engineers or an increased exogenous demand. As the HR supply size is large enough, this does not result in a risk of insufficient availability (see *Figure 7-2*).

Petroleum engineers

The HR supply size of petroleum engineers is limited with respect to their number, which can be deducted from their average starting salary of more than $83,000 annually. This is by far (> $18,000 difference) the highest wage of the thirteen engineering specialisms included in the 2009 (July) survey by the National Association of Colleges and Employers, referenced by the US Bureau of Labor Statistics (2010, p.169).

The need for petroleum engineers for CCS purposes provides indications for fierce competition with the sector that is currently virtually the only employer of these professionals: the oil and gas industry.

[1] "Coal manufacturing" is mainly included because 'Petroleum and coal products manufacturing' is a class used by US Bureau of Labor Statistics (2009)

The employment of petroleum engineers will grow with 18% (i.e. exogenous demand growth) over the next decade and "Excellent opportunities are expected for petroleum engineers because the number of job openings is likely to exceed the relatively small number of graduates." (US Bureau of Labor Statistics, 2010, p.169). Employment in the oil and gas industry fluctuates intensively (see *Figure H-8* based on Eurostat data). The possibilities of employing petroleum engineers will consequently depend on the conjectural dynamics in the oil and gas industry.

As oil and gas extraction are getting more labor intensive due to continuing depletion of oil and gas reserves worldwide, it is logical that the industry will increase the demand for petroleum engineers.

While the education of petroleum engineers is not significantly different for CCS from the training given for the oil and gas extraction industry (interview Prelicz, 2010), the limited number of petroleum engineers and the exogenous demand are expected to be unfavorable for CCS deployment. This results in a risk of insufficient availability of petroleum engineers (see *Figure 7-1*).

Looking into the number of rigs used for natural gas production (Baker Hughes) provides insight in the experience with natural gas production. For the US the current percentage used for natural gas production is 73%, whereas this 38% for OECD Pacific (Australia), 25% for OECD Europe, 16% and 8% for China and India 22% for other non-OECD countries. This implies that the natural gas experience is limited for OECD Europe, OECD Pacific and China and India. In combination with the high exogenous demand this results in a supply constraint risk of sufficient HR availability.

Specialized lawyers

Specialized lawyers are needed in order to be able to comply with new complex national and international CO_2 regulation. According to the US Bureau of Labor Statistics (2010), no more than 500 lawyers are working in the oil and gas extraction industry in the US. This number is expected to diminish slightly in the next decade, in absolute as well as in relative terms as the total legal workforce is expected to grow over the same period.

The limited number of specialized lawyers from the oil and gas industry will not suffice to equally serve the CCS demand for lawyers. Some experts who have gained experience in the oil and gas industry could find work in the CCS industry. But the most lawyers (with 1800 projects in 2050 according to the IEA scenario the number will most likely exceed 500) that will be needed in the CCS industry will need to be newly educated.

While the HR supply size of lawyers is large enough (759,200 in 2008), and the labor market is expected to be keen (US Bureau of Labor Statistics, 2010), specific experience is likely to become a problem with only (on the job education). As the labor market for lawyers in general is expected to be small with respect to number of graduates and the total number of lawyers will exceed 850,000 in 2018, there is room for extensive selection (US Bureau of Labor Statistics, 2010). Furthermore, because of the large number of schooled lawyers and the limited number of positions they have to compete for, law students might have the incentive to specialize in issues surrounding CCS during their studies. Therefore the risk of insufficient availability is low (see *Figure 7-3*).

7.1.2 Risk of insufficient performance

Chemical engineering for CCS purposes entails the development of new chemical plants. While building chemical plants is the work of chemical engineers, the development of new chemical plants with a limited or non-existent track-record on commercial scale can be seen as 'moderately new' with respect to average chemical engineering work in the manufacturing of basic chemicals, petroleum and coal products. This new chemical plant will need new knowledge, which will have to be developed in the CCS deployment itself. Therefore there is a risk of insufficient performance of chemical engineers is (see *Figure 7-1*).

Petroleum engineering for extraction of oil and gas is similar to the engineering needed for injecting: "Many of the best practices used in oil and gas reservoir characterization can be used to assess the potential of CO_2 storage sites (such as using seismic data, stratigraphic mapping and facies analysis to develop 3D geological models)" (Cooper, 2009). The risk of insufficient performance of petroleum engineers is low (see *Figure 7-2*).

The Interagency Task Force on Carbon Capture and Storage (2010) discusses which legal fields are applicable to CCS (storage) operations (see *Table H-5*). The environment protection legislation will apply because

"Based on information we have to date on the potential chemical composition of the injectate, it appears that under likely capture scenarios the injectate will contain hazardous substances (e.g., arsenic and selenium). CO_2 storage projects almost certainly fall within the definition of a facility. […]CERCLA defines the term "facility," inter alia, as "any site or area where a hazardous substance has been deposited, stored, disposed of, or placed, or otherwise come to be located" Interagency Task Force on Carbon Capture and Storage (2010, p.F5)

The so called 'right-to-know' legislation will be a critical point as it will have to deal with so-called 'not-in-my-backyard' (NIMBY) effects. Therefore the needed legal HR will have to include environmental law and NIMBY expertise. These are most likely the same lawyers as currently employed by the oil and gas extraction industry. For CCS specific new legislation will be developed, but the issues as mentioned above are not intrinsically new. Therefore the tasks that legal experts will have to execute can be considered as moderately novel with respect to other technologies, which causes a risk of insufficient performance (see *Figure 7-3*).

7.1.3 Graphical representation of supply constraint risks

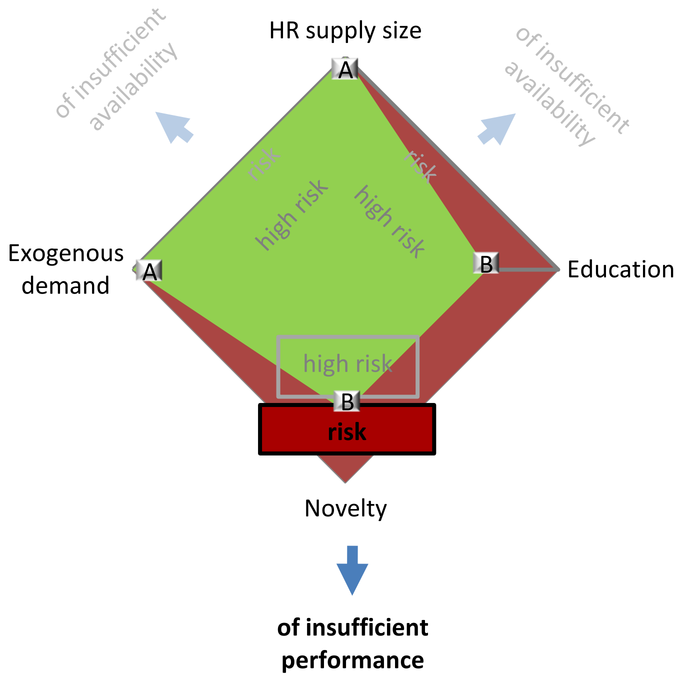

Figure 7-1 Chemical engineers: risk of insufficient performance

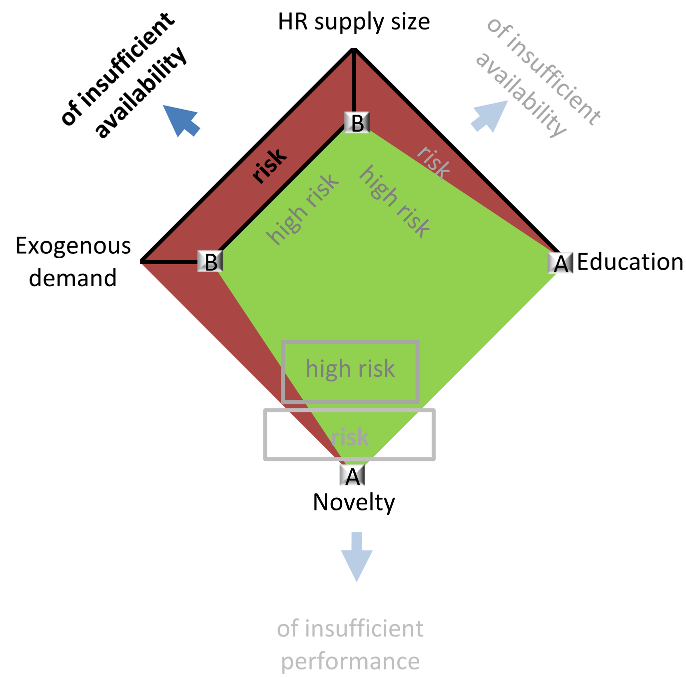

Figure 7-2 Petroleum engineers: risk of insufficient availability

Legend

A not problematic
B problematic
C very problematic

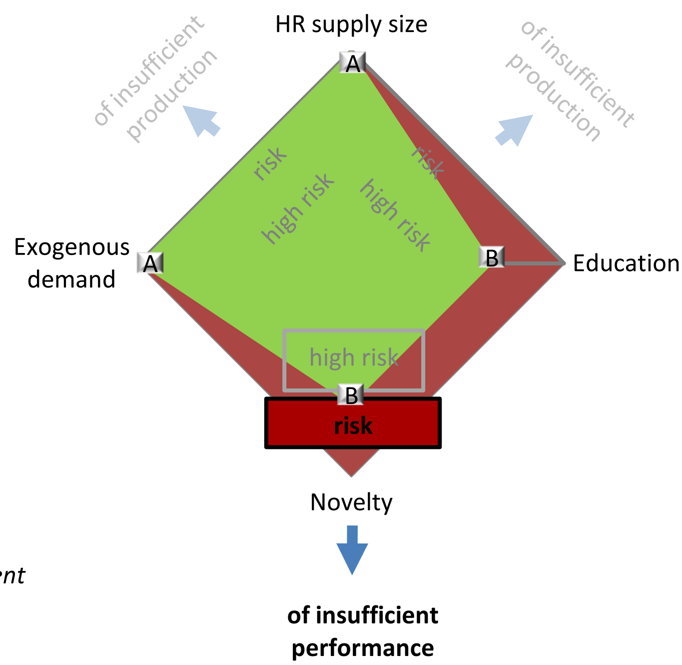

Figure 7-3 Specialized lawyers: risk of insufficient performance

8. Analysis

In *Chapter 2* it is described how this research on supply constraints should provide insight in specific parts of the technological innovation system (*Figure 2-3*). In the framework developed supply constraints are supposed to be based on the need to increase quantity or quality of production of physical resources, determined by the fulfillment of the system function resource mobilization, and the possibility to do this, determined by the supply side. The assessment of supply constraints and dimensions for the deployment of flue gas desulfurization between 1970 and 1999 has provided information about the usefulness of the dimensions in the framework. Data that is relevant to the occurrence of supply constraint risks has been gathered for all five dimensions of physical resources (not for all dimensions for FDG and CCGT). During data collection no data has been encountered that is relevant for the occurrence of supply constraint risks that was not a part of one of the dimensions, so the set of dimensions seems to be complete. Furthermore, the analysis of the historical cases of fast large scale development strengthens the claim that individual problematic dimensions can be overcome when combinations of a need for increased resource mobilization and an unfavorable supply side are absent.

For the CCS resources data that is relevant to the occurrence of supply constraint risks has been gathered for all five dimensions of physical resources (not for physical resources). During data collection no data has been encountered that is relevant for the occurrence of supply constraint risks that was not a part of one of the dimensions, so the set of dimensions seems to be complete. The same accounts for human resources. The need to increase resource mobilization and an unfavorable supply side have been found to be both present (for the resources mentioned in footnote 1), both not present or only one of those present. With respect to insufficient production, only resource mobilization (industry size) has been found to be problematic for 'advanced flue gas treatment for oxyfuel combustion'. Much resource mobilization is needed for these two resources, but it seems that the suppliers have no constraints to ramp up their production to meet a high CCS demand. Only an unfavorable supply side has been present for the physical resources 'catalysts for water gas shift reactors and acid gas recovery units' and H_2 turbines. These catalysts can be delivered without any lead times *and* they are widely applied, so even with an otherwise problematic exogenous demand and material availability the additional CCS demand. The future suppliers of hydrogen turbines are delivering large number of gas turbines (see *Section 5.2*) so similarly, even with an exogenous demand that would otherwise be problematic, supply constraints are logically not to be expected. With respect to insufficient performance only an insufficient resource mobilization has been found for H_2 turbines and advanced flue gas treatment for oxyfuel combustion. The are several gas turbine suppliers competing for the development of a H_2 turbine and even that they have developed it. Suppliers of the similar $deNO_x$ and $deSO_2$ systems are numerous, so if it possible to find a solution for the development of these physical resources the industry structure is suitable to find it.

For human resources an unfavorable knowledge infrastructure has been found in two cases: chemical engineers and specialized lawyers. For these professions education time is very long. However, the number of chemical engineers and lawyers graduated and yearly graduating allows for a such a number that there will be enough of these professionals (willing to) follow the lengthy educational paths. The risk of insufficient performance of human resources is not dependent on multiple dimensions, so an analysis additional to the assessment made in *Chapter 7* is superfluous.

