



# THE DESIGN OF A REGULATORY FRAMEWORK FOR A CARBON DIOXIDE PIPELINE NETWORK

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## EXECUTIVE SUMMARY

A Carbon Capture and Storage (CCS) system provides the opportunity to maintain the use of fossil fuels without the harmful CO<sub>2</sub> emissions to the atmosphere. CO<sub>2</sub> is captured at the source and then transported to a CO<sub>2</sub> sink, where it is stored under ground; the emission of CO<sub>2</sub> to the atmosphere is avoided.

The most likely form of onshore transportation of CO<sub>2</sub> is by using a network of pipelines. This research connects the general characteristics of networked infrastructure to the case of onshore CO<sub>2</sub> networks. The discussion on liberalizing infrastructures, regulations on vertical integration and the issue of ownership of a network also play a role with CO<sub>2</sub> networks. The existing literature on CCS and regulation concentrates on the implementation of CCS systems: building the regulatory framework for planning and safety issues, and creating financial incentives such as feed-in tariffs. This research extends the need for regulation to economic regulation of a CO<sub>2</sub> network, which provides a critical step for the creation of a CO<sub>2</sub> market.

Infrastructures are systems that provide the physical connection for an economic transaction. This basic property makes the partners in a transaction dependent on the infrastructure. It is an essential facility, without it, there can be no transaction. Connected to this notion is the natural monopoly aspect of infrastructure. A natural monopoly is characterized by strong economies of scale. The costs of investment are so large, that it is an economic impossibility to have two natural monopolies next to each other. And once the initial investments are made, the costs of operation are relatively small.

The designs discussed in the research propose distinct solutions for the economic regulation based on the variation in three variables: ownership [public, hybrid, private], competition regulation [none, for the network, over the network] vertical integration [unbundled, no restriction].

The options of the design variable ***ownership*** range from complete private investment to complete public investment. Based on the research we recommend that the government participates in the investment for several reasons. First, the risks for private investment are considered too high. An important part of these risks is made up of the risk of future policy changes. Following the rule of allocating a risk to a party that can best manage that particular risk, it follows that the government should take that part of the investment risk. Secondly investment of public funds in the infrastructure signals a commitment to CCS by the government, and as such provides certainty for private investors in at the ends of the value chain to invest in capture and storage equipment. This would significantly contribute to solving the hold-up problem, currently blocking CCS related investments.

Another argument for (partly) public investment is argued by the public good inherent in a well functioning CCS system. Public goods provided by CCS are regional economic development and reduction of emissions, leading to the achievement of committed CO<sub>2</sub> reduction goals. Benefits in terms of these public values are not perceived by private companies, substantiating the need for the participation of a government. The contribution to economic development plays a role in industrial areas such as the port of Rotterdam. A CO<sub>2</sub> infrastructure connected to a storage site

will play a role in site selection procedures of large industries. By having a CO<sub>2</sub> network in place, the port can ensure the attraction of new industry without increasing its CO<sub>2</sub> emissions.

A final argument for government participation is related to the technical design of the pipeline. Costs of increasing pipeline capacity are small before it is constructed. When capacity needs to increase in the future this becomes much more expensive. The time horizon of private companies is not long enough to take these capacity growth issues into account. Coordination by a public authority of the design could justify higher upfront investments.

The design variable on ***vertical integration*** considers the participation of CO<sub>2</sub> capture or storage companies in the investment of the value chain. The research has considered two options: either vertical integration is allowed, or it is not allowed, meaning that capture or storage companies can not participate in the value chain. The effect of vertical integration is twofold. On the one hand, vertically integrated companies can efficiently coordinate the supply and demand of subsystems in the value chain. This would lead to cost reductions. On the other hand, vertically integrated companies can use their possession of the network to strengthen their position in other markets. They can exclude their competitors from the network, or charge high access prices. This trade-off is similar to the trade-off present in the unbundling discussion in other infrastructure sectors such as electricity and gas. The natural monopoly elements of the network have been separated from the competitive elements of the network. A similar line of reasoning can be followed for CO<sub>2</sub> infrastructures. This leads to the recommendation of disallowing any control by parties who are significantly active in CO<sub>2</sub> emission or CO<sub>2</sub> storage over the management and operation of the network.

The options of the design variable on ***competition regulation*** are based on literature by the World Bank on this topic and include competition *for* the network and competition *over* the network. Competition *for* the network refers to a system of tenders and concessions. Competition is created between contestants who want to operate the infrastructure for a specific period of time. Competition *over* the network refers to a system where a monopolist delivers the monopoly service against regulated prices. The competition is created between the elements in the value chain positioned on either side of the network. Competition *for* the network offers the possibility to separate ownership and operation of the network. When public investments are concerned this is an advantage as companies can be attracted who can manage the network at the lowest costs. Competition *over* the network offers the possibility for controlling the network prices while allowing vertical integration. Based on the findings of this research we recommend a system with competition *for* the network, as it offers the owners of the network to redefine the terms of the concession between concession periods.

A final recommendation is aimed at the inclusion of storage parties in the ETS. If the storage parties are the ones receiving the benefits, they are the ones that employ the service of a transportation company and engage in contracts with capture plants. In this way, the product flows in the opposite direction of the monetary flow. This leads to a more balanced incentive structure of the CO<sub>2</sub> market.

## PREFACE

The report here before you is the end product of my education at the TU Delft. I started my studies in 1999 at the faculty of Aerospace Engineering. Although interesting engineering courses on a wide array of subjects kept me very busy, my interest in the courses dwindled, and I started looking for courses with more connection to problems with a more clear relevance to society. The realization that my true interests lay outside 'hardcore' engineering led me to look for a completely new direction in my education. In 2001 I started taking courses at the Faculty of Social Sciences at Leiden University at the section Political Science (Politologie). The experience of studying at a different university gave me a different view on what I wanted to do in life. I find problems with a clear impact on society are far more interesting than solving engineering puzzles. Although again the courses were very interesting I still missed something. The idea of identifying and solving a problem were not present in Political Science as taught in Leiden. Proposing a solution to a problem is a political statement. And political science is about analyzing statements of others, not making them yourself. After another 'switch' the quest for the education that fits my interests and personal goals in life came to an end at the faculty of Technology, Policy and Management. Here I can use engineering skills, combined with economic insights, and knowledge of organizations, to study complex problems with a great societal value.

The changes made in the current version with respect to the previous are summarized in Appendix F *Record of Changes from Green Light version*.

The Scientific Paper is added before the start of the Appendices, fitted between two blue pages.

I have performed the research for my master's thesis with great pleasure. There has not been one day during this research on which I have been reluctant to start working. The stimulating atmosphere at both Ecofys and Energy & Industry has had their effect. It has been a rewarding experience to work in such a friendly, intellectual, fun and interesting environment. For this I want to thank all my colleagues (although not technically colleagues, it truly feels like that) with whom I spent so much time discussing my own and their subjects. My thanks go out to Rogier, Erika, Marielle, Saskia, Jasper, David and Monique at Ecofys; and Jeroen, Michiel, Sharad, Jeroen, Emile, Petra, Ivo, Paulien, Hanneke, Zofia, Monica, Leslie, Catherine, Rob, Anish, Austin and Jean-François at TPM; and colleague students David, Kenneth and Catherine for the discussions as on our thesis subjects. Also, the organizing skills of Connie, Angelique and Rachel have made it possible to arrange meetings and plan rooms. Especially the work, advice and support from my supervisory committee have been a great enabler of my report. I want to sincerely thank them, Laurens, Chris, Aad and Margot, thanks for a great experience. Finally Meis can not go unthanked for supporting me outside and during office hours, and for just simply being great.

Diederik Apotheker

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# 1 INTRODUCTION

For clarity the research objectives, the research context and research methods are outlined below. This chapter will develop the ideas in further detail.

## ***What is this research about?***

The design of a regulatory framework for a CO<sub>2</sub> pipeline network in the port of Rotterdam

Objectives:

- design a regulatory framework for CO<sub>2</sub> pipeline networks
- further develop a design methodology for institutional design

The research will result in:

- conclusions on the performance criteria and design options for a regulatory framework
- recommendations for policy makers concerned with designing a regulatory framework
- recommendations for further research to find answers to remaining questions, necessary for designing a regulatory framework in reality

And the research will provide:

- a contribution to the discussion on institutional design

## ***Why is this research done?***

A pipeline network is a natural monopoly with network characteristics. For efficient operation of the entire CCS system understanding the institutional economic forces of the infrastructure and drafting regulations to control these forces is crucial.

The current ideas of a regulatory framework in a CCS system aim mainly at safety and leakage control or compensation of the costs. The economic aspects of a network infrastructure are not considered. To be successful in implementing a CCS system, it is important to consider both technology and institutions involved in a networked infrastructure.

## ***How is this research carried out?***

The research is divided in three phases. **Phase I Analysis:** based on desk research of scientific publications, policy and industry documents and based on the a series of interviews held with representatives of stakeholders. **Phase II Design:** the design exercise gives direction to the analysis and develops a perspective on possible solutions. **Phase III Evaluation:** the final chapters provide the answers to the questions posed at the outset of the research. It provides concrete recommendations for the regulatory framework for a CO<sub>2</sub> pipeline, and it provides a substantiated contribution to the discussion on institutional design.

## 1.1 RESEARCH PROJECT

The research project is the final assignment in the Master program of Systems Engineering, Policy Analysis and Management. The research is performed as an internship at Ecofys, a consultancy firm which focuses on sustainable energy policy. My research project is part of

Ecofys' contribution to the CATO research program. The CATO (CO<sub>2</sub>-Afvang-Transport-en-Opslag) program is led by the Utrecht Centre for Energy Research and is supported by a 'strong consortium of companies, research institutes and universities' (CATO, 2007). Ecofys is one of the participants in work package 1: systems and transitions. This work package aims to develop a system wide strategy for large scale clean fossil fuel systems. A focus is to propose policy and implementation strategies, in close cooperation with the stakeholders (CATO, 2007).

The technology of choice for onshore CO<sub>2</sub> transport infrastructure is a pipeline network (Svensson, Odenberger, Johnsson, & Strömberg, 2004). Such an infrastructure has certain aspects causing complexities in the design of regulations, most importantly the natural monopoly character of a pipeline network. This and other aspects substantiating the need for a regulatory framework will be confirmed by the analysis of chapter 2. Nonetheless it is crucial to state them here to describe the context of the research project:

- The implementation of a CO<sub>2</sub> pipeline network requires considerable irreversible investments. In other words: there are high sunk costs, or the assets are highly specific.
- Many parties, both private and public, are involved in the design, planning, construction and operation of the CO<sub>2</sub> pipeline network.
- Due to uncertainties in technology, economics and policy, it is not possible to draft complete contracts between participants in the value chain. A complete contract refers to a contract in which all possible futures fixed.
- A pipeline network is both a regulated natural monopoly and an economic natural monopoly. There are severe economies of scale making it uneconomical to build two parallel infrastructures. And, in some regions, it is not allowed to have two parallel pipelines transporting the same substance. The port of Rotterdam is one of those areas.
- The implementation of a CCS value chain involves the general public interest, such as economic development and CO<sub>2</sub> emission reduction, that apart from private interest public interest concerns play a role, justifying public involvement in the system.

The aspects indicate that a separate design of technology and institutions is not possible. Finger, Groenewegen and Künneke (2005) have argued convincingly that infrastructure sectors agreeing with the above conditions need to have a simultaneous design of technology and institutions. In other words, a CCS system cannot function when the design of the organization does not take into account both technology and institutions. As I will explain in the following section, the organization of an infrastructure system is determined by the regulatory framework wherein it is placed. The objective is twofold:

### **Research Objective**

To design a regulatory framework for a CO<sub>2</sub> infrastructure network for the Netherlands

To propose a design method for the design for a regulatory framework

The design of such an institution is a complex exercise. The scientific literature on institutional design is mainly descriptive rather than prescriptive (Klijn & Koppenjan, 2006), so there is no clear model available on how to design such a framework. Analyses of regulations and governance have generated an extensive list of requirements which a coordinative model needs to contain. Therefore this research is not only a quest for an effective and efficient regulatory framework; it is also an exploration of a design method.

For the design I use a typical design progression which has in the past been applied to design systems used by many actors with conflicting requirements (Herder & Stikkelman, 2004). Although the design approach is not completely free of criticism, it can be applied to the design of regulatory frameworks (Knops, de Vries, & Hakvoort, 2005; Koppenjan & Groenewegen, 2005). I will discuss the issue of institutional design in the next section, following the presentation of my research question.

The research question related to both research objectives is:

### Research Question

What regulatory design leads to an effective and efficient regulatory framework for a CO<sub>2</sub> pipeline network?