The usefulness of the distinction between the quantitative dimensions (*exogenous demand* and *material availability*) and the qualitative dimension (*competition*) of the supply side has been shown by the supply constraint risk assessment for air separation units (*Section 6.3*). There is a quantitative limited resource mobilization for this CCS oxyfuel component. It becomes a supply constraint risk of insufficient production because of a limited exogenous demand. At the same time, the competition is limited because the air separation unit industry has consolidated. This consolidation is expected to result in improvements with respect to economies of scale, efficiency and with respect to the use of the membranes. The limited competition is clearly not unfavorable to the quantitatively limited resource mobilization which is supply constraint risk solely because of the exogenous demand. The distinction between quantitative and qualitative dimensions of the system structure has thus been useful. One other methodological result is that the specific resources that are found to form supply constraint risk give a very specific meaning to the function resource mobilization with respect to nonfinancial resources. This is illustrated by the differences that are, bottom-up, found between the different technology options.

All the components for which supply constraint risks are identified[1] have a combination of quantitatively limited resource mobilization and an unfavorable supply side. It is striking that all three selected post-combustion components form supply constraint risks. This is caused by a problematic *material availability* in two cases (deNO_x catalysts and absorption towers) and by a problematic exogenous demand in three cases (solvents, air separation units for oxyfuel combustion and compressors in China and India and the OECD countries). Most physical resources have sufficient qualitative resource mobilization. For only two of those (solvents and compressors) there is in addition a combination of qualitatively limited resource mobilization and an unfavorable supply side. The services (transport and storage) have sufficient qualitative resource mobilization, because the services are very similar to services in the oil and gas industry. A risk of insufficient production is only found for transport in China and India and the OECD countries, as there is a combination of a problematic *industry size* and *material availability*. Only one of the three human resources, petroleum engineers, investigated has a combination of an insufficient quantitative resource mobilization and an unfavorable knowledge infrastructure. For human resources there is no definition of some sort of 'unfavorable knowledge infrastructure' to rapidly resolve qualitatively limited resource mobilization. Therefore the qualitatively limited resource mobilization for chemical engineers and specialized lawyers directly results in a supply constraint risk of insufficient performance.

There are supply constraint risks for three post-combustion resources but not for pre-combustion or oxyfuel combustion resources. This shows that it useful to distinguish between the different technology substitutes. The assessment of the CCS TIS system function fulfillment as Van Alphen et al. (2010) has performed (2.8 out of 5 for resource mobilization) thus depends on the technology option, with a slightly higher resource mobilization for pre-combustion than for post- and oxyfuel combustion. Post- and oxyfuel combustion have a relatively low fulfillment of the system function resource mobilization. Pre-combustion has a relatively high fulfillment of the system function resource mobilization. Next to the current fulfillment of the system function resource mobilization the risk that further fulfillment will be slow differs per technology option. For post-combustions this risk is high. For

[1] deNO_x catalysts, absorption towers, solvents (all three post-combustion), air separation units for oxyfuel combustion and compressors (with the exception of OECD countries)

pre- and oxyfuel combustion this risk is low. In addition, post-combustion is regarded as the most mature option for CO_2 capture and consequently receives the most attention for implementation (the UK government has for example chosen to limit its 2010 funding competition to post-combustion bids only, Lund et al. 2010). This indicates that time is pressing to avoid that these post-combustion supply constraint *risks* become supply *constraints*. Human resources are needed for all technology options, and they pose supply constraints as Van Alphen et al. (2010) have already briefly indicated. Furthermore there are insufficient petroleum engineers and the available chemical engineers and lawyers seem not knowledgeable enough of CCS specifics to be able to perform well in these settings. As for CO_2 transport, supply constraints in occur as a risk of insufficient production (high risk for China and India). The competition for this service with the petroleum sector will be fierce for all world regions, because the petroleum industry is financially very strong.

In combination with the findings of *Chapter 5, Historical cases*, it can be deducted that the CCS deployment as it is proposed by the IEA scenario will be difficult. While there have been no combinations of limited resource mobilization and a corresponding unfavorable supply side or knowledge infrastructure for FGD or CCGT at take off, deployment has been well under the rate of the IEA CCS scenario. Even the impressive CCGT deployment in the period 2000-2005 is only half of that needed for the IEA CCS scenario.

9. Methodological and empirical conclusions

Innovation system theory with its description of system structure and system functions has methodologically proven useful for an assessment of supply constraint risks. This is inter alia because supply constraint risks depend on both the current fulfillment of the system function resource mobilization, and the possibility to ramp up this supply, described by the development of a system structure component. On the other hand the supply constraints assessment has concretized the meaning of the system function resource mobilization with respect to nonfinancial resources: the identification of more supply constraints for one of the capture methods and a specification of the nature (quantitative or qualitative) of the supply constraints. It has shown that within that a systematic assessment of (a part of) an innovation system leads to insights that are precise. This way of proceeding has showed the specific risks that have for human resources been described in more general terms and for physical resources not at all by the system function fulfillment assessment of Van Alphen et al. (2010). The five dimensions developed for physical resources and the four dimensions for human resources seem to be a complete and sufficient set of dimensions.

The research question was: *In what ways do industry wide supply constraints form a risk to the fast large scale deployment of carbon capture as and storage at the scale described by the IEA BLUE Map scenario 2008?*

Empirically, five components and three human resources form supply constraint risks for CCS deployment in the rate as described by the IEA scenario. In one case (compressors in China and India) there is even a high supply constraint risk. All components for which supply constraint risks are identified (see *Footnote 1, p.60* for the list) form a risk of insufficient production, and two also a risk of insufficient performance (solvents and compressors, worldwide). There are insufficient petroleum engineers and the available chemical engineers and lawyers seem not knowledgeable enough of CCS specifics to be able to perform well in this setting. For CO_2 transport, supply constraints occur only as a risk of insufficient production in China and India (high risk) and the OECD countries.

The historical cases of fast large scale deployment, flue gas desulfurization (FGD) and combined cycle gas turbines (CCGT), have not suffered supply constraints. Their maximum deployment rate is one third (FGD) and half (CCGT) of the maximum rate for CCS according to the IEA scenario. The total deployment is six times (FGD) and even four times (CCGT) less than the total CCS deployment. Taking into account that the deployment of the IEA scenario is more ambitious than the very successful historical cases of fast large scale deployment which have not been hampered by significant supply constraints, the found CCS supply constraints indicate that it is unlikely that the scenario deployment will become reality in this rate. Sufficient resource mobilization will become even more unlikely if post-combustion will be the dominant design.

10. Policy implications to avoid supply constraints

The identification of specific supply constraint risks makes it possible for firms and governments to take early action on specific dimensions of these industries of resources that form a supply constraint risk. These actions can increase the likeliness of a fast deployment, although it is unlikely that CCS will be deployed in the rate as described by the IEA scenario. In this chapter some examples of such action are described[1]. As is shown in *Figure 2-3*, system structure does not only influence system functions, but system functions equally influence system structure. An early detection of disadvantageous supply industry dimensions could help to foresee problems with large scale roll out of a new technology. Policy (see *Footnote 3*, *p. 2*) to fulfill the system function *resource mobilization* earlier could allow for a reinforcement of supply industry that is needed for large scale implementation. In this way the impact of supply constraints will be limited in the take-off phase.

10.1 Components and human resources

Wu et al. (2005) have elaborated on the possibility of capacity expansion: "in industries in which capital equipment cost is high" (p.126) the firm has to fix capacity size at the time of installation for the entire life time of the facility. The selected critical components are manufactured at production sites that need significant capital equipment investments (for example the molds used for the manufacturing of compressors). And in "a fast-growing global market, the conservative capacity-expansion policy leads to severe shortfalls in service levels" (ibid, p.127). For such firms an uncertainty of the continuity of demand is a problem. This results in restraint investing in enlargement of manufacturing capacity. It also applies to human resources, as for human resources there is significant time delay between high school students perceiving the idea of and prepare to subscribe to a specific university program (such as a CCS master) and functioning as for example a specialized chemical engineer.[2] Uncertainty of demand for human resources can thus also lead to supply constraints.

As demand for many other sustainable energy technologies, CCS demand is dependent on government policies. Analysis of the large scale implementation of flue gas desulfurization systems has shown that due to the radical introduction of stringent regulations and the postponement of the industry due to uncertainty about government policy continuity (due to inter alia changing governments), the installation has known large peaks (see for example *Figure 5-3.b* Germany) that are difficult to deal with for the supply industry. It is therefore important that *a.* regulations are introduced more gradually than was the case with FGDs in the first phase of EPA regulation in 1995 in the US and in the 1980s in Germany and *b.* the gradual introduction of regulation will not sort large effect if it does not explicitly describe a large timeframe[3]. The same accounts for government funding programs for CCS projects. Private investments in manufacturing capacity enlargement will only take place if a prognosis of future demand can be made. Then orders can be placed a long time in advance.

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[1] The individual resources that form supply constraint risks and the nature of their supply constraint risks are not referred here. These resources, the nature of the supply constraint risk (insufficient production and/or performance) and the causing dimensions can be found in *Chapter 8*.

[2] For CCS specific on the job training this can however only be obtained by an increase in CCS activities. This makes on the job training a lengthy and recurrent process.

[3] This is in correspondence with the results of Alkemade et al. (2007).

This way the buyers would share risk by taking partial liability for the built up capacity (Wu et al. 2005).

While regulations do not explicitly describe long timeframes yet, public-private partnerships[1] could enlarge production capacity and performance now to avoid long lead times in the future. This is currently practice for the supply of human resources. The CCS master of the University of Texas at Austin has for example received significant funds from a Texas utility company (Forward, 2011). Such a master could be useful to instruct the novelties of CCS to chemical engineers and specialized lawyers. As for petroleum engineers the supply constraint not about CCS specific novelty but about number of graduates, petroleum engineering studies could be brought more under the attention of high school students. Making it possible to study petroleum engineering in more universities could increase the number of graduates. One of the reasons that there is currently a low number of petroleum engineers in the Netherlands is that it can only be studied at one single university (i.e. Delft University; interview Prelicz, 2010). Similarly, to increase capacity for components, subsidies could be given for the construction of production sites (factories) for specific components, such as catalysts for $deNO_x$, absorption towers, solvents and air separation units. This would stimulate the activity of firms that are already in the industry to increase their production capacity. Furthermore it would stimulate other firms to step in the industry at an early point in CCS deployment. Next to reducing the risk of insufficient production, in this way the subsidy would counteract the risk of insufficient performance as the increase of the number of firms active in the industry increases competition. This indicates that time is pressing to avoid that these post-combustion supply constraint *risks* become supply *constraints*.

10.2 Transport and storage services

A transportation network needs to be constructed, but transport services form a supply constraint risk for the OECD countries and China/India. This includes the construction of large scale offshore pipelines, a process that can absorb a company's capacity for three years (interview Billingham, 2010). The transport services needed for CCS are more or less the same as the transport services currently used by the petroleum industry. This service industry can only ramp up its production with large capital investment, because it is inter alia dependent on the price of steel. Especially a capital intensive industry will often aim for a production capacity that is unable to meet peak demand, because unused production capacity during low conjecture is very expensive. Longer lead times at peak demand are accepted. As these industries are furthermore often used to markets that show conjectural trends, they will rarely increase production capacity on the basis of a short term demand increase (Wu et al. 2005).

Without competing with the oil and gas industry for the same services, CCS could make use of conjectural dynamics. Due to important exogenous demand growth in times of high oil prices and the capital intensity of the petroleum industry it might be difficult for an emerging CCS sector to assure physical and human resources. Deployment of CCS will be dependent on government regulation / funding and thus less dependent on the oil conjecture. In a liberalized energy market the rate of construction of new power plants will be coupled with the oil conjecture as experience. This effect can

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[1] Comparable to the public-private partnerships advised by Van Alphen et al. (2010) for general performance increase of the CCS innovation system.

be attenuated because retrofit will be an important share early on. The important conjectural ups and downs that are typical for the petroleum industry could be exploited by planning intensive CCS activity during conjectural downtime. The high number of current Canadian CCS projects reflects the ease of finding competent suppliers during a down time in the petroleum industry (interview Fife, 2010). This way oil and gas industry services can be incorporated in the supply component of the CCS innovation system structure without actually having to create many new services.[1]

10.3 Geographical distribution

At the absence of supply constraint risks (as was the case for FGD and CCGT) deployment seems to be dependent on the type of push factor. CCS deployment can be stimulated by either regulation (CO_2 emission restrictions) or financial incentives[2] (by CO_2 emission rights trade), or a combination of the two. The deployment projected by the BLUE Map scenario (*Figure 1-1*) sees a relatively short acceleration period, but it is with two decades (2010-2030) still more than double that of FGD. This implies a combination of regulation and financial push, which is also what is described in the Roadmap (IEA, 2009). In the light of FGD and notably CCGT deployment, it should be acknowledged that some countries will deploy first and consequently deal with most of supply risks, problematic dimensions and external factors. This has been the case with CCGT deployment in the US (compare *Figure 5-4.a* and *Figure 5-5.b*), that has dealt with gas turbine development as an external factor. Because markets are coupled, laggard countries will have less issues with supply constraints. This issue is partly touched upon in the Roadmap by distinguishing between OECD countries, non-OECD fist mover countries and remaining non-OECD countries (see *Appendix K*). However, it should be stressed that the moment of take-off has differed more at (especially) FGD deployment (see *Figure 5-5.a*) than is anticipated by the BLUE Map scenario (*Figure 1-1*). The scenario implies that as early as the 2020s *all* (that is, not regarding the country) new coal fired power plants should be built with a CO_2 capture (*Figure C-1.a*), which is a very ambitious goal. In addition, a significant part of power plants initially built without CCS should be retrofitted from the 2030s on (ibid). The deployment curves of FGD and CCGT show the need for an early adopter country (the US in the case of FGD and CCGT) that accepts a slow deployment and deal with supply constraints. Once a supply industry has been built-up and is mature, this helps to make fast take-off possible in other countries. This could similarly happen with CCS, either with an early adopter country or with an early adopter world region (such as American or European OECD). This has also been described by the IEA CCS Roadmap, but for financial and political reasons. The combination of the supply constraint risk conclusion with financial and political differences makes large geo-political differences of deployment speed likely.

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[1] The relation between a high oil price and a high comparative advantage of the new technology as has been pointed out for the new technology 'deep geothermal energy' by Mackaaij (2010) is relevant for many energy producing technologies. As Mackaaij has pointed out, this would stimulate the new technology most at the point where resources (such as drilling rigs) are scarcest. CCS does not necessarily have a higher comparative advantage at high oil prices, so using low oil price times to use redundant capacity of the oil and gas service industry is possible.

[2] It should be noted that financial incentives by CO_2 emissions trade are remain dependent on regulations to a certain extent.

11. Discussion

The class borders defining which value of a dimension should be determined as 'problematic' or 'very problematic' have been estimated by Ecofys experts. These class borders determine the classification of the dimensions the components, and consequently determine which component forms a supply constraint forms a risk and which component does not. The choice of these class borders influences the results of the research thus directly. So when industry experts are using these results, they should keep the chosen class borders in mind. They could have more fine grained knowledge of applicable class borders in their industry. A certain industry might have shown a higher (or lower) long term growth rate without any problems than the general class borders used in this research. It is important that also consultancy agencies and governments are interviewed. Their responses are probably less vulnerable to social desirability, which can occur if interviewees want to give a good impression (Baarda and De Goede, 2006). Industry/power sector representatives could be tempted to exaggerate the capacity expansion possibilities of their firm. Indeed their statements seem in general to be more optimistic than those of non-industry experts.

The value (and classification) of the dimensions *industry size* and *exogenous demand* of the components are in many cases based on expert estimations. The reason for this is that information about total market size or future demand is often subject of a complete separate study. These studies, if performed, have often be commissioned to strategic consultancy agencies and the results are not made public. In some of these cases the reports can be purchased at commercial prices. Market and demand estimates based on such studies would provide a more precise estimate of the value of the dimensions *industry size* and *exogenous demand*. *Exogenous demand* has been determined reliably for those resources that are only demanded by one or two sectors. However, if there is a large number of competing sectors a prognosis of an overall exogenous demand growth was difficult to give. Furthermore for some dimensions the value/classification has been difficult to determine, for example for absorption towers and deNO$_x$ catalysts exogenous demand. In these cases it has been mentioned in the text, for absorption towers and catalysts for deNO$_x$ systems there has been no indication that there will be a growth in exogenous demand. Either the confirmation that there is indeed no growth of exogenous demand (and the dimension is not problematic) or data supporting a classification as '(very) problematic' would increase the reliability of the results. Furthermore no only industry size and exogenous demand for physical resources and HR availability, exogenous demand and education could be assessed quantitatively. For example the physical resource dimension *material availability* could be assessed quantitatively by comparison of the need of a material per MtCO$_2$ CS and the quantity of the material worldwide, which can for example be found in (USGS, 2010). The dimensions of insufficient performance (engineering, competition and novelty) are by their nature not suitable for quantitative assessment.

For physical resources, the supply constraint risk of insufficient performance has less of a predictive value for the occurrence of a supply constraint of insufficient performance than the supply constraint risk of insufficient production has for the occurrence of a supply constraint risk of insufficient production. This is because solving technical innovation problems contains an inherent element of uncertainty, which cannot be totally governed by the supply side dimension *competition*. Within the theoretical assumption of the IEA Roadmap that the technology issues can be solved the speed of solving these issues could be well governed by the degree of competition, but obviously some engineering problems will prove harder to solve during the process notwithstanding the ideal degree of competition present.

The data that has been used in this research is in some cases indirect. If the needed variable has not been available for a world region, sometimes the size and growth of the natural gas market (if applicable) in the world region with respect to that of the US and Canada is used to extrapolate US data. While this gives some indication of the situation in other parts of the world, the accuracy of these conclusions obviously below an accuracy that could be obtained by direct data for other world regions. The availability of human resources differs per world region. The critical human resources are however so specialized, that it will be both difficult (because it is difficult to obtain data for highly specialized HR specified per world region) and of limited use (because such highly specialized HR will go where they are needed in the world) to assess their numbers per world region. Human resources are therefore to limited extent assessed with respect to different regions, i.e. only if there is a remarkable geographic distribution. Following the same reasoning the components of the different capture technologies are not assessed per world region, as most of the components are highly specific and components can be shipped to other world regions with greater ease then HR.

In this study it has been shown that there are in some cases combinations of dimensions present that render a supply ramp up difficult. However, actual deployment speed depends on more factors than dimensions of supply constraints alone. As has been pointed out in the research delineation in the introduction (see *Footnote 3, p.4*), deployment speed is not only a function of supply constraint risks, but also of stimulating factors. The historical comparison with FGD and CCGT deployment has taught that the nature of the push factors plays an important role in the appearance of the deployment curves (*Figure 5-5.a* and *b*). The governmental regulations that pushed deployment in the case of FGD have lead to a very different deployment curve than the economic push factors in the case of CCGT. This shows that an elaboration on the supply component of the innovation system structure and the resource mobilization system function cannot explain deployment speed on its own. All the components of the system structure and all seven system functions should be taken into account to do that. In view of the different potentials as used by Mackaaij (2010), such as technical and economic potentials, the current analysis is a *supply constraint potential*. Like the technical potential, this potential does not determine deployment alone, but it is one of the potentials that have to be superposed[1] to obtain a realistic deployment curve. It would be interesting to have an scientific estimate of all these potentials and superpose them.

It would be interesting and useful to apply the developed framework to assess the dimensions and supply constraints for specific resources of flue gas desulfurization systems and combined cycle gas turbines. In *Chapter 5* the focus for these industries has been on an aggregate level. This has shown the supply constraints on the assembly firm level. For CCS capture the focus has been on an upstream tier level (the availability of components), and a similar analysis of FGD would enhance comparability on the level of supply constraints. Furthermore the parallels between the transport infrastructure needed for CCS and that needed to fuel CCGTs could shed light on which problems to expect with the construction of such an infrastructure.

[1] Theoretical potential should be superposed with the technical constraints, and that potential should be superposed with economic constraints. Supply constraints are then placed between technical and economic constraints (Mackaaij, 2010).

The policy implication suggested with regard to effective use of oil and gas industry conjectures could be subject of further quantitative research. This could focus on the questions as ‘How much transport and storage services are unused during conjectural low times?’ or alternatively, ‘What are the price differences between conjectural high and low times?’ These questions could be addressed more than has been the case in the current research (for example with respect to the number of drilling rigs being brought back into service before any new are manufactured). The policy option of making use of conjectural low times is particularly interesting as it would not be practical to build large construction capacity until 2050, while it will be excessive for the period afterwards. This issue is not included by the delineation of the current research and has consequently not been treated. However, while it is important to realize a fast large scale deployment to limit temperature raise to 2.0-2.4 degrees Celsius by 2050, it might be questioned if the maximum deployment rate will be sustained after 2050. Would the deployment as described by the IEA scenario become reality, then there would be a very large production capacity in the supplying industries by 2050. It would be questionable if (but not necessarily impossible that) deployment would keep up the high rate. Especially gas fired and biomass fired power plants could be equipped after 2050, as according to the current scenario almost all coal fired power plants will be equipped with CCS. However, due to locally limited storage capacity CCS will need to be gradually phased out after 2050 (IEA, 2008). These are considerations that should be subject of further policy guideline reports such as scenarios. A realistic vision of the post-2050 era would, however unsure, be a stronger justification of the apparently significant efforts needed by inter alia the supplying industries.

A. APPENDIX References

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B. APPENDIX List of interviewees

Industry

Henk Bak	E.On	7th of December 2010
Bjørn Berger	Statoil	26th of October 2010
Andreas Brautsch	Alstom	24th of November 2010
Elvira Huizeling / Geir Rørtveit	Road2020 / Statoil	21st of September 2010
Frank Kluger	Alstom	8th of November 2010
John Midgley	BP	21st of September 2010
Ruth Prelicz	Shell	7th of December 2010
Jenny-Ann Nilsson	Vattenfal	9th of November 2010
George Koperna*	Advanced Resources International	22nd of September 2010

Consultants

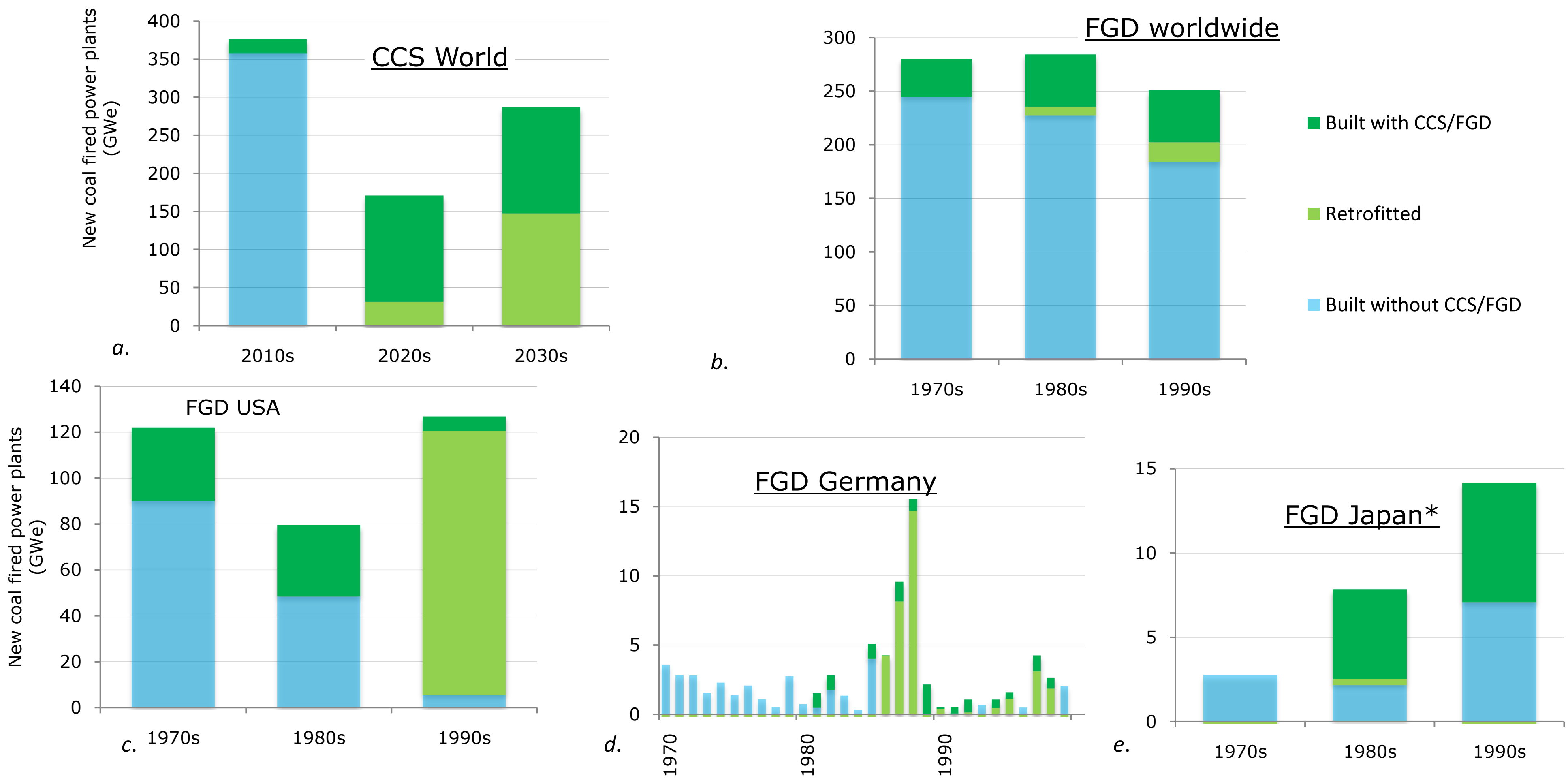
Mike Billingham	Intetech	28th of October 2010
Robert Burdock	Currently independent consultant, former Nuon Magnum	7th of December 2010
Calum Hughes	Yellow Wood Energy	27th of December 2010
Paul Noothout	Ecofys	21st of December 2010
Joris Koornneef*	Ecofys	September 2010 – April 2011
Chris Hendriks*	Ecofys	September 2010 – April 2011