A set of sub-questions support the research question. Each supporting research question addresses aspects of the main question. The questions correspond to a building block in Figure 1, and to a chapter or subsection further in the report. Before addressing the sub questions, we first present the design approach.

Figure 1 represents the applied design approach in building blocks. The approach is an adaptation from the original model, developed by Herder & Stikkelman to design a methanol plant (2004). In the original version of the model, the design is placed along the line between the nodes *design space analysis* and *execute test*.

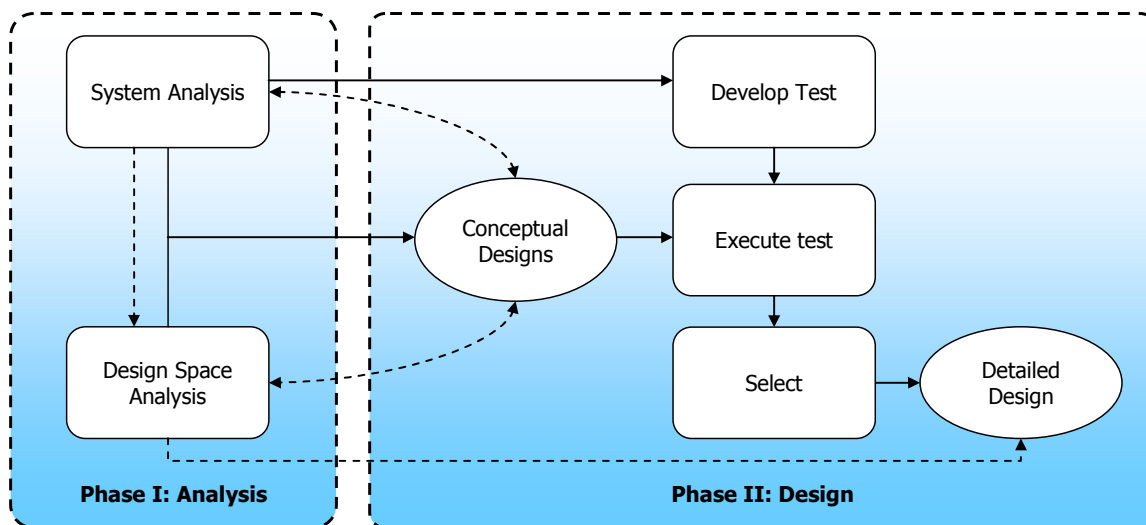


Figure 1: Build up of the research project (adapted from Herder & Stikkelman, 2004)

To provide direction for the analysis of the design space, findings from the system analysis are used, and the design exercise of the conceptual designs provides an input for direction of both the system analysis and the design space analysis. The design process will be discussed in section 1.1.1. Each building block has its own set of research questions.

### ***Research Questions***

The following research questions correspond to the building blocks of Figure 1.

What are the characteristics of a pipeline network in a Carbon Capture and Storage (CCS) system which cause the need for the design of regulatory framework?

System Analysis

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with the concerned companies.

**Result:**

List of requirements posed by technology  
Direction for research of solution space

**Sections: 1.2, 2.1, 2.3**

What are the requirements on the design of a regulatory framework for a CO<sub>2</sub> pipeline network from the perspective of:

- Technology;
- Stakeholders, and;
- Institutions?

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

**Result:**

List of requirements from technology, stakeholders and institutions.

**Sections: 2.1, 2.2, 2.3**

What are performance criteria for an effective and efficient Carbon Capture and Storage system from the perspective of:

- Technology;
- Stakeholders, and;
- Institutions?

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

**Result:**

Set of Performance criteria concerning effectiveness and efficiency

**Sections: 2.1, 2.2, 2.3**

What are the design variables for a regulatory framework?

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

**Result:**

A set of design variables spanning a design space with a range

**Sections: 2.1, 2.2, 2.3, chapter 3**

Design Space Analysis

What are the primary and secondary design decisions for a regulatory framework?

**Method:**

Literature research, use of the Structure-Conduct-Performance paradigm

**Result:**

A set of primary and secondary design variables

**Sections: chapter 3**

How can the primary design variables be combined to produce concrete design options for a regulatory framework?

**Method:**

Analysis of the primary design variables

**Result:**

Insight in the possible conceptual designs, and three detailed descriptions of the conceptual designs

**Sections: chapter 4**

Conceptual Designs

Which of the conceptual designs generates the most promising results and is selected for detailed analysis?

**Method:**

Multi Criteria Analysis

**Result:**

Insight in the performance of the conceptual designs and, an input for the detailed design exercise

**Sections: chapter 4**

Develop Test

Execute test

Select

What can be solutions to the issues of the detailed design?

**Method:**

Usage of the insights from phase I and the conceptual designs to propose solutions for detailed design issues

**Result:**

Detailed Design

Recommendations for solving the issues of the detailed design

Now we first turn to the further definition of the methodology and provide some definitions of central concepts in this research.

### **1.1.1 Institutional Design & Methodology**

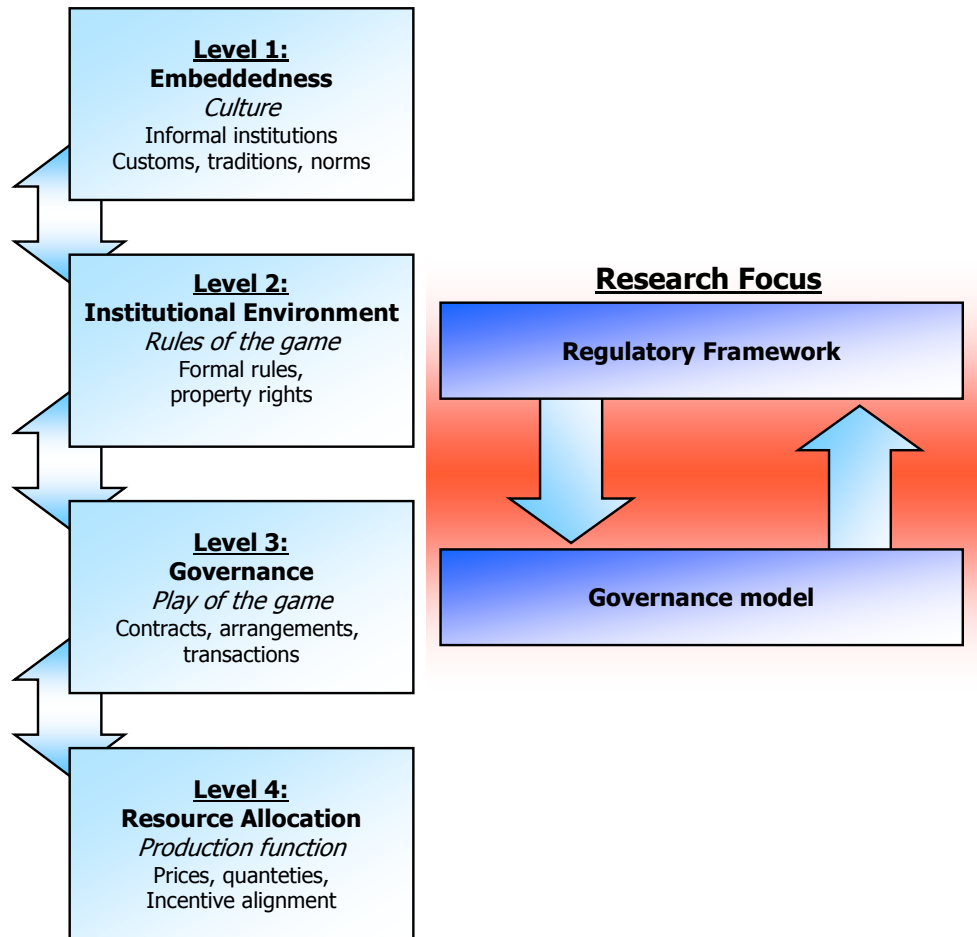
To speak of institutional or regulatory design does not go without a discussion on the possibility of designing institutions in the first place. Is the origin of a particular institution the result of a design process, or do institutions emerge? Those embracing the idea of emerging institutions see an institution as a result of choices and actions which have created a stable pattern of behavior (Hodgson, 2006). Others see that institutions can be designed and need to be designed to come to efficient outcomes (Finger, Groenewegen, & Künneke, 2005; Goodin, 1996; Klijn & Koppenjan, 2006; Knops, de Vries, & Hakvoort, 2005).

#### ***What is an Institution?***

There is no clear definition of an institution available in the literature. Douglas North defines institutions as 'humanly devised constraints that structure political, economic and social interactions' (North, 1990). Geoffrey Hodgson defines institutions as 'systems of established and prevalent social rules that structure social interactions' (2006, p. 2). A sound of goal seeking can be heard in both definitions. In the first definition by North the efficiency of an organizational arrangement is an important requirement for an institution. In the second definition the effectiveness of institutions is addressed. Efficiency and effectiveness are indicators for the judgment of suitability of institutions.

A famous author in the field of institutional economics can help us make the institutions more clear. Oliver E. Williamson distinguishes four levels for institutions, indicated in the following figure:





**Figure 2: the four layer model (adapted from: Williamson, 1998, p. 26)**

All layers are interdependent on each other. The first level of culture, norms and values make up the basics whereby society is ordered. It is the domain of social scientists. Institutions at this level can change, but the change is slow and gradual.

The second level provides 'the rules of the game within which the economic activity is organized' (Williamson, 1998, p. 27). The outcome of the second level is the product of a political process. In the second level, special attention goes to property rights. Property rights are a crucial factor in determining the play of the game, the institutional arrangements between organizations in level three (North, 1990). The regulatory framework is the set of formal laws and regulations that determine the regime wherein the involved organizations can shape their relations. The emerging relations exert influence upwards onto the regulatory regime. The research will focus on this interaction. The design of the regulatory regime for a CO<sub>2</sub> infrastructure pipeline infrastructure has the objective to shape the governance of relations in such a way, that the basic goals of effectiveness and efficiency are realized. At the third level, the costs of transactions play a large role in determining the most efficient form of institutional arrangement. The question which form of organization fits each type of transaction best has been around for a while (Coase, 1937). One of the objectives of this research is to find which

factors are important in determining the adequate governance structure for a CO<sub>2</sub> infrastructure. The main focus therefore lays at levels two and three of the Williamson model.

At the fourth level decisions on production volume and resource allocation are made. This level is dominated by a marginal analysis and the production function. It is of interest for the research what factors are involved in determining the level of CO<sub>2</sub> production.

### ***Governance structure & Regulatory Framework***

A governance structure is the set of institutional arrangements in a value chain. They can be controlled by laws, rules and other formal arrangements: the regulatory framework. This view is derived from Oliver E. Williamson, who describes governance as outlined in the following quotation:

“[G]overnance is the means by which to infuse order, thereby to mitigate conflict and to realize “the most fundamental of all understandings in economics,” mutual gain from voluntary exchange.”

(Williamson, 2002)

A regulatory framework results in a set of boundaries on governance models. Where governance is the organization of relations by which the production process, from CO<sub>2</sub> capture to storage, can take place. And the set of constraints within which the market parties can operate is open for design. As such, the constraints on the functioning of the market are a designed system. The regulatory framework thus creates a framework where actors can engage in contractual agreements. It provides a degree of certainty of behavior within constraints, and as such it provides a basis for relations and arrangements. A regulatory framework provides a vessel coordination of the network through codes, standards and regulations, both technical and economic. In essence, the regulatory framework as defined here embodies the integration between technology and institutions.

Readers who are familiar with literature on Carbon Capture and Storage may have another interpretation of a regulatory framework in the context of CCS systems. In CCS literature, a regulatory framework is limited to the regulations concerning safety and responsibility. The regulatory framework in this contains regulations on the transfer of responsibility of stored CO<sub>2</sub> from the storage company to the state on whose territory the storage location is situated (ZEPP, 2006a). More specifically, economic regulation in the context of CCS refers to extra financial incentives to trigger investments in CCS (demo)projects. It should be absolutely clear the regulatory framework under design here extends the regulations to the monopoly factors of the pipeline network. The exact contents of the regulatory framework are part of the analysis, for that reason it cannot be presented here. As outlined in the next section, this is the topic of chapter 3.

We must note here that the definition and use of the term 'governance' is a source for arguments and discussion. The term governance has a different meaning in different fields of academic research. As a member of the faculty of Technology, Policy and Management, we are accustomed to use the term regulatory framework as described above, where it can be used alongside the concept of market design. However, combining the many interpretations with the large number of literature references from different fields, the risk of misunderstanding is apparent. Therefore it should be clear that the regulatory framework determines the rules of the game, where governance structures emerge as a result of interactions between organizations. The relations and arrangements in the governance structure provide the coordination of the functions in the value chain and is directly related to the performance of the value chain. From this it is clear that the involved technology is important in delivering constraints and requirements for the possible options of the design of a regulatory framework. These dependencies will be clarified in the following section, where the design approach is outlined and substantiated.