Governmental organisations

David Fife	NRCan	27th of October 2010
Wina Graus	Utrecht University	3rd of January 2011
Filip Neele	TNO	7th of December 2010
Marc Wickham	NRCan	10th of November 2010

*personal communication, no formal interview

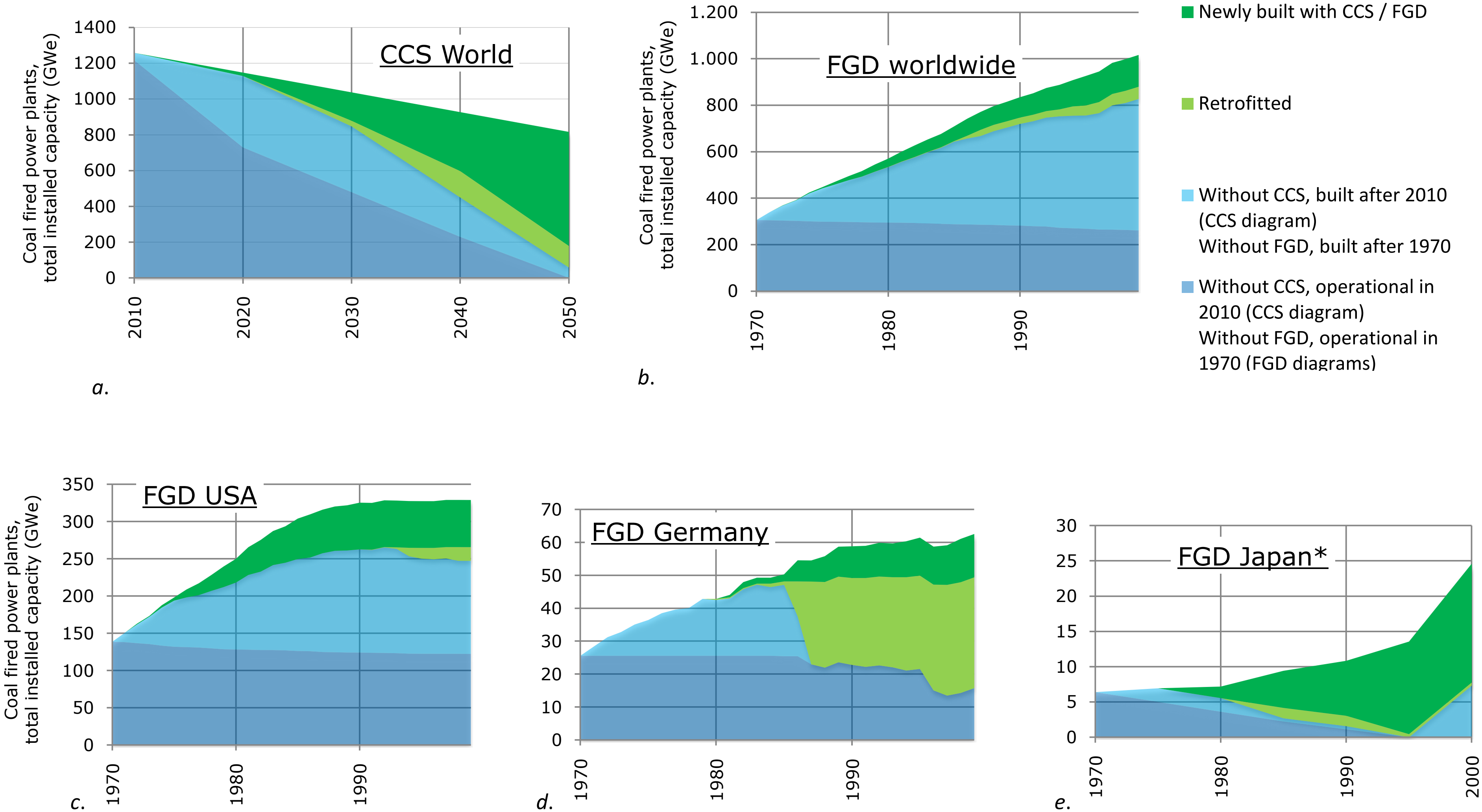
C. APPENDIX Flue gas desulfurization



C-1.a. CCS installed on coal fired power plants and new built coal fired power plants without CCS, per decade 2010-2040

b.c.d.e. FGD installed on coal fired power plants and new built coal fired power plants, per decade 1970-1999

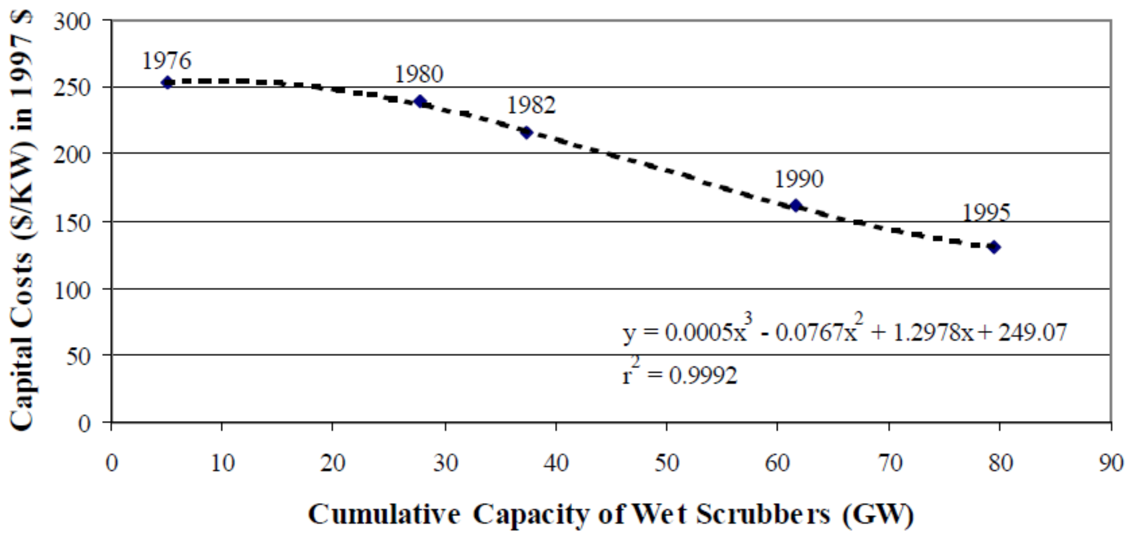
*Based on data extracted from IEA (2009) for CCS, Rubin et al. (2004) for FGD and Platts (2006) for coal fired power plants. Forecast modelled with IEA (2010) as described on page C—3. *The Japan diagram retofit is based on decade averages*



C-2.a. Coal fired power plant capacity 2010-2040

b.c.d.e. Coal fired power plant capacity 1970-1999

*Based on data extracted from IEA (2009) for CCS, Rubin et al. (2004) for FGD and Platts (2006) for coal fired power plants. Forecast modelled with IEA (2010) as described on page C—3. *The Japan diagram is based on decade averages.*



C-3 Learning curve of wet FGDs (Taylor, 2001)

Models

The FGD models are based on a combination of FGD deployment (Rubin, 2004) and the total coal-fired power plant capacity (Platts, 2006). The total coal fired power plant capacity increase for a year is expected to be equipped with FGD with the FGD capacity installed during that year according to Rubin. It is assumed that retrofit only appears when the total FGD capacity installed during a year exceeds the total coal fired power plant capacity during that year, because reliable data on the part that is retrofitted has not been found [1]. However, in reality retrofit will also have occurred when the total FGD increase in a year was smaller than the total coal fired capacity increase. As retrofit is more expensive than equipping a new built power plant[2], the model proposed can be regarded as reasonably reliable.

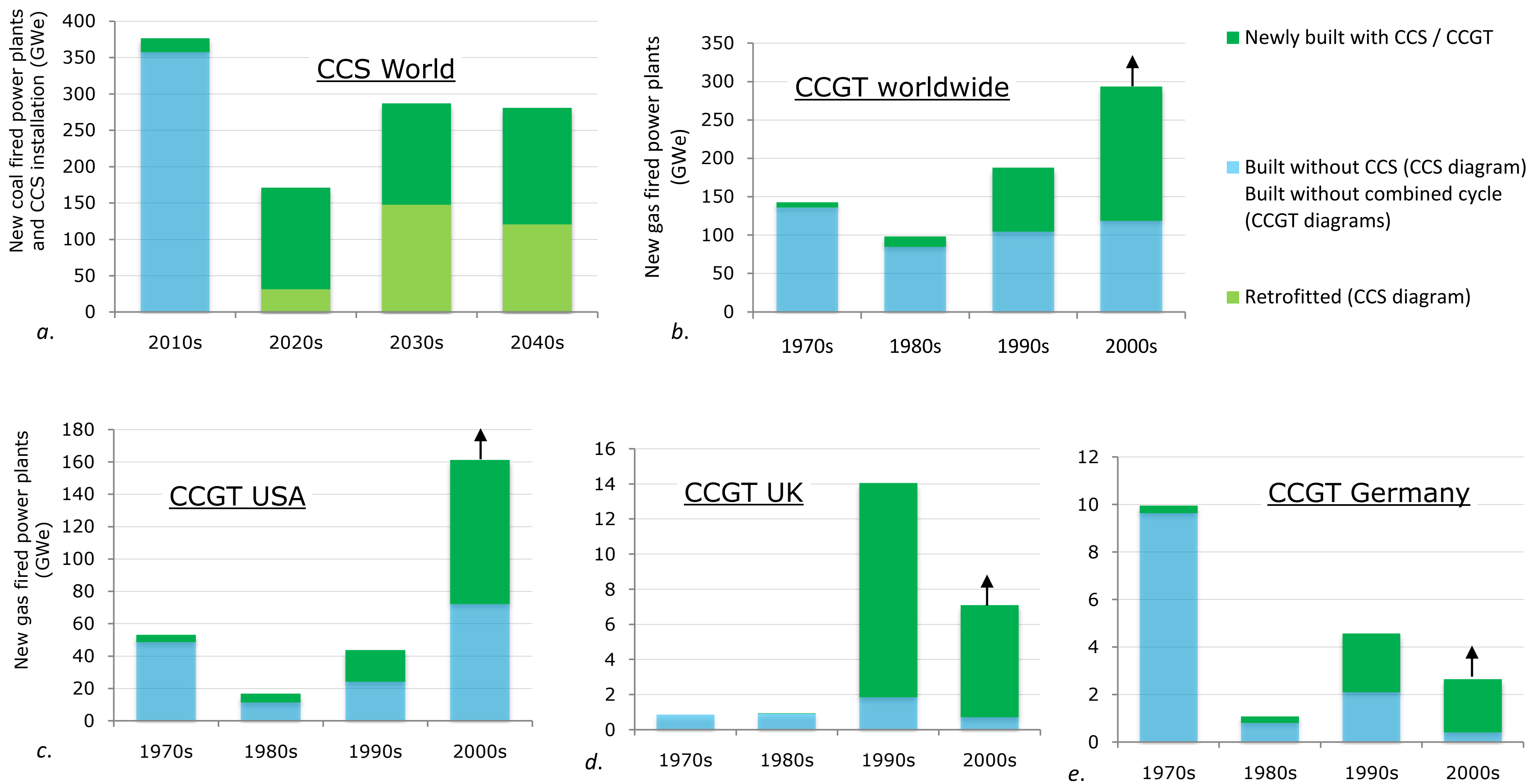
The CCS model assumes a life time of forty years on average for a new built coal fired power plant. Furthermore it is assumed that the new built power plants can be equipped with a CCS installation easier than an existing power plant can be equipped with CCS[2]. Therefore it is assumed that the goals described by the CCS Roadmap will only be achieved by retrofit when all new coal fired capacity (based on IEA, 2010) is equipped with CCS. In reality retrofit is likely to start before all new built coal fired power plants will be equipped with CCS installations, because it is unlikely that all new built coal fired power plants worldwide will be equipped with CCS at any point in time. Not forgetting these remarks, the model proposed gives a first order estimation of the power plant capacity until 2040/2050.

---

[1] Taylor (2001) provides data on number of retrofit FGD units. In this research, following Rubin (2004) the installed capacity is used as a basis to model deployment. Commercial scale deployment is key, and from the number of FGD units alone one cannot tell the size of power plant it has been fitted to.

[2] To compare this assumption with FGD retrofit: FGD retrofit was 25-30% more expensive during the 1970-1976 period (Ackerman and Hassler, 1981 referenced by Taylor, 2001).

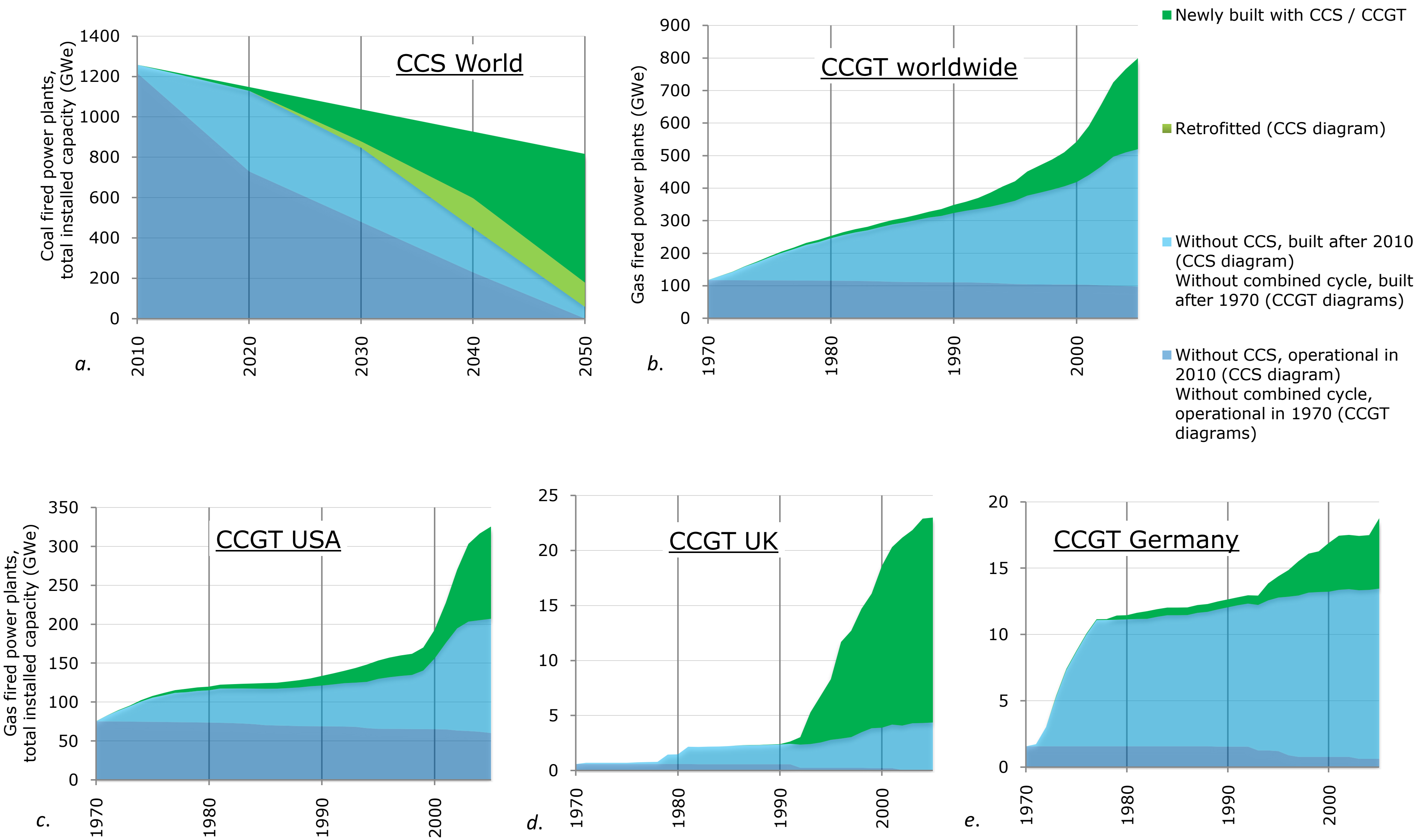
D. APPENDIX Combined cycle gas turbine



D-1a. CCS installed on coal fired power plants and new built coal fired power plants without CCS, per decade 2010-2050

b.c.d.e. CCGT installed and new built gas fired power plants without CCGT, per decade 1970-2005. The column '2000s' only contains data until 2005. The arrow indicates that the column should, if extrapolated for the whole decade consequently be doubled in height.

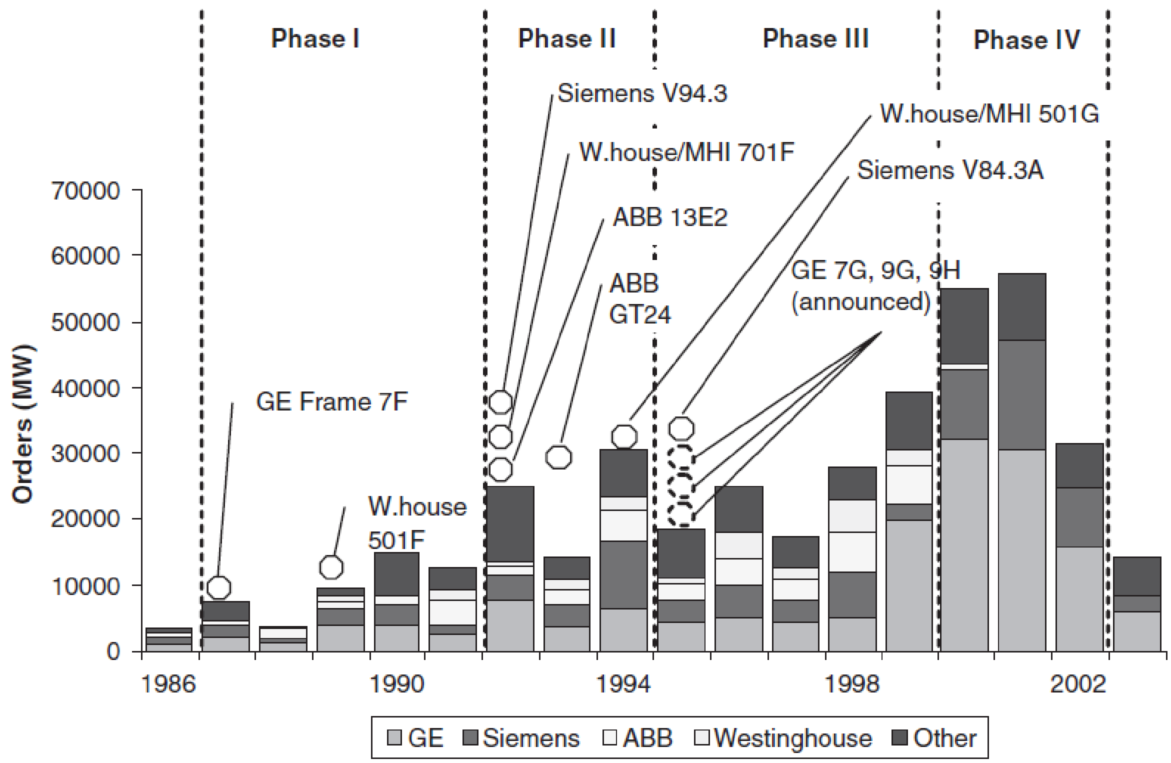
Based on data extracted from IEA (2009) for CCS and Platts (2006) for CCGT, OCGT and coal fired power plants. Forecast modelled with IEA (2010) as described in Section C-3.



D-2 a. Coal fired power plant capacity 2010-2040

b.c.d.e. Gas fired power plant capacity 1970-2005

Based on data extracted from IEA (2009) for CCS and Platts (2006) for CCGT, OCGT and coal fired power plants. Forecast modelled with IEA (2010) as described in Section 5.4.



D-3 CCGT market development, market share and product launches during 1986–2003. Source: Bergek et al. (2008)

E. APPENDIX Resource selection

Technology	Process step	Component
Post	$DeNo_x$	Catalysts for $deNo_x$
	Scrubber/absorber	Pumps for direct contact coolers
		Flue gas cooler
		Flue gas fan
		Amine pumps
		Absorption towers
		Heat exchangers
		Solvents (e.g amines)
		Membranes
	Stripper	Stripper
	other	Filters
Pre	ASU	Distillation column
		Heat exchanger
		Booster compressor
	Gasifier	Gasifier
		Feeding system
		Syngas filters
		Syngas cleaning with catalysts
	Acid Gas Recovery	Catalysts for acid gas recovery
	Sulphur recovery	Sulphur recovery unit
	Water Gas Shift	Syngas cleaning
		Shift reactor

	Conversion	H_2 turbine
Oxy	ASU	Distillation column
		Heat exchanger
		Booster compressor
	Combustion	Heat Recovery Steam Generator (superheater/heat exchangers)
		Boiler
		Acid condenser
		Steam turbines
		steam condenser
		Gas turbines
		burners/combustor
		Advanced flue gas cleaning for oxyfuel
Compression	CO_2 compressors	
	Heat exchangers	
	Dehydration	
	CO_2 pumps	

ASU: Element within the focus of this research

Source: Expert estimation (Hendriks and Koornneef, 2010)

Post-combustion

Catalysts for deNO$_x$ systems. In deNO$_x$ systems, NO_x is turned into nitrogen and water with catalysts.

Aborption towers / Solvents. In the absorption tower, the CO_2 is removed from the flue gas and absorbed by a solvent. The absorption tower is typically a large steel or concrete (?) vessel that contains packing material to allow for a large contact area between the flue gas and the solvent.

Pre-combustion

Air separation units. Air separation units are equally used for oxyfuel-combustion. See below.

Catalysts for acid gas recovery and water gas shift reactions. Catalysts are used in pre-combustion to recover SO_2 (acid gas recovery) to convert CO to H_2 and CO_2 in the water gas shift reactor.

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

Oxyfuel combustion

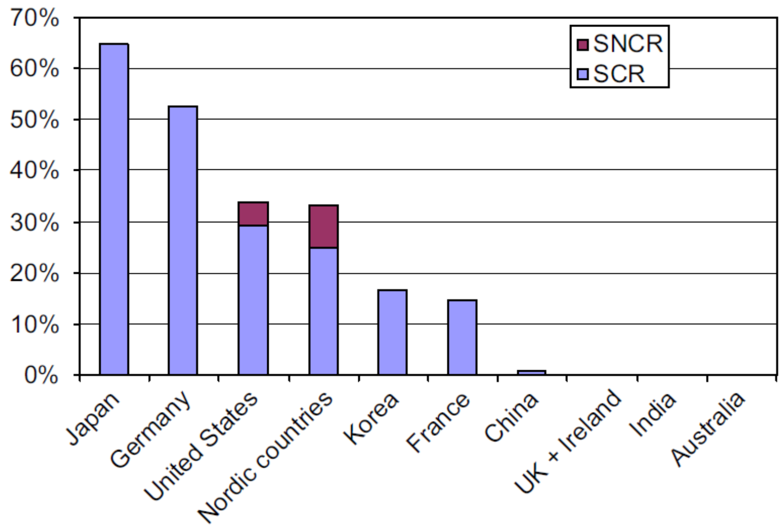
Air separation units. The first step in oxyfuel- and pre-combustion is producing an almost pure O_2 stream by separating air in a so-called 'Air Separation Unit' (ASU). The oxygen is subsequently led to a gasifier where it reacts with the fuel to form syngas.

Advanced flue gas treatment systems. The CO_2 stream produced by oxyfuel combustion contains (i.a.) NO_x and SO_2. An alternative to the application of a separate deNO$_x$ and desulfurization system, is to clean the raw CO_2 stream during compression by phase separation (partial liquefaction, White et al. 2010). This second option is designated 'advanced flue gas treatment' for oxyfuel combustion because it takes advantage of the particularities of the oxyfuel combustion CCS system to eliminate impurities.

Compression

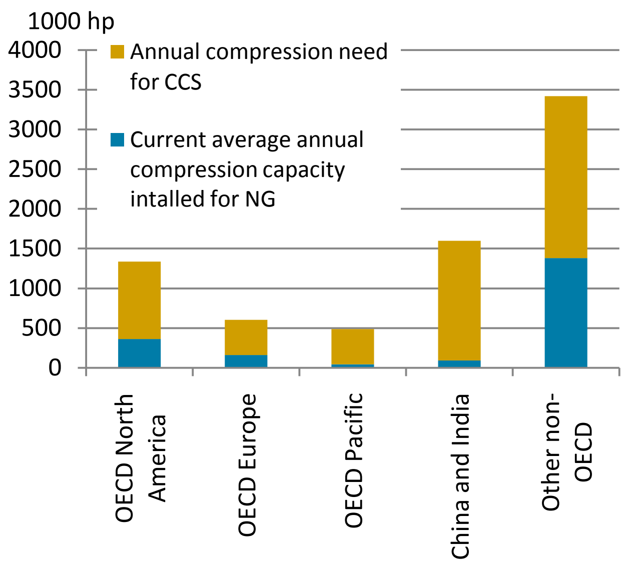
Compressors. After the separation of the CO_2 of the flue gas it has to be compressed by large scale compressors, because the needed pressure for CO_2 transport and storage to 150 bars (ICF, 2009a), or even more than 200 bars for offshore storage (interview Neele).