### 1.1.2 Design approach and the Report Structure

As mentioned before, there is no generally adopted design method for institutions. Groenewegen and Koppenjan (2005) describe a method using the meta-model as shown in Figure 1. In their view institutions cannot be seen separate from the technology, existing institutions and the interests of stakeholders. Therefore, the design of an institution should at least be based on an analysis of these areas, which we refer to as the system analysis, the subject of chapter 2.

A second building block of the design process is the analysis of possible design options. Starting from scratch with all possible design options will lead to an endless list of possibilities. Therefore, the design space analysis starts with the input of the system analysis. The options of the design space, their consequences and their dependencies are the topic of chapter 3 *Design Space Analysis*.

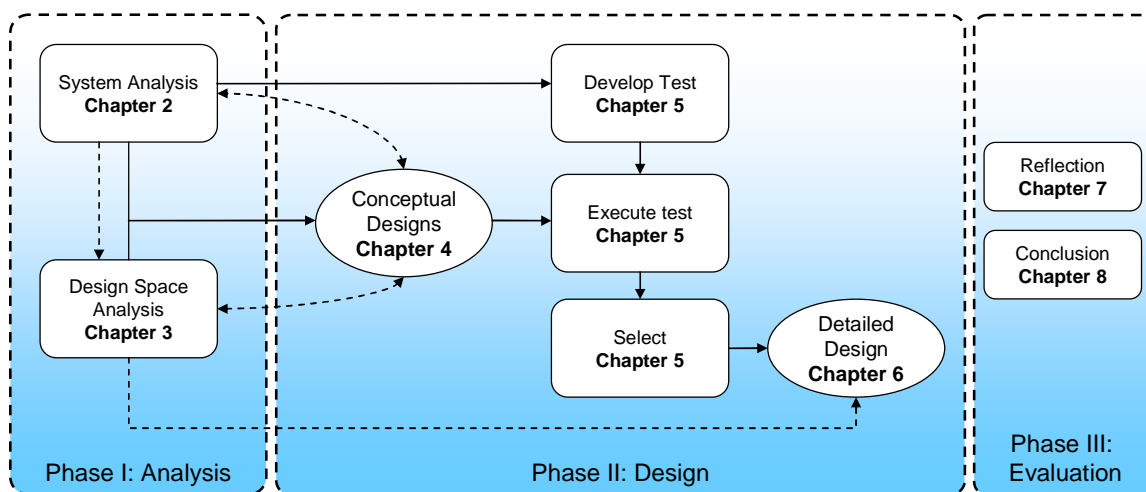


Figure 3: Design approach

The results of chapters 2 and 3 are combined in descriptions of conceptual designs. The step to make these conceptual designs is the novelty of the design approach. By including the design exercise so explicitly in the research structure, a direction is given to the analysis of phase I. The conceptual designs create important insights in the complex mechanisms of the interaction between governance and regulation. Chapter 4 describes the conceptual designs made up of combinations of design options based on the results of phase I.

To evaluate the merits of the conceptual designs, tests are introduced in chapter 5. The tests are based on the requirements and performance criteria of chapter 2.

Finally in chapter 6, a proposal for a detailed design is presented. A detailed design itself is too complex to present as the result of this study. More time and effort is required than is available for the current research. Chapter 6 therefore produces an extended analysis of design issues identified in chapter 3, but not taken up in chapter 4.

Added to Figure 3 there is a third phase to this research: Evaluation. The final chapters of the report treat the conclusions and recommendations. Also, chapter 7/8 delivers a contribution to the discussion on institutional design.

## 1.2 RESEARCH CONTEXT

This section discusses the context of the research, first by discussing the recent developments that have led to increased interest in carbon capture and storage systems. Then a second section describes the basic elements of the technology.

In the Netherlands and in the rest of the world a sense of urgency on the issue of climate change is growing. Three subsequent reports by the International Panel on Climate Change (IPCC) have each signaled an appealing development on climate change. The first report provided persuasive evidence that climate change is indeed caused by anthropogenic emission of CO<sub>2</sub> (IPCC, 2007a). The second report has signaled a warning by showing the effects of climate change on the earth (IPCC, 2007b). Some regions are drying where others are getting more humid. It shows the vulnerability of the climate system to human impact. The third and final report of the series has a more hopeful tone. It argues that if action is taken now the climate change effects can be limited to acceptable levels (IPCC, 2007c). It also proposes strategies on how to achieve this goal.

While the researchers of the IPCC were doing their research for the above mentioned reports public awareness of the climate change was building up. A popular movie by Al Gore expressed the inconvenient truth of climate change to the general public. Other circumstances such as a hot summer and warm winter may also have contributed to the public interest. In any way, the increased public awareness together with the scientific backing of the IPCC has brought climate change mitigation measures high on the policy agenda.

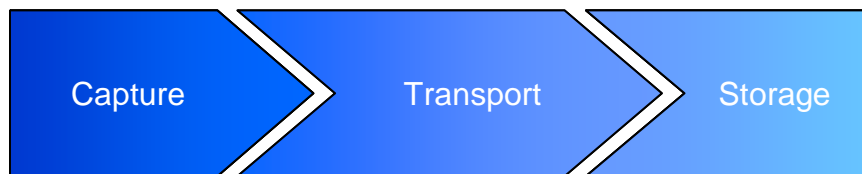
Researchers in another field, that is energy and economics, have also presented a contrasting prediction. In the world energy outlook it is predicted that in 2050 the world will still be using 80% fossil fuels for their energy supply (IEA, 2006).

In this context, the interest in Carbon Capture and Storage systems can be seen. Carbon Capture and Storage offers a way out of the dilemma. The prolonged use of fossil fuels is possible without the emission of CO<sub>2</sub>.

But CCS is no panacea. In sustainability literature there is a common hierarchical distinction amongst options of CO<sub>2</sub> reducing technologies called the Trias Energetica (Lysen, 1996). This concept prescribes that the first efforts of implementing technologies should first aim at efficiency improvement. The second step is to introduce energy from renewable sources. And finally, the option to use clean fossil fuel technologies is regarded as an option. CCS is such a clean fossil technology, even stronger, clean fossil, clean coal and CCS are concepts that are used to indicate the same technology. In this report I use the term CCS. Before continuing the discussion on the sustainability of CCS and defining the scope of this study, I will now first describe the CCS value chain.

### 1.2.1 The Carbon Capture & Storage System

The CCS value chain consists of three links (Figure 4). In the following section I will describe them in reverse order, starting at storage, taking the possible business models of storage options as a starting point.



**Figure 4: the CCS value chain**

The CO<sub>2</sub> in a CCS system has more options than to leave the exhaust pipe with the rest of the flue gas. There are four different business models to where CO<sub>2</sub> can play a role at a final destination. For clarity, regardless of the exact application, it is referred to as "storage".

First, it can be put underground, in geological reservoirs where it is removed from atmosphere indefinitely. The site selection procedure is a critical step. Reservoirs that are selected that have the characteristic to trap the CO<sub>2</sub> underground. In the current regulatory period CO<sub>2</sub> stored in geological reservoirs does not count as a certified emission reduction. It is however broadly expected that in the post 2008 period CCS will be included as a valid emission reduction technology. So, the related revenues come from the EU Emission Trading Scheme (ETS), where an emission reduction can be sold (ZEPP, 2006a).

Second, CO<sub>2</sub> can be used to increase the yield of oil and gas fields. On the North Sea basin, there is a large market potential for CO<sub>2</sub>, many near empty oil and gas fields are looking for technologies which can increase the yield. Higher oil prices make this possible, and CO<sub>2</sub> injection competes with other yield enhancing methods (Warmerhoven, 2006).

Thirdly, CO<sub>2</sub> can be injected in coal seams which cannot be accessed with conventional technologies. Methane, trapped in the coal formations, is freed by the CO<sub>2</sub> and can be collected. The CO<sub>2</sub> forces the methane out because of its stronger absorptive characteristic (IPCC, 2005).

Finally, the CO<sub>2</sub> can be used in greenhouses or other niche applications (C-Fix, 2007; OCAP, 2007). Remember here that the CO<sub>2</sub> emission reduction is not realized at the original source of the CO<sub>2</sub> but at its destination. Greenhouses for example burn natural gas to produce CO<sub>2</sub> to stimulate plant growth. The transported CO<sub>2</sub> is in this case a substitute for the locally produced CO<sub>2</sub>.

The earlier steps of the CCS value chain contain the capture and transport of CO<sub>2</sub> to the storage location.

The choice for technology of capture depends on the industrial plant which is considered as a CO<sub>2</sub> source. Some industrial processes such as ammonia production or oil refining produce streams of CO<sub>2</sub>. Capture refers to a process where the CO<sub>2</sub> is separated from the flue gas (=exhaust gas). Therefore, capture is not necessary at pure sources of CO<sub>2</sub>. The largest volumes of CO<sub>2</sub> originate elsewhere however. Power plants, most notably coal fired power plants produce large amounts of CO<sub>2</sub>. Here the exhaust gas is a mixture of gases from which CO<sub>2</sub> can be extracted by a so-called capture plant. Depending on the power plant technology different types of capture equipment can be used. All capture processes require energy and capital investments, making it the most expensive subsystem of the CCS value chain.

After capture, the CO<sub>2</sub> needs to be transported to the storage site. Again, many alternatives are technologically feasible: truck, rail, ships and pipelines are all feasible alternatives from a technology perspective. However, economically only one option remains feasible for onshore transport and two for offshore transport. For onshore transport a pipeline is the only alternative, where a network of pipelines is the preferred above one-on-one connections because of strong economies of scale (Svensson, Odenberger, Johnsson, & Strömberg, 2004). The dominance of the option for an onshore pipeline network infrastructure is of key importance for this study.

For offshore transport CO<sub>2</sub>-ships can compete with pipelines. Ships have the advantage of destination flexibility but the disadvantages of required intermediate storage facilities and limited capacity (M. Barrio et al., 2004). Pipeline routes are fixed, but can transport large volumes against lower costs per unit (Svensson, Odenberger, Johnsson, & Strömberg, 2004).

This gives a first outlook of the technological system under study in my research. Chapter 2 System Analysis will provide a more in depth analysis of the technological system, the existing rules and regulations and the position of the stakeholders. It will also provide a description of the current developments in the Netherlands on the CCS value chain.

### **1.2.2 Carbon Capture & Storage Sustainability**

As I mentioned earlier, the sustainability of CCS is debated. CCS is considered as a transitional technology. While renewable energy sources become increasingly competitive, CCS can reduce the harmful effects of an endured use of fossil fuels (CATO, 2007). The downside of this is that

the competitiveness of renewables will be postponed. It is widely agreed that to substantially reduce greenhouse gas emissions a range of mitigation measures is necessary (Li, 2005).

In sustainability literature the clean use of fossil fuels traditionally gets the least attention, since it does not concern energy efficiency or renewable energy sources. Rather, it promotes a prolonged use of fossil fuels. The extended use of fossil fuels however is predicted by the recent IEA world energy outlook. This report foresees an 80% use of fossil fuels in the energy mix up until 2050 (IEA, 2006). Another downside of CCS from a sustainability perspective is the required monitoring of the stored CO<sub>2</sub>. Once underground, the return of CO<sub>2</sub> to the atmosphere must be prevented to achieve a net effect of CO<sub>2</sub> reduction. To secure the deposit of CO<sub>2</sub> a constant monitoring is required. By some authors this is termed a Faustian bargain (Spreng, Marland, & Weinberg, 2007). So whereas sustainable technologies are by definition beneficial to next generations, CCS creates an extra concern for them.

Then there is the issue of leakage. Public concerns on the safety of CCS systems and massive leakage of CO<sub>2</sub>. This fear originates from a disaster which took place in Rwanda at Lake Kivu in 1986 killing 1,800 people and 3,500 livestock by asphyxiation. The disaster is believed to be caused by a build up of volcanic CO<sub>2</sub> on the bottom of the lake in combination with an earthquake (Wikipedia.org, 2007). It is completely clear that such a hazard is nonexistent with geologically stored CO<sub>2</sub>. This is confirmed by many sources (IPCC, 2005).

Although there are some serious objections towards the sustainability of a CCS system, it provides an excellent opportunity to reduce greenhouse gas emissions in the relatively short term. CCS can claim its place among the range of other energy technologies that can be applied to reduce the emission of greenhouse gas (Morgan, Apt, & Lave, 2005).