F. APPENDIX Components: capture

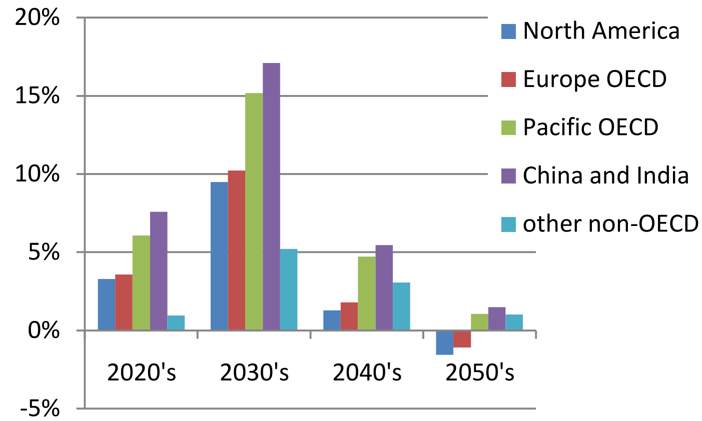


F-1 Flue gas treatment for NO_x emissions of coal-based power plants (Graus and Worrell, 2007)

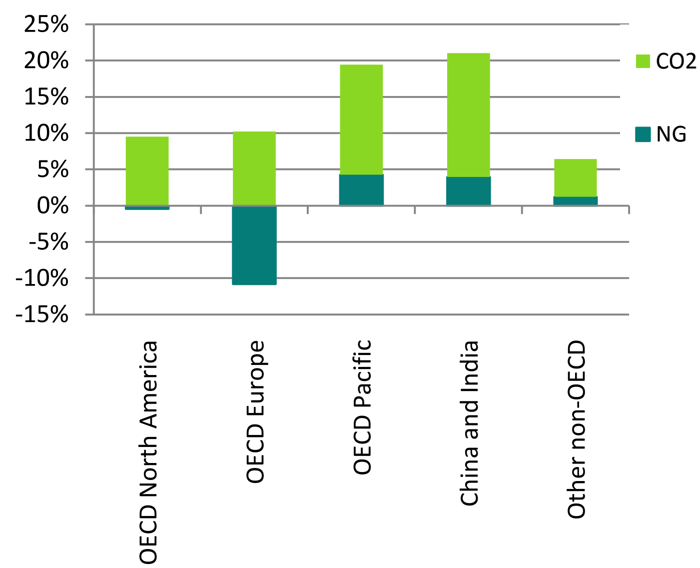
G. APPENDIX Components: compression



G-4 Compression industry size. Based on data from: IEA, 2006; IEA 2009; ICF, 2009b

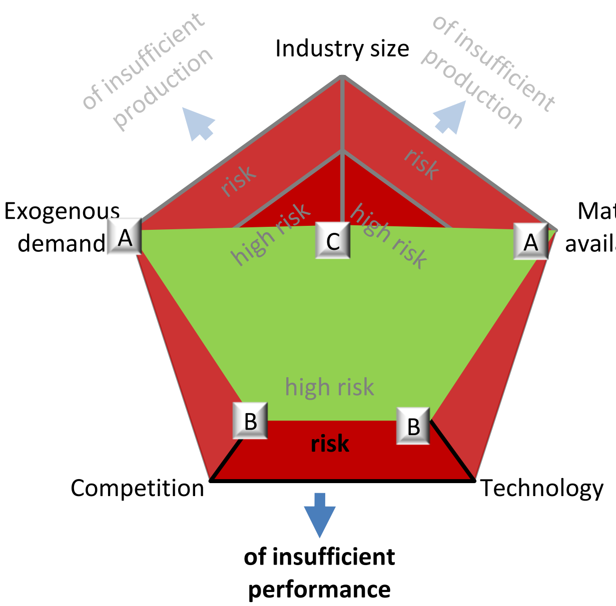


G-1 Compression annual industry growth. Based on data from: IEA, 2006; IEA 2009; ICF, 2009b

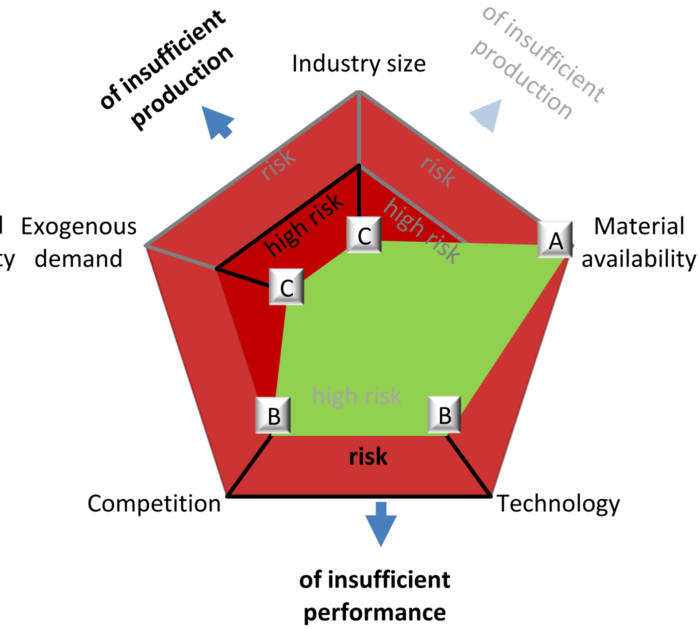


G-2 Compression annual exogenous demand growth Based on data from: IEA, 2006; IEA 2009; ICF, 2009b

Spider diagrams of compression dimensions and supply constraints by world region.



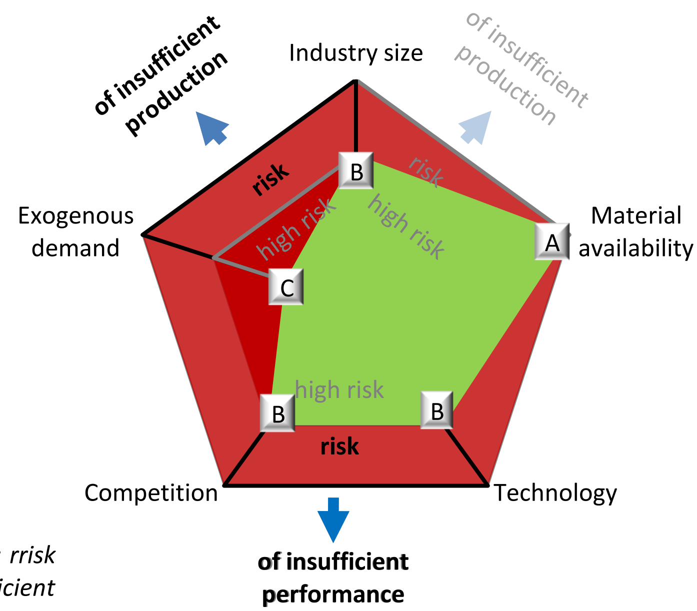
G-5 Compression OECD: risk of insufficient production and risk of insufficient performance



G-7 Compression China and India: high risk of insufficient production and risk of insufficient performance

Legend

- A not problematic
- B problematic
- C very problematic



G-6 Compression OECD other than China and India: rrisk of insufficient production and risk of insufficient performance

H. APPENDIX Human resources

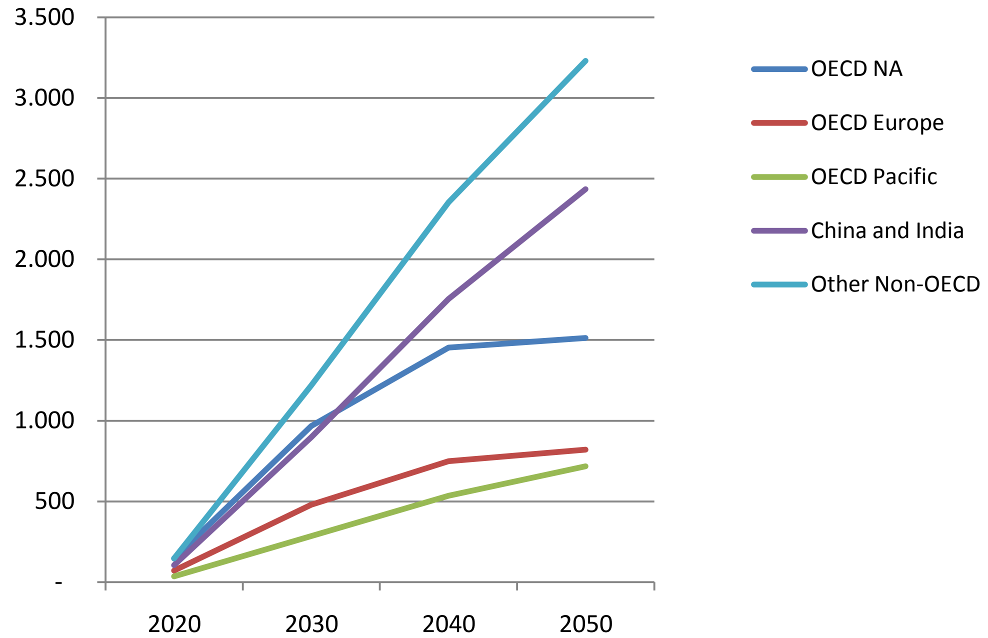
Application		Commercial-scale, minimum tonnes CO_2 per year	Proven Operating Scale, tonnes CO_2/year											
			CO_2 Capture Technology				Compression	Transportation		Storage				
			Pre-Combustion	Oxyfuel Combustion	Post-Combustion			Pipeline	Ship	On-Shore Saline	Off-Shore Saline	Oil/Gas Reservoir	Basalt	Coal Seam
Industrial	Oil & Gas Production	1,000,000	5,000,000[6]	75,000[19]			5,000,000[6]	5,000,000[6]		1,000,000[15]	1,000,000[16]	5,000,000[17]		
	Oil Refining	1,250,000[1]												
	Chemicals Production	100,000	750,000[7]		130,000[18]		250,000[7]							
	Biofuels Production	100,000				365,000[13]								
	Cement Production	750,000												
	Steelmaking	3,000,000												
	Coal Synfuels Production	3,000,000	25,000,000[8]				3,000,000[14]	3,000,000[14]				3,000,000[14]		
Power	Natural Gas	700,000[2]			100,000[11]									
	Coal	3,500,000[3]	35,000[9]	50,000[10]	300,000[12]		300,000[12]			50,000[10]		300,000[12]		
	Petroleum Coke	3,500,000[4]												
	Biomass	500,000[5]												

H-1 CCS Application Matrix GCCSI. Green: demonstrated at commercial-scale volumes. Yellow: sub-commercial scale operation has been demonstrated (McConnell et al. 2009)

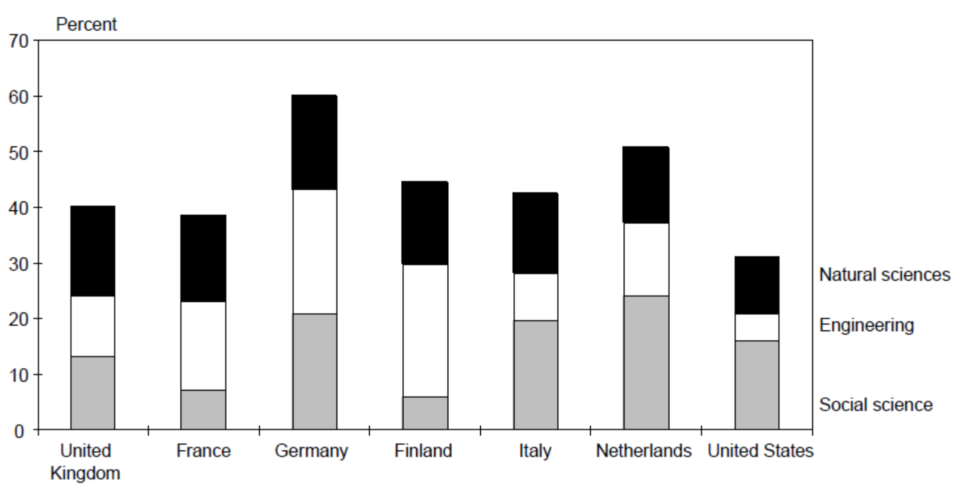
Table 3.18: Top 5 patent owners in cartbon capture sub-spaces

	Top Assignees	No. of patents
CARBON CAPTURE: ADSORBENT		
	Total	504
1	Air Products and Chemicals Inc	27
2	Praxair Technology Inc	21
2	Questair Technologies Inc	21
4	UOP Inc	14
5	BOC Group Inc	11
5	ExxonMobil	11
5	General Electric Co	10
CARBON CAPTURE: ABSORBENTS		
	Total	1,395
1	ExxonMobil*	78
2	ConocoPhillips	54
3	UOP Inc (Honeywell Subsidiary)	30
4	Air Products and Chemicals Inc	28
5	Praxair Technology Inc	22
CARBON CAPTURE: SOLVENTS		
	Total	568
1	ExxonMobil	32
2	BP	17
3	UOP Inc (Honeywell Subsidiary)	16
4	Marathon Oil Company	15
5	Shell	14
CARBON CAPTURE : MEMBRANES		
	Total	623
1	Air Products and Chemicals Inc	28
2	ExxonMobil	25
3	General Electric Co	16
4	Praxair Technology Inc	15
4	Shell Oil Company	15

H-2 Patents on capture technologies (Lee et al, 2009)



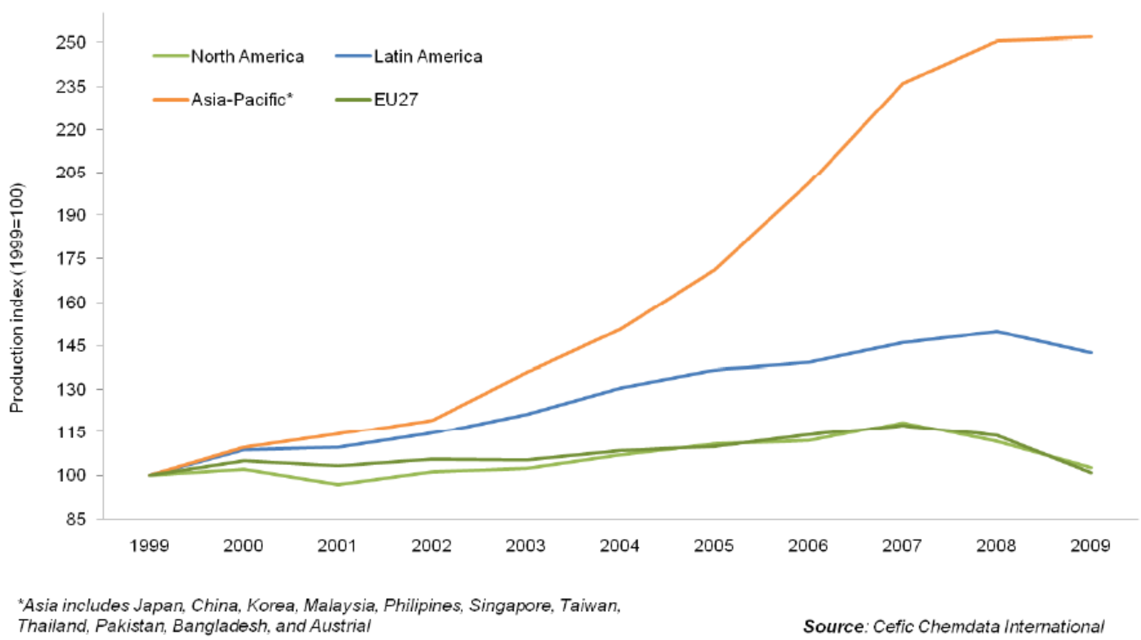
H-3 Number of chemical engineers for different world regions based on ten engineers during the construction of a capture installation (four years on average) and one during the operation of an installation. Number of capture installations taken from the IEA CCS Roadmap.



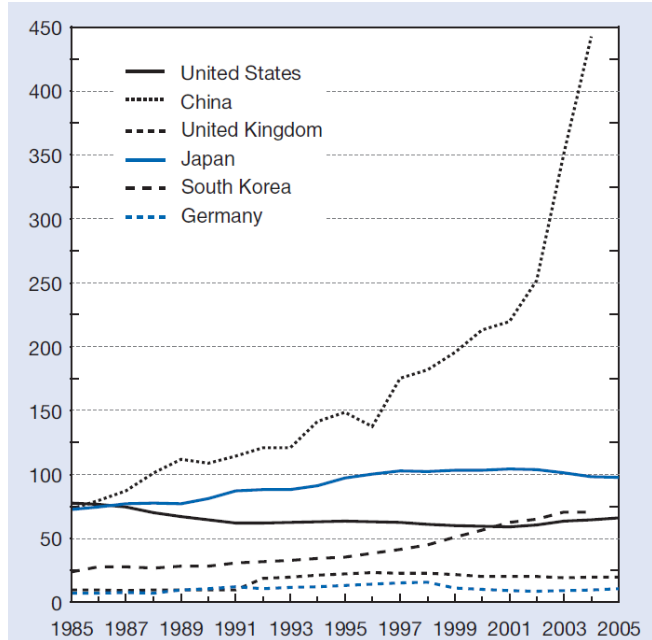
H-4 Percentage of science and engineering degrees among total first university degrees: the U.S. and Europe (Source: National Science Foundation, 1996)

H-5 Relevant legislation (Source: Interagency Task Force on Carbon Capture and Storage, 2010)

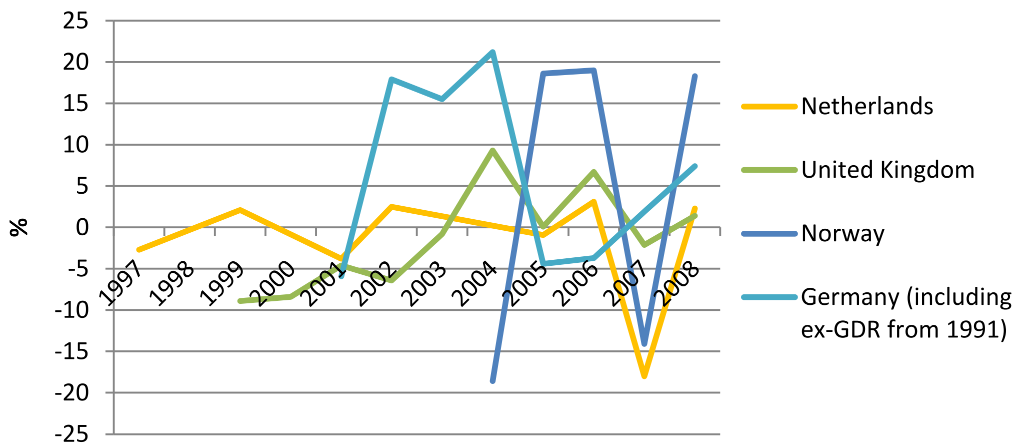
Primary	Safe Drinking Water Act
	Resource Conservation and Recovery Act
	Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)
	Emergence Planning and Community Right-To-Know Act
	Clean Air Act (low amounts of emissions of CO_2 at sequestration)
Secondary	Federal Water Pollution Control Act (with respect to offshore pipelines)
	National Environmental Policy Act
	Endangered Species Act
	Federal Land Policy and Management Act
	Mineral Leasing Act



H-6 International comparison of production growth of the chemical industry. (Cefic, 2010)

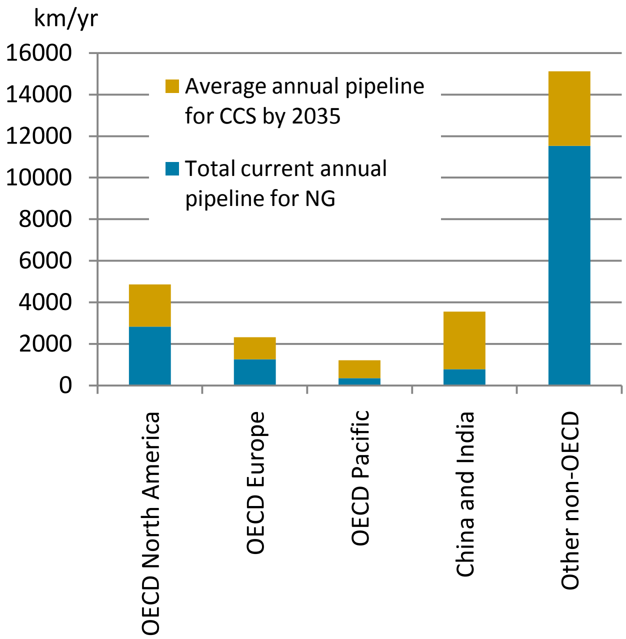


H-7 Number of university engineering degrees in thousands (Source: National Science Board, 2008)

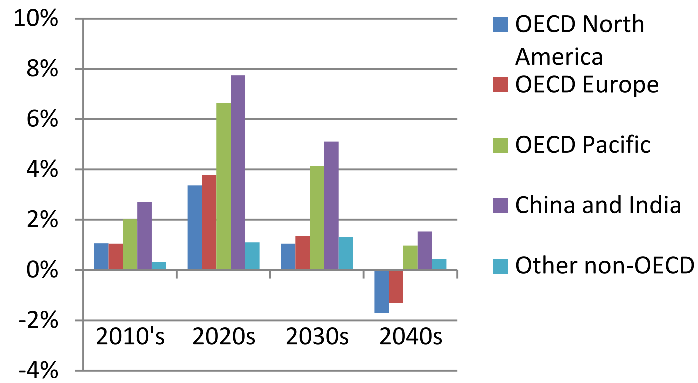


H-8 Growth rate of employment in the mining and quarrying sector in Europe (SME, based on Eurostat data)

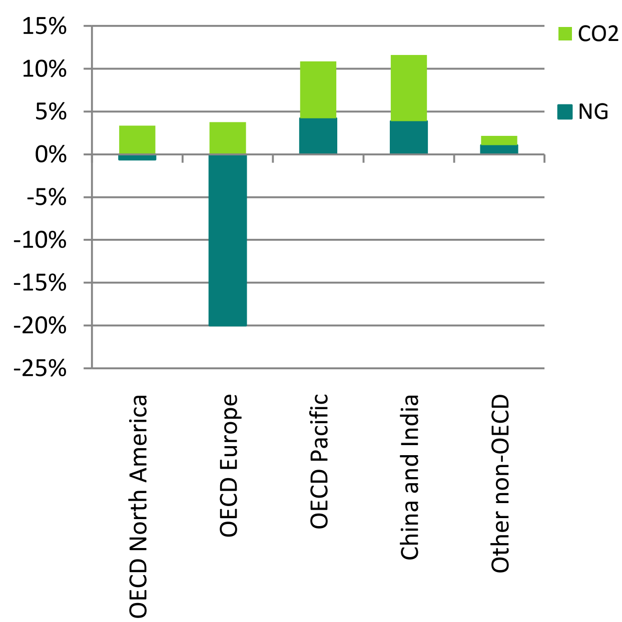
I. APPENDIX Transport



I-2 Transport industry size Based on data from: IEA, 2006; IEA, 2009; ICF, 2009b. By 2035 the pipeline construction for CCS will be close to maximum.



I-1 Needed annual industry growth. Based on data from: IEA, 2006; IEA, 2009; ICF, 2009b

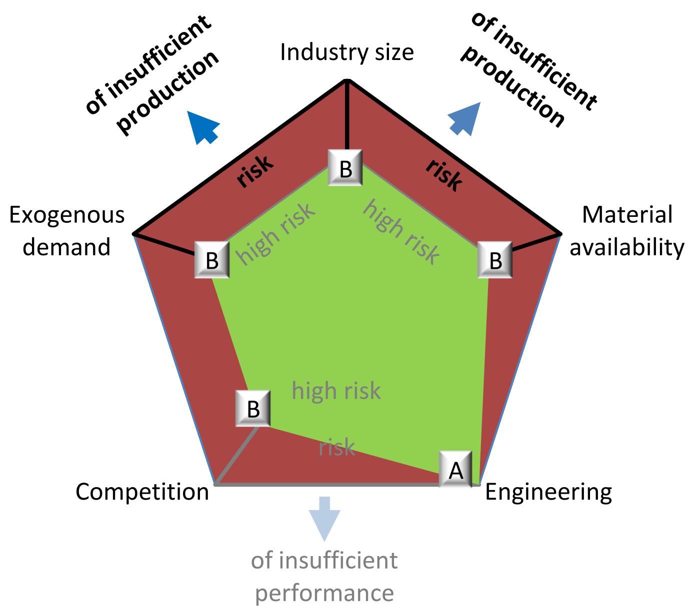


I-3 Transport annual exogenous demand growth by 2025-2030, because CO_2 production growth will be close to maximum then. Based on data from: IEA, 2006; IEA, 2009; IC, 2009b.

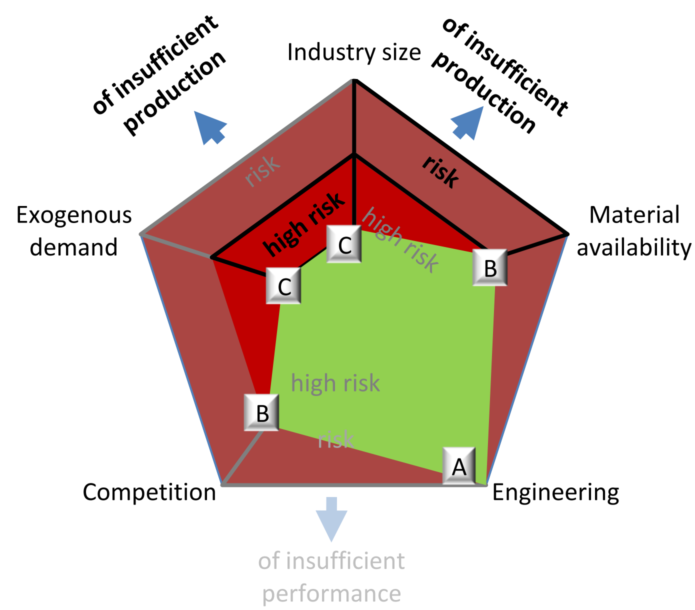
Models

Exogenous demand. There are significant differences in projected natural gas infrastructure investments in the IEA (2010) and the ICF (2009b) publications, differing from 18.4 billon $ for North America (IEA) and an estimate of 5.5 billion $ annual average for the US and Canada (ICF, 2009b, arctic projects excluded because of uncertainty of execution). Although it is unlikely that this large difference is because of the inclusion of Mexico in the IEA projections, it is likely to be due to the inclusion of natural gas distribution next to transmission. As already stated, in particular transmission of natural gas is an interesting comparison for the CO_2 case, as it is most likely that supply constraints occur for the construction of this part of the infrastructure. We are dependent on the IEA (2010) aggregate data (transmission, distribution taken together) for projections of natural gas infrastructure investments worldwide. Therefore a correction factor of 18.4 / 6 = *3.1* applied to correct for the inclusion of distribution in the IEA (2010) figures. 6 billion $ instead of 5.5 billion $ is used to correct for the inclusion of Mexico in the IEA figures. A very limited part of these annual 5.4 billion $ needed for US and Canada is needed because of an increase of natural gas production (0.25 billion $). 5.15 billion $ (INGAA low electric case) is annually needed to maintain a NG network of the size of that in the US This is needed to accommodate for major shifts in the location of NG supply. Direct replacement of NG pipeline is rare. The US and Canada have a projected NG production growth of 1.18 bcm, the conclusion can be drawn that about 212 million $ is needed per bcm increase of production. At the same time, the US and Canada have a NG production market of 750 bcm. Therefore 6.87 million $ is needed to maintain infrastructure for 1 bcm.