### **1.2.3 Carbon Capture & Storage in the Netherlands**

The conditions which a region needs to have at its disposal for the implementation of a CCS system are (IPCC, 2005):

- a concentration of large point sources;
- access to nearby storage locations, and;
- experience with gas infrastructure.

All three are satisfied in the Netherlands. Together with the earlier mentioned public awareness and political will to do something about the climate change issue, a clear window of opportunity for the implementation of a CCS system exists in the Netherlands. Both the port of Rotterdam and the Groningen port area satisfy the conditions and accordingly are considered as potential CCS sites.

This view is backed if one considers the statements of political leaders, where especially the prime minister's comment on his support of a CCS system in the north of the Netherlands (NRC-Handelsblad, 2007). The statement preceded the signing of a letter of intent for the development of a CCS demonstration project.

It is clear that the process of realizing a CCS system in the Netherlands has already started. Companies and public bodies are looking for opportunities to cooperate in demonstration projects. However, in contrast with plans, there are no advanced large scale projects for a CCS system in the Netherlands yet (CATO, 2006; DCMR, 2006). There are still many barriers between planning and implementation.

#### **1.2.4 Carbon Capture & Storage barriers to implementation**

The CCS system. For completeness, I will briefly summarize them here:

##### **High Cost**

The costs of investments are high and the returns are uncertain. Moreover, the basic characteristics of a CO<sub>2</sub> infrastructure provide a business foundation for small returns over a long period. Such a business is inherently risky and unattractive for market parties.

Also this leads to potential participants waiting for the moves of others. Making the first move might result in a disadvantageous position, where the first mover is dependent on others. In this situation, commonly referred to as the 'hold up' problem, theory (Goodin, 1996; Koppenjan & Groenewegen, 2005) is very close to practice (DCMR, 2006; Huizeling & Groeneveld, 2007; Jacobsen & van de Woudenburg, 2007; Kuijper, 2007; Santen, 2007) as both sources of information signal 'hold up' as one of the major barriers to the implementation of large infrastructure projects.

##### **No regulatory framework for storage**

As of yet, there are no clear regulations for storage yet. This is one of the prerequisites for including CO<sub>2</sub> storage as a certified emission reduction, tradable at the EU Emission Trading Scheme (ZEPP, 2006a). The regulatory framework referred to in CCS literature commonly refers to safety regulations, mainly focused on the distribution of responsibility for the monitoring and control of leakage from storage sites. For the purpose of this report, the regulatory framework consists of a broader spectrum of regulations, including economic regulation. This concept will be clarified in section 1.1.1.

##### **Public acceptance**

It is not yet clear if the general public will approve of CCS as a valid method to reduce CO<sub>2</sub> emissions. The sustainability of the measure is debated, and N.G.O's do not support the concept. Rather, they prefer efficiency increases or renewable energy supply (Goerne, 2006).

##### **Required R&D to reduce costs**

The costs of the CCS value chain can be reduced by additional Research & Development. Demonstration project can provide the required learning (ZEPP, 2006a).



Now that the basic aspects of CCS and the opportunity of implementation of CCS in the Netherlands are clear, I can turn to a more detailed description of my research project, leading to the main research question.

But how can this objective be achieved? What basic elements does it need to contain to successfully perform its function? More specifically, what are the important elements for the development of a regulatory framework for a CO<sub>2</sub> network? And what could be a suitable approach to the design process? These questions are the main elements of my research project. The next section will discuss the research objective and research question in more detail.

### **1.2.5 Delineation, assumptions and System boundary**

A system boundary for the CO<sub>2</sub> infrastructure network is given here. Up to now, the reader should be sufficiently familiar with the involved technology to be able to interpret these delineations.

First, as a realistic case, the port of Rotterdam industrial area can be seen as the setting of my research. There a large conglomeration of point sources exists, nearby storage possibilities are accessible and CCS as a mitigation technology is seriously considered. Most of the stakeholders I interviewed have an interest in the port of Rotterdam.

Second, I assume that a pipeline network will be built. It is unclear who will build it, or who will provide the lion's share of the investment. Nonetheless there is consensus on the need for a pipeline network to connect sources and sinks of CO<sub>2</sub> (Svensson, Odenberger, Johnsson, & Strömberg, 2004). The pipeline network will connect multiple sources of CO<sub>2</sub> with multiple storage facilities.

Thirdly, CO<sub>2</sub> captured and stored in an operational CCS system will count as certified emission reductions, tradable at the EU ETS. This assumption is broadly accepted in researches in CCS. It is a firm prerequisite for implementation of a CCS system of sufficient scale as is agreed by many parties (Eurelectric, 2007; Warmerhoven, 2006; ZEPP, 2006a).

Fourthly, I assume that the responsibility for the stored CO<sub>2</sub> will transfer to the state where the storage site is located after the site is abandoned. As with the inclusion of CCS in the ETS this is an assumption broadly shared by industry and governments (Kuijper, 2007; Spiegeler, 2007).

As a fifth assumption, I assume that the ETS will be at a sufficient price level to compensate the costs of the CCS value chain.

The system boundary encloses the entire CCS system. Only the technical properties that are related to economic properties are considered. The setting of the system boundary is the result of the system analysis. For here, we can suffice interactions with electricity production or oil prices are not considered.

# PHASE I: ANALYSIS

## 2 SYSTEM ANALYSIS

The system analysis builds further on the system description as provided in chapter 1. The analysis provides a basic building block for the research, it has two functions. First, the insights gained in the analysis supply an input for the design. Each subsection results in a contribution to the list of requirements. Second, the problems and dilemmas identified in the system analysis offers a starting point for the theoretical analysis of the design options discussed in chapter 3.

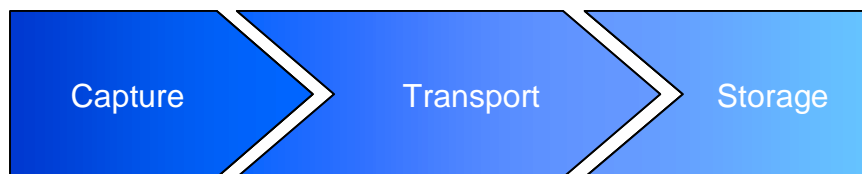
The analysis follows the structure of the TIP approach (Koppenjan & Groenewegen, 2005). TIP categorizes the system aspects into three sections.

- T Technology; Analyzes the technological system
- I Institutions; Analyzes the important institutional requirements
- P Process; Refers to the interplay of stakeholders and their interests

The chapter is built up as follows. 2.1 provides a more in depth analysis of the technology. After a brief introduction on the concept of institutions, section 2.2 provides an analysis of the stakeholders. Then, section 2.3 discusses the influence of existing institutions, their position and interests. Finally 2.4 raps up the chapter and it presents the most important conclusions which will be part of the design chapter.

### 2.1 ANALYSIS OF TECHNOLOGY

The first area to treat is the involved technology. The discussed options represent the choices industry has for implementing CCS in their system. The analysis follows the value chain, so first capture, then transport and finally storage. Requirements uncovered during this analysis are added to the list of requirements listed in the Appendix C Basis of Design.



**Figure 5: Value chain CCS system**

#### **2.1.1 Capture**

The first step of the CCS value chain is the capture of the CO<sub>2</sub> from the flue gas. The emissions of industrial point sources in general are a mixture of gasses containing CO<sub>2</sub>. Before the CO<sub>2</sub> can

be transported and stored, it needs to be separated from the flue gas. There are several processes available to remove CO<sub>2</sub> from the flue gas: post-combustion capture, pre-combustion capture and the so called oxyfuel technology. Each of these technologies and their characteristics is described in Appendix B dedicated to technology of CCS sub systems (see Appendix B Capture Technology).

Capture represents the largest share of the cost for CCS (IPCC, 2005). A main cost element for this is the high energy demand of the capture process. The costs for capture cover investment cost as well as operational costs. The main determinants for the costs of capture are:

- The capture technology
- The type of power plant
- The required purity of the CO<sub>2</sub>
- The pressure of the CO<sub>2</sub>

A definite calculation of capture cost is difficult to make since few full scale projects are operational. Many publications on the matter diverge in their calculations. The IPCC has bundled research and summarized the results in their special report. We have selected elements from those tables which are presented here in Table 1. All power plants in the table are newly built power plants; the generally more expensive retrofits are not represented in this table.

**Table 1: Comparison of Capture cost (IPCC, 2005)**

	<b>Natural Gas Combined Cycle</b>		<b>Pulverized Coal combined cycle</b>	<b>Integrated Coal Gasification Combined cycle</b>
<b>Capture technology</b>	Post combustion capture with amine based sorbent	Oxyfuel	Post combustion capture with amine based sorbent	Pre combustion capture – Selexol
<b>CO<sub>2</sub> reduced per KWh</b>	82-88%	97%	81-88%	81-91%
<b>% Increase in COE</b>	32-61%	50%	42-66 %	20-55 %

The oxyfuel natural gas example has results from only one study. The results are promising and more of such systems are being built (Anderson, Doyle, & Pronske, 2004). The ranges in the table indicate the differences between the studies. Factors influencing the difference also are part of the main performance indicators for capture systems.

Research is being done on capture technology to bring down the costs. The main objective of the cost reduction is to bring down the energy demand because of the high cost of extra fuel required to drive the capture process (ZEPP, 2006a). The main directions for cost reduction are in the direction of economies of scope and scale.

Economies of scope can be found with companies experienced in gas treatment. Economies of scale can be aimed at reducing the investment costs of capture systems as capture equipment companies increase their scale of production and become more experienced in their production process.

Other possible solutions are in the area of using heat from turbines to drive the capture process. Such options can use the energy from nearby industrial plants in co-siting projects. An example in this area is the proposed project by Eneco for using the cold of a nearby LNG regasification plant (Enecogen, 2007). The development of demonstration plants is an important step towards more insight in the optimization of the capture process (Strömberg, 2006).

### ***Conclusions Capture***

The energy requirement of the capture process is partly determined by the requirements for the transportation and storage steps further up the value chain. The transportation requires certain temperature levels and pressures. Storage can pose requirements on purity. This shows the interlinkedness of the elements of the value chain. Coordination of activities between elements of the value chain can lead to cost reductions (ZEPP, 2006a).

#### **2.1.2 Transport**

The transport of CO<sub>2</sub> has several available alternatives. It can be transported over land by rail, pipeline or ship. For offshore, CO<sub>2</sub> carrier ships could compete with pipelines. Rickard Svensson et al. (2004) have made a scenario study of several alternative transport combinations for the transportation of CO<sub>2</sub> in a CCS system. One of their scenarios includes a combination of large power plants (1000 MWe) with a total yearly capture of 40 Mton CO<sub>2</sub>. This scenario is a relevant comparison to the case of the port of Rotterdam network. Svensson concludes that the only feasible onshore transportation is through pipelines, and for offshore a system of pipelines or ships with intermediate storage facilities, or a combination of these (Svensson, Odenberger, Johnsson, & Strömberg, 2004).

For that reason, in this section we will treat both pipeline and ship transport of CO<sub>2</sub>.

#### ***Pipeline transport***

Zhang et al (2006) show that transporting the CO<sub>2</sub> in its subcooled liquid state is the most energy and cost efficient method. Investment in transport through pipelines is relatively low cost and straightforward (Zhang, Wang, Massarotto, & Rudolph, 2006). Companies in the Netherlands have experience with the deployment and operation of pipeline networks. There is experience with complex multi regional spatial planning issues, with extensive environmental impact assessment studies and there are extensive emergency plans for calamities. Knowledge and experience on these issues can reduce the cost of other pipeline infrastructure (De Wolf, 2007).

Existing pipeline transport in the Netherlands is not in accordance with Zhang's findings, instead of transportation in the subcooled liquid state CO<sub>2</sub> is transported as a gas from refineries to greenhouses in the OCAP project. The OCAP project uses an old kerosene pipeline between the port of Rotterdam and the Schiphol Airport to supply CO<sub>2</sub> to greenhouses along its route (OCAP,

2007; Santen, 2007). In the U.S. several CO<sub>2</sub> pipelines are operational. Figure 6 shows a metering point in New Mexico where the Cortez pipeline connects a natural source of CO<sub>2</sub> with an enhanced oil recovery project (see 2.1.3 Storage).



**Figure 6: Inspection of the Cortez pipeline, New Mexico, U.S.A (KinderMorgan, 2006)**

The use of existing natural gas infrastructure is considered an interesting option for cost mitigation (Hanegraaf, 2007; ZEPP, 2006a). However there are several issues that need to be solved before old pipelines can be used for CO<sub>2</sub> transportation. It is not straightforward that a natural gas pipeline is able to transport CO<sub>2</sub>. The operating pressures differ and the characteristics of CO<sub>2</sub> are different from natural gas. CO<sub>2</sub> is much more reactive and can have corrosive effects. Also pressurized CO<sub>2</sub> with a high temperature has the affinity to permeate porous materials (ZEPP, 2006b). The Gasunie<sup>1</sup> does not consider the use of onshore natural gas infrastructure for CO<sub>2</sub> as a feasible option for three reasons. First all existing capacity is in use and it is not expected that significant capacity will become available in the coming years. Second the natural gas is transported as a gas. The diameters of the pipelines are such that only pressurized transport of liquid CO<sub>2</sub> is required to transport sufficient quantities of CO<sub>2</sub>. The technical difficulties converting the pipeline are such that it is more economical to build new ones. Thirdly, projects with CO<sub>2</sub> pipelines should be as safe as possible. Introducing old an used pipelines into a CCS systems adds a safety risk (De Wolf, 2007). Taking this into account, for the transportation of high pressure liquid CO<sub>2</sub> onshore, it is not possible to use existing onshore natural gas infrastructure. Offshore pipelines on the other hand do provide possibilities for re-use (EEEgr, 2006).

**Box: CO<sub>2</sub> quality specifications**

**Carbon Dioxide.** Product should contain at least 95 mole percent Carbon Dioxide

**Water.** Product shall contain no free water (meaning not solved in CO<sub>2</sub>) and shall not contain more than  $4.8 \cdot 10^{-4}$  kg/m<sup>3</sup> in the vapor phase.

**Hydrogen Sulfide.** The product shall not contain more than 1500 ppm by weight of HPINDAS.

**Total Sulfur.** The product shall not contain more than 1450 ppm by weight of total sulphur.

**Temperature.** The product shall not exceed a temperature of 48.9 °C.

**Nitrogen.** The product shall not contain more than 4% mole of N<sub>2</sub>.

*Adopted from IPCC, 2005, p182*

<sup>1</sup> The Dutch national operator of gas pipelines

The purity requirements of pipeline transport are mainly focused on the water content. Dried CO<sub>2</sub> does not corrode the steel grades generally used for pipelines. The presence of compounds as N<sub>2</sub>, NO<sub>x</sub> and SO<sub>x</sub> contaminants does not influence corrosion in pipelines (IPCC, 2005). The maximum allowed water content which keeps corrosion within sufficient limits depends on the pressure. An example of a CO<sub>2</sub> quality specification is given in the box on the previous page.

### ***Water carrier / ship transport***

Since a capture process is a continuous process and ship transport is discrete in batches, intermediate storage facilities are needed. This issue is not specific to CO<sub>2</sub> alone; LPG and LNG marine transport systems need similar facilities for loading and unloading of their cargo. The use of CO<sub>2</sub> in ship is limited today to only four small ships. These carry food grade CO<sub>2</sub> from a pure CO<sub>2</sub> point source to customers in the North sea area (IPCC, 2005). A report by Mitsubishi Heavy industries shows that ships with a capacity of 10 to 50 kton could be build with existing technology . A currently operational CO<sub>2</sub> carrier by is depicted in Figure 7.



**Figure 7: A CO<sub>2</sub> carrier of Larvik Shipping; capacity is 1.2 kton CO<sub>2</sub> (Larvik-Shipping, 2007)**

Technical difficulties with the design of these ships still need to be solved. Most work needs to be done on the offshore unloading of the liquid CO<sub>2</sub> where issues as ice formation, reheating and pressure control are the main design problems (Aspelund et al., 2004).

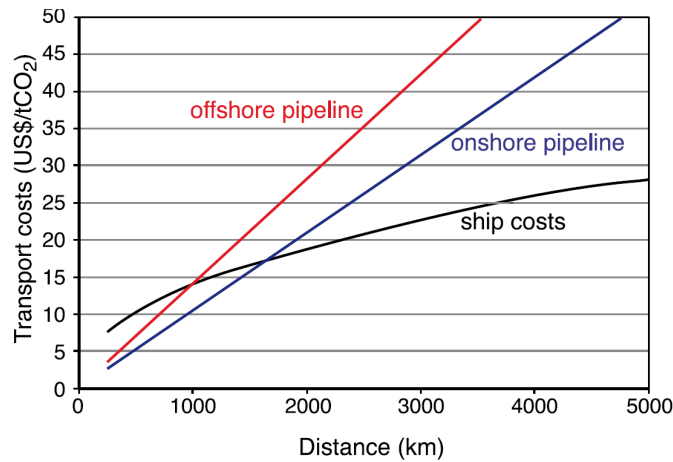
The requirements for purity for a ship are somewhat higher than for a pipeline. Since the CO<sub>2</sub> in ship tanks is kept at a temperature of approximately -50 °C at 6-7 bar (IPCC, 2005) the effect of impurities such as nitrogen can result in two phase flows. In pipelines operational pressures are much higher (80-240 bar) and there is no occurrence of two phase flows (IPCC, 2005).

Important to note here is that the availability of ship transport can result in a competition between infrastructures (offshore pipelines vs. ships). We will come back on the implications of this issue at a later stage in the analysis (see section 3.1 on competition and infrastructures), in the next section I will sketch the performance of both systems from a technical viewpoint.

### ***Performance of transport systems***

Figure 8 shows the different costs for the alternative transport modes. The costs for ship transport include "intermediate storage facilities, harbor fees, fuel costs and loading/unloading

activities” (IPCC, 2005, p. 192). The figure is made for a yearly transport of 6 Mton. Increasing the volume shifts the break even point for offshore transport to the right (IPCC, 2005).



**Figure 8: Cost of CO<sub>2</sub> transport, 6Mton/yr (IPCC, 2005, p. 192)**

Ship and pipeline transportation can also complement each other. This would combine the flexible deployment of ships with the lower transportation cost of pipelines over short distances (Svensson, Odenberger, Johnsson, & Strömberg, 2004). The main advantage of ship transport is to provide CO<sub>2</sub> for EOR/EGR activities. The flexibility of ship transport is a significant cost reduction since EOR/EGR projects only require CO<sub>2</sub> for relatively short periods of time (see section 2.1.3. *Storage*).

Both pipelines and ships put requirements on the CO<sub>2</sub> that is delivered to them. The requirements are on pressure, temperature and CO<sub>2</sub> purity and need to be satisfied by the capture process.

According to the platform on zero emission power plants the choice for a type of infrastructure depends on the required volume, the distance between source and storage and geography and geology of the route. More specifically, in a choice for a route and mode, the best options minimize the environmental footprint and have the lowest cost (ZEPP, 2006b).

### ***Conclusions Transport***

This section leads to four clear conclusions: first, it is confirmed that for onshore transportation a pipeline network is the best available option. Secondly, for pipeline networks the upfront investments are high but the costs of use are relatively low. Thirdly, the use of network with multiple sources and sinks of CO<sub>2</sub> requires a standard for the conditions of the CO<sub>2</sub> stream. Fourthly, ships offer a competitive alternative for pipelines in offshore transport. Technical difficulties remain, especially with offshore unloading. Attractive combinations however of ship and pipeline transportation are possible.

### 2.1.3 Storage

The end of the CCS value chain is storage. After capture and transport the CO<sub>2</sub> reaches its final destination at a storage site. The CO<sub>2</sub> can be either stored underground, on or offshore or it can be used as feedstock in a new production process. In this section I will treat the underground storage, more formally known as geological storage in three separate sections. A section on the use of CO<sub>2</sub> in greenhouses and other applications is also included. Finally a section on the performance and requirements generated by storage applications as well as the requirements put on the storage projects will serve as a conclusion.

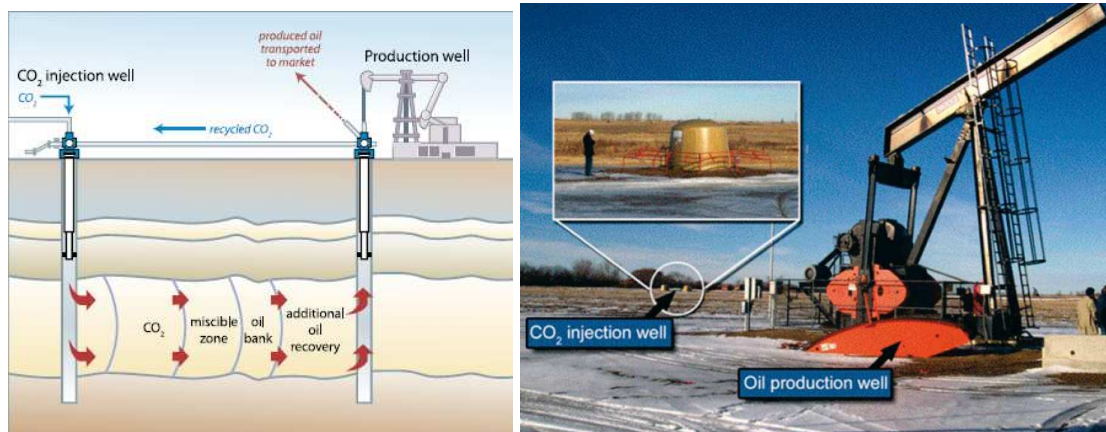
There are three possible forms of geological storage that have been researched and which can be applied in practice. These are oil and gas reservoirs, aquifers (deep saline formations) and unminable coal beds (IPCC, 2005).

#### ***Geological Storage***

Depleted oil and gas reservoirs provide rock formations that can be used as a storage site for CO<sub>2</sub>. The depth of such formations is such (> 800m) that ambient temperature and pressure result in conditions where the CO<sub>2</sub> is in liquid or supercritical state (IPCC, 2005).

Storage in reservoirs can be either in completely empty reservoirs or in reservoirs which already peaked in production. The latter option results in the possibility to increase the yields from an oil or gas field. In porous rock formations the CO<sub>2</sub> takes the place of oil or gas, pushing the fuels out and thus increasing the life span of a field. Such an application is known as Enhanced Oil Recovery (EOR) or as Enhanced Gas recovery (EGR) (IPCC, 2005).

The revenues generated by the EOR/EGR application of CO<sub>2</sub> can greatly increase the financial feasibility of a storage project (Di Zanno & Giger, 2006; Warmerhoven, 2006).



**Figure 9: Enhanced oil recovery at Weyburn, Canada (IPCC, 2005)**

Originally, EOR existing projects were not designed for permanent storage purposes. Monitoring has not been done, making it hard to assess the total volumes stored. A project that has been monitored by the IEA GHG is the project at Weyburn in Canada.

Application of EGR activities are fewer than its oil counterparts. For the Netherlands however EGR offers a prospect of revenues. A project initiated by Gaz de France and TNO at the K12-B



offshore gas field has already stored CO<sub>2</sub> and is looking to expand the capacity (Hanegraaf, 2007). The recovery of the gas however has been disappointing, gas yields have not increased as a result of CO<sub>2</sub> injection. However, there is no general agreement on the conclusion that EGR does not work (DCMR, 2006). A second project which incorporates EGR is the SEQ project mentioned earlier (see section 2.1.1 Capture). The volume of gas to be injected in the gas field here is around 10 times that of the K12-B field. Therefore SEQ expects to be able to recover natural gas as a result of CO<sub>2</sub> injection (Drenth, 2007).

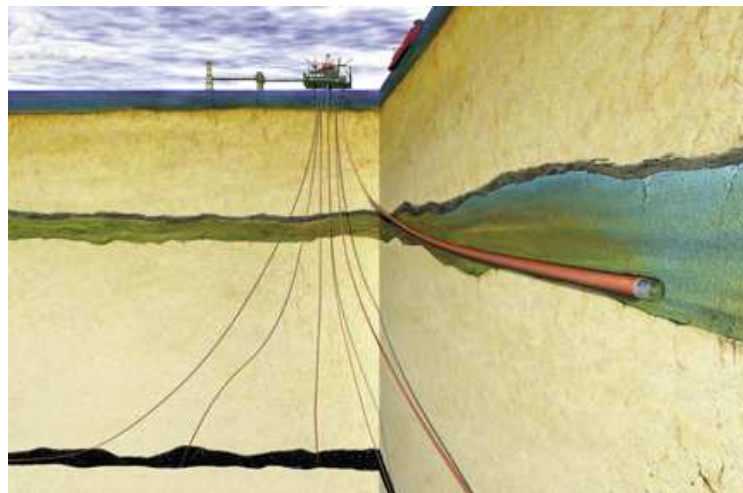
**Box: Storage Capacity**

**Rule of thumb:** A depleted reservoir that has been able to contain 1 billion m<sup>3</sup> of natural gas has a storage capacity of 2,7 Mton CO<sub>2</sub>.