Spider diagrams of transport dimensions and supply constraints by world region.



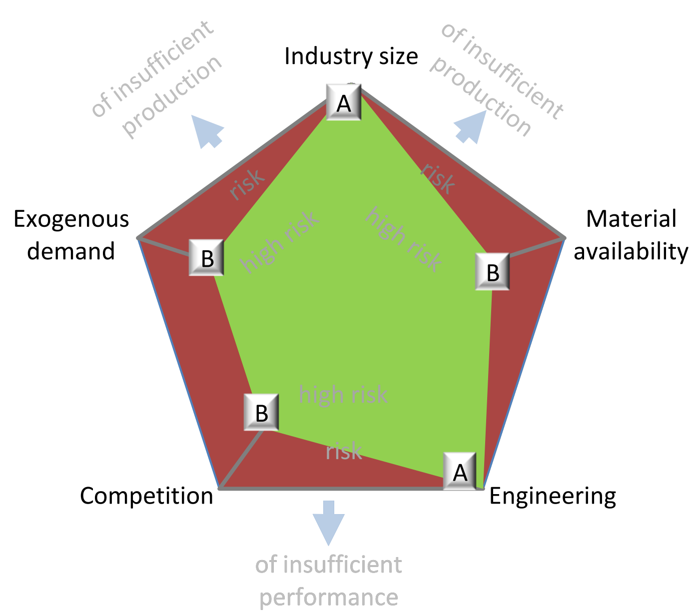
I-4 Transport OECD: risk of insufficient production



I-6 Transport China and India: risk of insufficient production

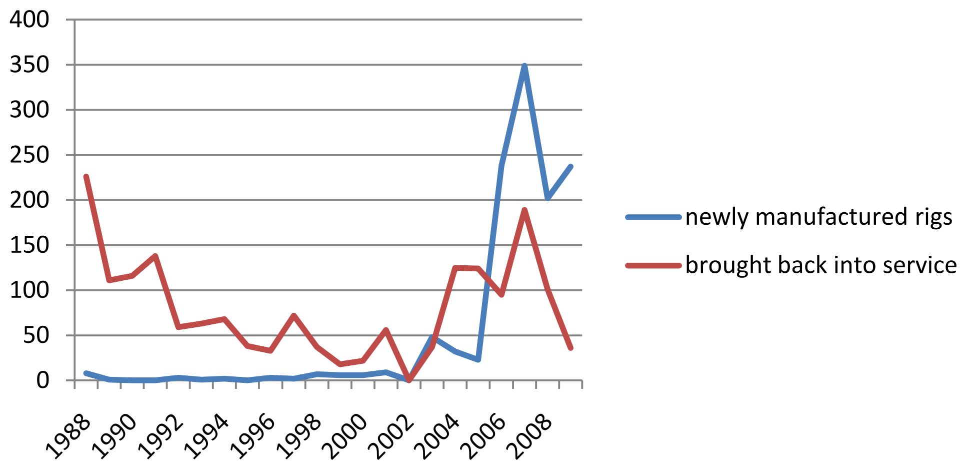
Legend

A not problematic
B problematic
C very problematic

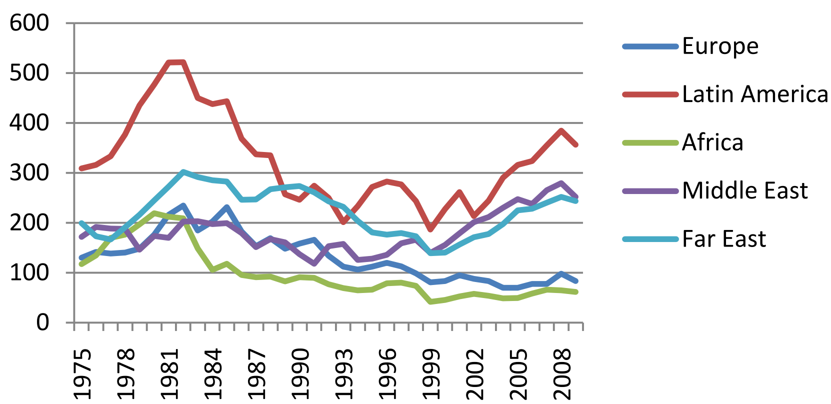


I-5 Transport non-OECD, other than China and India: low risk of supply constraints

J. APPENDIX Storage

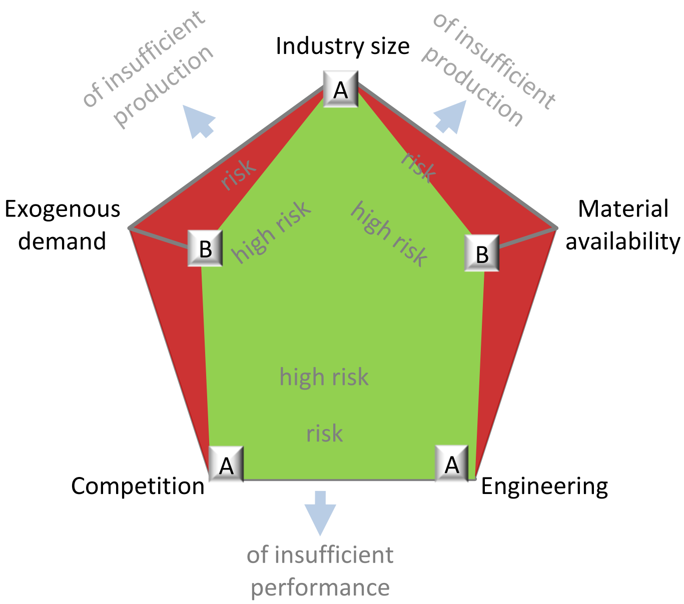


J-1Newly active rigs in the U.S. (based on data of Berkman and Stokes, 2009)

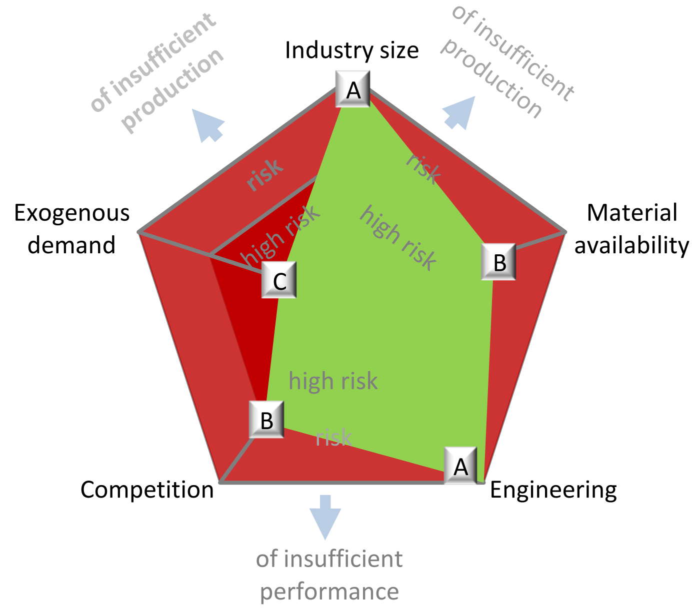


J-2 Number of non-U.S. active rigs (based on databases of Baker Hughes, 2010)

Spider diagrams of storage dimensions and supply constraints by world region.



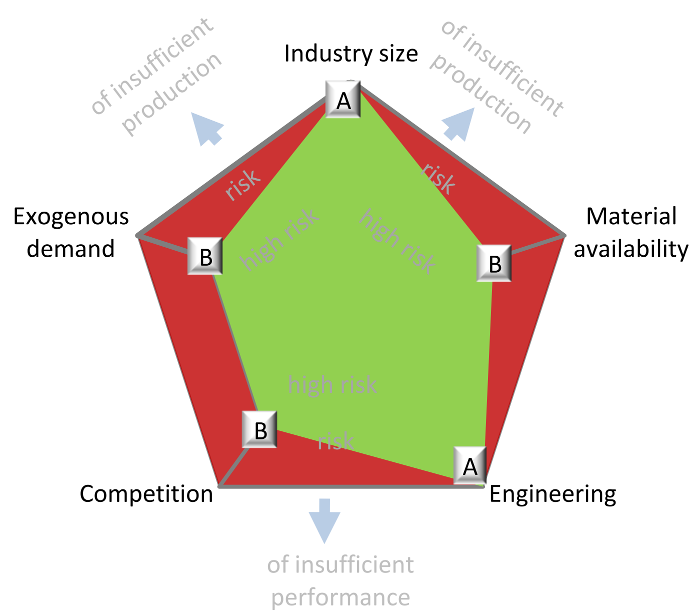
J-4 Storage OECD: low risk of supply constraints



J-3 Storage China and India: low risk of insufficient production

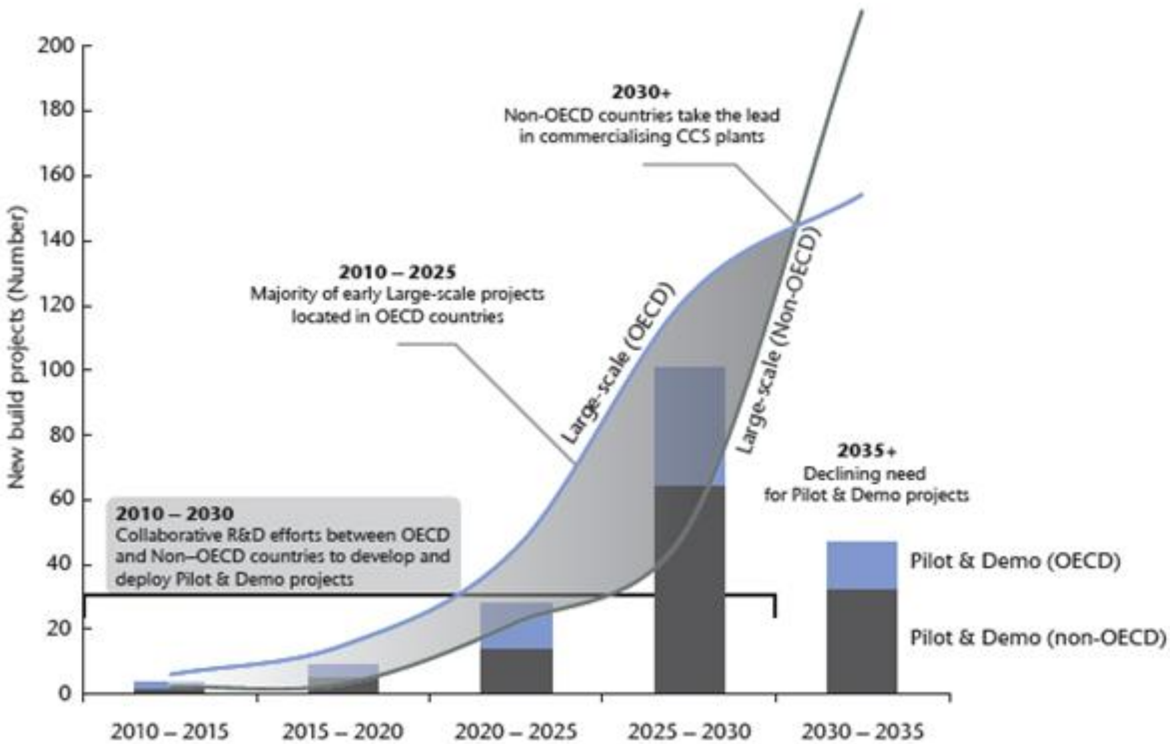
Legend

A not problematic
B problematic
C very problematic



J-5 Storage non-OECD, other than China and India: low risk of supply constraints

K. APPENDIX Policy Implications



Equation K-1 Geographical distribution deployment