*From: Shell Venster may/june 2006*

A second form of geological storage is injection of CO<sub>2</sub> in saline aquifers. A saline aquifer is a water holding formation with high concentrations of salts, at a depth of around 1000 m. The storage potential of aquifers is believed to be enormous but needs more research before accurate estimations can be made (ZEPP, 2006a). Aquifers are accessible both on and offshore. One of the publicly best known CO<sub>2</sub> storage projects is the injection of CO<sub>2</sub> in an aquifer in the Ustira formation above the Sleipner field. The natural gas recovered from that field contains a high concentration of CO<sub>2</sub>. The CO<sub>2</sub> is separated from the natural gas

at the site and instead of emitting the CO<sub>2</sub> to the atmosphere it is injected in a nearby aquifer, called the Utsira formation (Statoil.com, 2007). To give an idea of the available capacity in aquifers, the Utsira formation alone has an estimated capacity of storing 600 billion tons of CO<sub>2</sub>, equivalent to the emission of all power stations in Europe for the next 600 years (ZEPP, 2006a, p. 10).



**Figure 10: the Sleipner project (Statoil.com, 2007)**

### ***Enhanced Coal Bed Methane***

A third application of CO<sub>2</sub> storage is Enhanced Coal Bed Methane (ECBM). Here the CO<sub>2</sub> is injected in coal beds which are inaccessible for technical or economic reasons. Again the adsorptive quality of CO<sub>2</sub> is employed. The CO<sub>2</sub> forces out the methane present in the coal seam.

The CO<sub>2</sub> remains underground in the coal bed and the methane can be collected (IPCC, 2005). This technology is however still in the research phase. Demonstration projects are needed to bring the technology to a mature state before it can be applied on a large scale (ZEPP, 2006a). Because of the release of methane gas, ECBM can generate extra revenues. Especially in former coal mining regions which often haven't to cope with declining economic growth, such a technology might provide an opportunity to attract new business to the area (Di Zanno & Giger, 2006).

### ***Horticulture and other applications***

In the Netherlands a distributive CO<sub>2</sub> network is already in operation. In the OCAP project CO<sub>2</sub> from an oil refining plant is collected and led through pipelines to greenhouses. These greenhouses use the CO<sub>2</sub> to improve the growth of their crops. This process leads to a reduction of CO<sub>2</sub> emissions. The reduction however does not occur at the refinery, but at the greenhouses themselves. Normally, a greenhouse operator would burn natural gas for the production of heat and CO<sub>2</sub>. Most greenhouses use a micro combined heat and power plant to produce electricity as well. When outside air temperature is high enough that no additional heating is needed, the greenhouses connected to the CO<sub>2</sub> network purchase larger amounts of CO<sub>2</sub> to increase the CO<sub>2</sub> concentration inside the greenhouse.

It should be clear that only in this situation a reduction of CO<sub>2</sub> emission is realized. The motivation of the project is more dependent on economic factors than a reduction of CO<sub>2</sub> emission. It is however an interesting case for this study, since a CO<sub>2</sub> network infrastructure was built to supply CO<sub>2</sub> from an industrial source to a commercial application.

Another interesting product is the use of CO<sub>2</sub> in the production of a construction material. Research by Royal Dutch Shell has delivered a process which uses CO<sub>2</sub> exhaust from a refinery as a source for a new type of concrete (C-Fix, 2007). However these kind of technologies all have in common that the capacity for use of CO<sub>2</sub> is small compared to the actual levels of emissions.

The main drawback of horticulture and industrial use of CO<sub>2</sub> is the available capacity. The volumes consumed are just not big enough. The total capacity of the horticulture sector near the port of Rotterdam is 3,5 Mton. This compares to half the emission of one 600 MW coal fired power plant (Knippels, 2007). This makes horticulture a niche application. It remains interesting however because of the revenues generated. The CO<sub>2</sub>-supplier offers the gas at a price just below the production cost of CO<sub>2</sub> with natural gas. This makes the entire operation highly profitable, with a CO<sub>2</sub> price of around €45,- ton (Hanegraaf, 2007).

### ***Performance of Storage Systems***

In the case of a CCS value chain the downstream market is the market for storage capacity. There is sufficient capacity available on the North Sea basin to presume a competitive supply (see section 2.1.3). There is even competition between storage types: aquifers, EOR or depleted reservoirs are available at different costs to the suppliers of CO<sub>2</sub>. The revenue for each type is

different, so ideally, owners of CO<sub>2</sub> want to sell their Mtons to EOR sites, where they can fetch the highest market price for their product (see section 2.1.3).

The performance indicators of a storage site can be deduced from the above sections. The main performance indicators are:

- Cost [€/ton]
- available capacity [Mton]
- risk of leakage & safety [ton/yr]
- public acceptance [% of public]

### **Cost**

Cost of CO<sub>2</sub> storage is made up of many different factors. Storage costs are made up of:

- capital expenses
- operational expenses
- site development costs
- drilling costs
- surface facilities
- monitoring costs

(Hendriks, Brandsma, Wildenborg, Lokhorst, & Gale, 2006)

The main parts of the costs are arise from drilling at the start of operation and operational costs during operation. Storage costs range from '1-8 €/ton CO<sub>2</sub> depending on the depth and permeability of the storage reservoir and the type of reservoir' (Hendriks, Graus, & van Bergen, 2004, p. 3)

### **Available capacity**

The available capacity determines the life time of a storage reservoir. As a rule of thumb, the following calculation can be applied as a rule of thumb for estimating the storage capacity of a reservoir: a depleted reservoir that has been able to contain 1 billion m<sup>3</sup> of natural gas has a storage capacity of 2,7 Mton CO<sub>2</sub> (Groeneveld, Kuijper, & Maas, 2006). The life time of the storage reservoir is of course also determined by the inflow of CO<sub>2</sub>. When a storage reservoir is filled with CO<sub>2</sub> it needs to be closed.

Linked with the available capacity is the issue of purity. For geological storage the CO<sub>2</sub> is not required to be very pure, with the exception of EOR/EGR applications. However, to extend the life time of the field only CO<sub>2</sub> needs to be stored and voluminous substances such as N<sub>2</sub> should be kept out of the CO<sub>2</sub> stream. The reservoir is considered to fill too fast.

### **Risk of Leakage & Safety**

The risk profile indicates the risk of leakage. Leakage is considered to be the main safety concern, therefore they are grouped together. Leakage is not only a safety concern. The effectiveness of the storage location is determined by it.

The potential for leakage is determined by the amount of bore holes and the geophysical structure of the reservoir. Risk of leakage can be minimized by doing an extensive site selection procedure (IPCC, 2005; Kuijper, 2007; ZEPP, 2006a).

### **Public Acceptance**

The acceptance of the public is an important prerequisite for any CCS project. Onshore storage sites are highly susceptible for NIMBY behavior of nearby residents. Offshore storage projects are more easily accepted by the public than onshore projects. Transparency is an important aspect of project planning and site selection to acquire the support of the public (Spiegeler, 2007).

In the previous sections we have discussed the requirements put on the processes in the value chain from outside the subsystems. The capture, transport and storage activities are linked to each other. As such, they also put requirements on each other. These are discussed in the next section.

### ***Conclusions Storage***

The technology involved with injecting CO<sub>2</sub> is well known and can be applied directly. The reaction of the reservoir on the injected CO<sub>2</sub> is unclear however. To resolve the remaining deficiencies practical experience is needed. Demonstration projects are widely considered as a suitable next step (ZEPP, 2006a). Also the available volume of reservoirs is unclear. And finally, when reservoirs will become available is unclear.

For the sake of this study it can be assumed that there are multiple storage sites available within range of the network, within 100 km of the CO<sub>2</sub> source.

#### **2.1.4 Technology System perspective**

In the previous sections we have discussed the requirements put on the processes in the value chain from outside the subsystems. The capture, transport and storage activities are linked to each other. As such, they also put requirements on each other and the performance of the entire system depends on the successful cooperation of subsystems. In this final section we will discuss the value of flexibility in a CCS value chain, the role of purity issues and the position of technology.

### ***Flexibility***

An important constraint on a CCS system is the available capacity in the reservoir. Another aspect of storage systems is that extra revenues can be generated when the CO<sub>2</sub> can have a useful application apart from being kept out of the atmosphere. The most prominent example of

such an application is Enhanced Oil Recovery. Unfortunately, for the revenues to be made with EOR the CO<sub>2</sub> needs to be transported to remote locations and on demand of the EOR operator.

At the other side of the value chain sit the CO<sub>2</sub> sources. Most often, these sources are industrial point sources with a constant rate of CO<sub>2</sub> production, for example a coal fired power plant. If the CO<sub>2</sub> is produced constantly but not required constantly a mismatch between subsystems exists.

One of the possible solutions for this problem is to distribute CO<sub>2</sub> through a network. A network that connects enough sources and sinks of different types can balance out the different production and consumption schedules (Svensson, Odenberger, Johnsson, & Strömberg, 2004).

However, a pipeline network requires a prolonged period of use to recover the large investment. This gives rise to another mismatch: when a storage site is able to generate revenues but not long enough for economical justification for the construction of a dedicated pipeline. In this view, the flexibility of transport infrastructure is a clear performance indicator.

The transport mode that matches this best is ship transport. A clear trade off between costs and the value of flexibility emerges. The costs for the development and operation of dedicated CO<sub>2</sub> ships are enormous. And the associated revenues are small.

### ***Purity issues***

The subsystems in the value chain have conflicting requirements on the purity of the CO<sub>2</sub>. For capture installations costs are low when the required purity is low. Especially for coal fired power plants the thorough cleaning of the flue gas is an expensive process as the flue gas contains many different substances. However, low purity requirements generate extra costs further up the value chain. CO<sub>2</sub> in itself is not corrosive, but with presence of water the product stream does become reactive. Materials used in the transportation subsystem need to resist the corrosive effects, and such materials are more expensive. Also if the transport system crosses populated areas the H<sub>2</sub>S concentration needs to be minimized or cancelled out completely because of safety issues.

Further up the value chain in the storage subsystem the requirements for purity diverge. Industrial applications such as horticulture and food grade CO<sub>2</sub> require very high quality CO<sub>2</sub>, whereas geological storage can deal with impurities. EOR requires a low nitrogen content (IPCC, 2005).

Other requirements that can be found along the value chain are the state conditions of CO<sub>2</sub>, temperature and pressure. The optimal levels depend on technology choices in the CCS value chain. Horticulture requires CO<sub>2</sub> at ambient pressures and temperatures whereas ship transport requires semi-refrigerated CO<sub>2</sub>. To match the requirements on purity, temperature and pressure among the different subsystems along the value chain, a technological standard is required. Possibly such a standard has similarities with grid codes as applied in electricity infrastructure. I will take up this issue in the design phase of my research and look into the possible solutions in the next chapter.

### ***Environment, Health and Safety***

Concerns for EHS are of course an issue along the value chain. The main risk is leakage. CO<sub>2</sub> leaking from a pipeline forms a hazard for humans and animals. CO<sub>2</sub> is not toxic, but when it accumulates in one area it can cause a hazard of asphyxiation. Furthermore, if some H<sub>2</sub>S or other toxic impurities are present in the CO<sub>2</sub> stream a pipeline leak could lead to substantial environmental impacts (ZEPP, 2006a).

Requirements on minimal leakage are present in all subsystems of the value chain. The main objective of a CCS system is to store CO<sub>2</sub> underground. Leaked CO<sub>2</sub> does not contribute, so it is clear that leakage should be minimized. However, to what extent companies operating subsystems in the value chain should direct their resources to preventing all leakage is unclear. A trade-off between costs for monitoring, cost of leakage and cost of prevention or repair needs to be made, and this is a not an easy trade off because not all of the involved costs are explicit monetary values.

Technologically complex systems with many linkages to other systems are by their nature prone to failures and accidents (Perrow, 1984). For this reason, complex and coupled systems need to satisfy very stringent safety requirements.. The exact scope and depth of such requirements need to be studied extensively. Permitting procedures satisfy this need, and generate sufficient safety requirements. The oil and gas industry have extensive experience with the construction and operation of gas pipelines and as such can use their knowledge when investing in CO<sub>2</sub> pipelines (De Wolf, 2007; ZEPP, 2006a). We will return on this subject in the shareholder analysis.

#### **2.1.5 Conclusions Technology Analysis**

Because of strong economies of scale the transportation network can be considered a natural monopoly. Also, economies of scope lead to benefits of integration of activities. It is for example easier to match supply and demand between capture and storage or generate a standard that is optimal with respect to conflicting requirements of capture and storage when the subsystems of the value chain are in one single organization.

The expected technological development is relatively static. Only on process, cost reductions focused on energy use are expected. In general, the technologies known now will not change dramatically. The consequences for the bigger picture will be discussed in section 2.5

The requirements, constraints and performance criteria put forward by the technological system are an input for the design of the regulatory framework, as it puts constraints on the possible governance modes. It is possible to design near perfect economic regulations, but when linking it to a technological system, it fails. Therefore, the design needs to consider both technology and institutions. The technology contributes to the list of requirements, poses constraints, recognizes performance criteria and identifies areas of interest for research in design options. The products are presented in Table 2 below.

**Table 2: Requirements, criteria, constraints & design option Technology**

<b><u>Requirements</u></b>	<b><u>Criteria</u></b>	<b><u>Constraints</u></b>	<b><u>Design options</u></b>
The regulatory framework should promote efficiency considering issues of scale and scope	Utilize economies of scale and scope Efficiency Minimal costs	Dependence of the control of capture process for industry	Vertical integration Competition regulation,  Entry conditions
The purity, temperature and pressure should match between steps in the value chain	Purity, temperature, pressure, network balance Minimal costs	Technological constraints by capture, transport and storage technologies	Quality standards,
The entire value chain should be monitored	Minimal cost, Independent monitoring & arbitrage	Safety and permitting constraints, Privacy of company related figures	Monitoring of performance
The institutional arrangement should stimulate innovations	Cost decrease in time, "innovativeness"		

## 2.2 STAKEHOLDER ANALYSIS

The stakeholder analysis has three main parts. First we discuss the general welfare interests and the position of relevant government agencies. Then we turn to the interests and objectives of companies in the value chain. Finally, public acceptance and the role of Non-Governmental-organizations are discussed.

Since the public good characteristics are apparent in a CCS value chain, government involvement in the infrastructure is a strong requirement. We will develop this argument in the next section. The following analysis will determine that the regional economic and environmental authorities that are in the ideal position to 'own' the problem. This is a crucial conclusion for the treatment of the problem.

### 2.2.1 The government & general welfare

The implementation of a CCS system serves societal goals as part of the Netherlands energy system. Next to the energy sector a CCS also provides the possibility to reduce emissions from other industries, such refineries and other industries. Energy systems are so important for the functioning of society, a set of basic and well known societal objectives for energy systems are defined:

- **Affordability:** energy is a basic enabler of business and comfort. It must be affordable for everyone.

- **Availability:** also known as 'security of supply'. Energy must be available to all who want to use it. This means that the entire energy value chain, from fuel input to the distribution grid must be reliable.
- **Acceptability:** the damage done to the environment must be acceptable. Emissions of SO<sub>2</sub>, NO<sub>x</sub> and CO<sub>2</sub> cannot exceed certain acceptable levels. For SO<sub>2</sub> and NO<sub>x</sub> emission levels are regulated. CO<sub>2</sub> is currently the central issue.  
(De Vries, Correljé, & Knops, 2005; Directive 2003/54/EC; Directive 2003/55/EC)

The three A's (as these goals are commonly referred to) contain internal contradictions. To reduce emissions, investments are necessary, increasing costs. Also, coal is widely available, in politically stable regions, but coal fired power plants are notoriously dirty emitters. Carbon capture and storage provides a way out of this latter issue, by dramatically reducing emissions of coal fired power plants (European Commission, 2007). This is one of the main arguments for the involvement of government in CCS systems.

But carbon capture and storage issues reach further than electricity generation alone. Other industries such as steel mills and refineries are also included in the value chain (see section 2.1.1). Therefore, from a perspective of government authorities, regulation and governance goals need to be extended on a more general level.

Therefore the objective of a regulation is defined into two sub goals: effectiveness and efficiency (as is broadly recognized: Directive 2003/54/EC, 2003; Directive 2003/55/EC, 2003; Estache & Martimort, 1999; Finger, Groenewegen, & Künneke, 2005; Santen, 2007).

**Effectiveness** refers to the extent to which a goal is achieved. The choices made in the design of a regulatory framework for a CCS value chain should ensure that a certain volume of CO<sub>2</sub> emissions is avoided. For the port of Rotterdam area, this is 19 Mton before 2025 (Knippels, 2007).

**Efficiency** refers to the cost involved with reaching the objective. Maximum effectiveness means most CO<sub>2</sub> stored at minimal costs. The total costs involve a whole range of types of cost, from capital expenses to administrative costs. Finger, Künneke and Groenewegen have identified three concepts of market efficiency (2005, p. 8):

- **Static efficiency:**
  - o Price efficiency: prices equal marginal costs
  - o Allocative efficiency: all customers are served that are prepared to pay at least the market price
- **Dynamic efficiency:**
  - o Refers to the capacity of the system to innovate from a systemic perspective and to the benefit of the overall system.
- **System efficiency:**
  - o Refers to the overall efficiency of the industry, throughout all activities in the value chain.



The three distinct types of efficiency provide clear requirements for a regulatory framework. The preceding sections of the system analysis have already provided further requirements for effectiveness and efficiency (see Appendix C Basis of Design). The following section on the stakeholders will extend the list further. Finally, in the concluding section of this chapter, we will come back on the effectiveness and efficiency, and present a formulation of both that matches the specific technological, institutional and stakeholder characteristics appropriate for a CCS value chain. We first turn to the analysis of stakeholders and their interests.

### **2.2.2 Government Agencies**

Based on the three societal goals for energy systems (triple A's), several public authorities have concerned themselves with the implementation of a CCS system. For the area around the port of Rotterdam these are: the ministry of VROM, the Rotterdam Port Authority, the environmental authority the DCMR and the Municipality of Rotterdam. All endorse roughly the same societal welfare goals of effectiveness and efficiency as sketched above (DCMR, 2006; Gemeente Rotterdam, NV havenbedrijf Rotterdam, DCMR Milieudienst Rijnmond, & Deltalinqs, 2007; Hanegraaf, 2007; Port of Rotterdam, 2007).

The involved government agencies can not be seen as a single actor. For a large part, they share the same interests, although with a different focus. We will treat three different public authorities in this section. Before treating the interests of the governmental bodies, we will first discuss the public good characteristic. This leads to the conclusion that government involvement is justified, and that the government can be seen as a problem owner. Then, we will explain the position of the ministry of VROM (housing, spatial planning and environment) representing the interests of the national government. After that, we will treat the interests of a local public authority specialized in environmental regulations, the DCMR. Finally, we will discuss the port of Rotterdam harbor authority, which has the opportunity to fulfill a key role in the governance of a CO<sub>2</sub> network.

#### ***Public Interest and Externalities***

The issues of public interest are captured through the concept of external effects, or externalities of a CO<sub>2</sub> network. An externality is a cost or benefit related to a good or service which is not included in price. External effects can be positive, for example the indirect effects of constructing a road, or they can be negative, where pollution caused by industries is the best-known example (Khemani & Shapiro, 1993).

A CO<sub>2</sub> network has two public interest external effects. This means that apart from transporting the CO<sub>2</sub> from source to sink, the pipelines also contribute to realization of other goals. These are:

**Regional Economic Development:** The availability of pipeline connections for CO<sub>2</sub> provides an advantage to companies situated next to the network compared to companies in regions which do not provide a CO<sub>2</sub> network. For power plant location decisions it is expected that the costs of including a CCS value chain will be integrated in the location decision (ZEPP, 2006b). Attracting investment in power generation capacity sufficient to supply power needs in a reliable

fashion is one of the major concerns of public authority. Securing generation adequacy is one of the major public interests in electricity markets (De Vries, 2004).

On another level, economic regions compete with each other to attract industry (as discussed by Porter, 1998). The agglomeration of industries in a region has external effects of its own. Industries can share resource streams, when more industries are attracted, network effects bring down costs (Steinle & Schiele, 2003).

Both consequences are external effects, as the benefits that surface are not part of an economic transaction.

**The reduction of CO<sub>2</sub> emissions:** As mentioned in the introduction, a CCS value chain has the opportunity to reduce CO<sub>2</sub> emissions on a large scale. At a European level, national governments have committed to adopting ambitious emission reduction goals (Greenprices, 2007). Although the costs for emission reductions are internalized through the EU-ETS, the reduction of CO<sub>2</sub> remains a public good for two reasons:

- Because of the absence of long term views in private companies, it is difficult for them to make the decision on voluntary CO<sub>2</sub> reduction of sufficient scale to avert the effects of climate change. An influential study by Nicholas Stern has shown that the costs of reducing CO<sub>2</sub> emissions now are negligible compared to the costs of adaptation to climate change (Stern, 2006). Still the investments are not in line with this view.
- Even if the long term view of climate change is accepted, applying CO<sub>2</sub> reduction on a voluntary basis is easier said than done. A cost is involved with CO<sub>2</sub> reduction. Therefore, companies who apply measures incur costs which its competitors avoid. There is a prisoner's dilemma game, and gains from free riding (gaining from behavior of others without contributing) are clear.

Furthermore, the Dutch government has committed itself internationally to ambitious CO<sub>2</sub> reduction targets. If these are not met, the Netherlands suffers reputational damage. The concept of making international agreements in general loses value if countries do not commit to promises.

As mentioned, a related public interest is the security of energy supply. Fossil fuel diversification is a strategy, where coal plays a role. As such, the public interests of security of supply and emission reduction conflict. CCS can provide the solution to realize both security of supply and emission reduction (European Commission, 2007).

Now that the basis for the interests of government is clear, the next sections go into the more concrete interests prevalent at different levels of government agencies. The analysis covers the two regional public authorities. For the Rotterdam area, these are the DCMR and the Rotterdam Port Authority. The DCMR is a collection of environmental committees of municipalities in the Rijnmond area. The Rotterdam port authority represents the economic interests of the harbor.

### **Ministry of Housing, Spatial Planning & the Environment (VROM)**

The ministry is "dossierhouder", meaning that they are responsible for the drafting of policy. The minister of VROM is the official spokesman of the national government on CCS issues. There are some overlapping issues with the ministry of Economic Affairs (EZ) considering the mining law and energy policy, but VROM can be considered the leading government authority (Spiegeler, 2007).

The Dutch government has committed itself to a reduction of 20% emissions in the year 2020. According to Hans Spiegeler of the ministry of VROM, an implemented CCS system of considerable size should play a major role in achieving this target (Spiegeler, 2007). Spiegeler expects emission reductions from CCS projects starting in 2013 at the Nuon Magnum plant and at 2015 in the port of Rotterdam.

Since CCS can play an important role in realizing the emission reduction targets, VROM is willing to play a role in the projects. VROM however, does not want to directly finance CCS projects. Commercial viability of a CCS system is a requirement in VROM's view. Only for demonstration projects with a clear learning curve can subsidies be made available. If another governmental body at a different level of government wants to make an investment, it is possible for them to approach VROM for financial support (Spiegeler, 2007).

The general policy of VROM for CCS originates in Brussels. The European Commission communication on clean coal technologies is leading. The EC sees CCS as a crucial technology to both secure supply of energy sources and reduce CO<sub>2</sub> emissions. Therefore, new coal fired power plants should be made 'capture ready'. This concept means that during the design phase of the power plant, the future installation of a capture plant must be taken into account. Possibly, capture for coal fired power plants can become mandatory after 2020 (European Commission, 2007).

VROM has no view yet on a possible regulatory structure for a CO<sub>2</sub> infrastructure. The knowledge and expertise for such concepts is at EZ or at the NMA and DTe. There are ideas on technical regulation of the CO<sub>2</sub> value chain.

Furthermore, to cover safety concerns, VROM envisages a detailed protocol for the transportation and injection of CO<sub>2</sub>. Such a protocol can be transferred from practice in the oil and gas industry, where an excellent record on safety measures exists (Spiegeler, 2007).

### **Dienst Centraal Milieubeheer Rijnmond**

The DCMR is a combination of environmental departments of several municipalities in the Rijnmond area and the province of Zuid-Holland. The DCMR's mission is to promote

#### **Box:** definitions of "Capture ready":

"... new fossil fuels power plants built and to be built in the EU use best available technologies regarding efficiency and whether, if not equipped with CCS, new coal- and gas-fired installations are prepared for later addition of CCS technologies."

*European Commission, 2007*

"... initially factoring in the changes necessary to add capture and with sufficient space and facilities made available for simple installation of CO<sub>2</sub> capture at a later date."

*IPCC, 2005*

environmental quality and safety through regulations, based on their expertise (DCMR, 2007). They determine emission quota, they also have a monitoring and enforcement department.

The DCMR, together with the Rotterdam municipality, Deltalinqs and the Rotterdam Port Authority have joined the Clinton Climate initiative. Together, they have committed themselves to 50% emission reduction in 2025 compared to the 1990 level (Rotterdam Climate Initiative, 2007). The DCMR has a large role in this. More specifically, they are involved in setting up a CO<sub>2</sub> pipeline project in close cooperation with the Rotterdam Port Authority (Hanegraaf, 2007). In the opinion of the DCMR it is a possibility that the government can participate in a pipeline venture. When private companies alone start up the investment, the DCMR fears that they might make an adequate consideration on the scale of the pipeline, resulting in a pipeline with too small scale to transport all the required CO<sub>2</sub>. To avoid this economically suboptimal lock-in, the DCMR finds it important that a public authority participates in the investment (Hanegraaf, 2007).

### ***Rotterdam Port Authority***

The Rotterdam Port Authority (HbR) is a regional public authority concerned with the economic development of the Rotterdam port area. Recently the port authority has expressed its ambition to increase their business in pipeline transport services. In the Dutch newspaper *het Financiële Dagblad Ger van Tongeren* (commercial director of the HbR) has expressed that pipelines are a crucial step towards a more sustainable economy. He also supports the idea of CO<sub>2</sub> capture and storage and has informed the newspaper that the HbR has recently started a feasibility study for a CO<sub>2</sub> pipeline (*het Financiële Dagblad*, 2007b, p. 1, February 12th). The HbR considers developing pipeline infrastructure as an important part of their business. The harbor area is already covered in a grid of pipelines offering all kinds of utilities (steam, 500 kV, natural gas, hydrogen, ethylene, etc...). A CO<sub>2</sub> pipeline network would fit the existing portfolio and help achieve the goal of the Clinton initiative (Port of Rotterdam, 2007).

The HbR is also involved in the Clinton Climate Initiative of the municipality. As a partner in this project, it has committed to participate in the reduction of emissions in the municipality of Rotterdam with 50% according to 1990 levels. Concretely, this corresponds to a yearly emission reduction of 30 Mton (Rotterdam Climate Initiative, 2007).

Another interest for the HbR is related to the CO<sub>2</sub> capture and storage. The income of the port authority is for a large part made up of ship movements. Transfer of bulk goods is their main business, and coal takes up a large share. The construction of coal fired power plants is a guarantee for the port that the important coal will have a secure demand (Gemeente Rotterdam, 2004). The strategic importance of CO<sub>2</sub> capture and storage now becomes clear. For the port, CCS enables them to continue their business in transferring coal and reducing CO<sub>2</sub> emissions at the same time.

The HbR is willing to carry part of the risk for the investment. It is easier for them to recover the investment of an infrastructure over the long term (25 years). They are looking for partners in the private sector to build a consortium to share the investment burden and incorporate knowledge and experience from private partners (Port of Rotterdam, 2007).

As the HbR is also responsible for regulating planning of infrastructure within the harbor perimeter, it has posed the following constraint on pipeline construction: The port authority does not allow more than one pipeline of the same product in the same route. So no parallel pipelines transporting the same substance are permitted (Port of Rotterdam, 2007).

And regarding the possibility of mandatory capture, the HbR shares the view that mandatory capture can only occur if a pipeline infrastructure to connect to storages sites is also provided (Port of Rotterdam, 2007).

Another important development to mention here is the possibility for the port of Rotterdam to become the CO<sub>2</sub> hub of North West Europe. There is a large share of demand available in industrial areas close to Rotterdam. The port has the ambition to become the CO<sub>2</sub> hub of North West Europe. The CO<sub>2</sub> from Antwerp, the Ruhr industrial area and other CO<sub>2</sub> point sources can be collected through a large scale pipeline network and transported to the available storage capacity in the North Sea basin (Gemeente Rotterdam, NV havenbedrijf Rotterdam, DCMR Milieudienst Rijnmond, & Deltalinqs, 2007; Hanegraaf, Santen, & Knippels, 2007; Port of Rotterdam, 2007).

So generally for all government actors, the realization of emission reduction objectives set by international agreements is the most important criterion for a successful application of a CO<sub>2</sub> value chain.

### **2.2.3 Companies in the value chain**

There are many stakeholders involved in a Carbon Capture and Storage system, both directly by participating in the value chain, as indirectly, where the activities associated with CCS influence the stakeholders environment. In this section I will sketch the interests of stakeholders based on research done by the European Platform for Zero Emissions Power Plants (ZEPP), company statements and press notices, insights from conferences on CCS (CATO, provincie Zuid-Holland) and on interviews held with companies who consider becoming active in the value chain.

#### ***Power Industry***

The power industry is a large contributor to the CO<sub>2</sub> emissions. In the port of Rotterdam area they are responsible for around 10 Mton of yearly CO<sub>2</sub> emissions (Knippels, 2007). Carbon Capture and Storage enables the power producers to use fossil fuels while at the same time reducing CO<sub>2</sub> emissions. This opportunity is certainly recognized by the sector and research is being done on the implementation of capture installations (E.On, 2007). To join the CO<sub>2</sub> value chain, the power companies have four main concerns:

- investment costs;
- reduced efficiency of power plants;
- stability of CO<sub>2</sub> emission related policy and regulations, and;
- the need for a transporter and storage party to which can guarantee to take all the CO<sub>2</sub> of the power plant.

We will go into each below.

The most obvious drawback is the high cost of a capture plant (see 2.1.12.1.1). To be able to bear the costs of such an investment the power companies need to secure income to cover the investment. According to the European research centre for Zero Emission Power Plants (ZEPP), the power sector demands higher returns on investment for a shorter period of time, because of perceived increased risk in fuel supply (Di Zanno & Giger, 2006). Fiscal incentives are needed to generate a basis for the investment. And these incentives need to be guaranteed over a long enough period and at a high enough level to allow recovery of the costs (Huizeling & Groeneveld, 2007; Jacobsen & van de Woudenburg, 2007; ZEPP, 2006a).

The exact required level and duration of the incentive are still unclear; stakeholders disagree over the correct values and mechanisms to attain those values. Even within the power industry, the views of different companies diverge. Company culture, fuel mix and risk attitude differ and consequently the stance towards future policies on capture are different. This ranges from possible obligatory CO<sub>2</sub> capture to a proposed reduction of carbon credits to increase the price level at the EU-ETS (Huizeling & Groeneveld, 2007; Jacobsen & van de Woudenburg, 2007).

The companies do agree on the required stability of incentive policy. It is more important that the decision made on any kind of incentive is not altered or turned back during an investment period. The requirement of regulatory stability and robust decision making can be found in many places, from scientific literature to company statements (Di Zanno & Giger, 2006; Dixit & Pindyck, 1994; Estache & Martimort, 1999; Kessides, 2003).

And not only is the cost of investment an important consideration, also the operation of the capture equipment is costly. Every capture technology requires energy from the plant facility. This leads to lower fuel efficiencies of electricity production. Also, the operational costs increase because of the extra fuel needed to power the capture equipment. Furthermore, capture equipment requires cleaning of membranes, solvent replacement or other forms of maintenance. All three capture technologies have been demonstrated in demo plants, but before capture can be applied at a large scale, research needs to be done to minimize the energy requirement (ZEPP, 2006a).

Finally, the power plants need to find a party which can take off all the CO<sub>2</sub> during the life time of the plant. Two aspects are important: the reliability of the other party and the revenues or costs associated with CO<sub>2</sub>. Since the plants produce large amounts of CO<sub>2</sub> ( $\pm 500$  Mton yearly for a 1000 MW plant, Knippels, 2007) the party that will take all the CO<sub>2</sub> produced needs to be able to reliably transport and use or store large volumes of CO<sub>2</sub>. If the CO<sub>2</sub> is for some reason not transferred to another party, the power plant will need to buy emission certificates, increasing his costs.

The availability of a CO<sub>2</sub> network with sufficient capacity will play a role in the location decision for power plants. A trade-off between the costs for CO<sub>2</sub> transport versus power transmission can become a serious issue in power plant location decisions (ZEPP, 2006b).

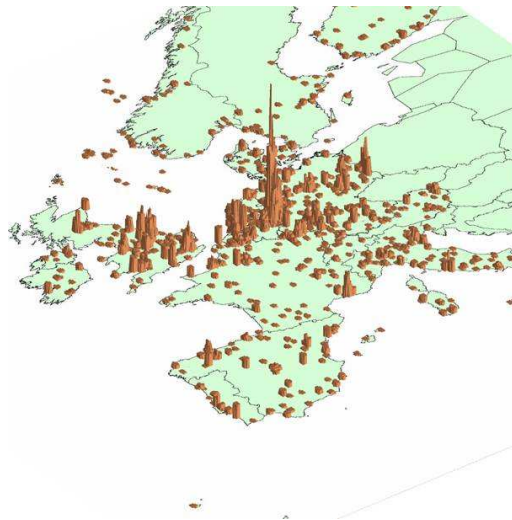
The potential revenues of the captured CO<sub>2</sub> are a more complex matter. The revenues depend on the contracts with the transportation company and are linked with the destination of the CO<sub>2</sub>, see section on storage 2.1.3. Many options are open on which party will be alleged to trade the CO<sub>2</sub> emission quota or take up the revenues associated with the use of the captured CO<sub>2</sub>. There is no business model yet which has emerged as the most successful way to trade CO<sub>2</sub> in a CCS system (Di Zanno & Giger, 2006).

Again the power companies have different opinions on the matter. Some prefer to have a steady guaranteed income which is fixed for a number of years. Others want to take more risk and trade the CO<sub>2</sub> themselves (Hanegraaf, 2007; Huizeling & Groeneveld, 2007; Jacobsen & van de Woudenburg, 2007; Kuijper, 2007; Santen, 2007).

For parties to be able to deal with volatile prices, it is required that there is security over the long term on the level of the price. The level must be high enough to cover at least the long run average costs. Whether such a minimum level is created by a market mechanism or a regulatory intervention is not important for a power company. As long as they receive a guarantee that government commits to maintain policy on CO<sub>2</sub> emission, independent of the content of regulation, then power companies have a sufficient framework to base their investments on. The robustness of regulation is an important requirement for many stakeholders, and it certainly applies to the interest of stakeholders in the power industry (Goodin, 1996; Huizeling & Groeneveld, 2007; Jacobsen & van de Woudenburg, 2007; Kessides, 2003; Klijn & Koppenjan, 2006).

### ***European CO<sub>2</sub> sources***

There is a large potential capacity of CO<sub>2</sub> production in Europe. The port of Rotterdam is looking for possibilities to collect the CO<sub>2</sub> of close by (<500 km) CO<sub>2</sub> sources. The strategic position with pipeline corridors in place, and access to storage sites gives the port of Rotterdam an opportunity to become the European CO<sub>2</sub> hub.



**Figure 11: Representation of CO<sub>2</sub> emission density of stationary point sources in Europe(Hendriks, Brandsma, Wildenborg, Lokhorst, & Gale, 2006)**

The peaks indicate the location and volume of CO<sub>2</sub> emissions. The highest peaks are located in the Ruhr area where large scale lignite plants are located. These plants are part of the dirtiest power plants in the Europe union of 25 (WWF, 2007). The port of Rotterdam sees it as an opportunity to connect these sources of CO<sub>2</sub> to their network and provide a transfer service to storage sites in the North Sea basin.

For this reason, it is a requirement for the regulatory frameworks to leave open the possibility to connect other industrial areas, such as Antwerp and the Ruhr area, into the Rotterdam pipeline network. Or, such operation can even be incentivized.

### ***CO<sub>2</sub> producers / shippers***

The production and transport of CO<sub>2</sub> is not a new technology or business. The introduction of CCS and the concept of zero emission power plants provide an opportunity for companies in CO<sub>2</sub> production and shipping with an opportunity for dramatic scale increase.

The construction and operation of a CO<sub>2</sub> network infrastructure thus provides an interesting opportunity to provide expand their services.

Apart from transportation of CO<sub>2</sub>, these companies are also specialized in the production of CO<sub>2</sub> for food-grade or medical application. The same technologies for production are applied in the capture step (Lindegas, 2007a).

Lindegas and Visser & Smit Hanab are two companies with extensive experience in gas production and pipeline construction (Lindegas, 2007a; VS Hanab, 2007). The earlier mentioned OCAP pipeline is a joint venture owned by these two companies (OCAP, 2007). From presentations held by these companies at a conference organized by the Provincie Zuid-Holland it appears that drafts for the construction of a pipeline network are being made.

#### **Box: *Non-cooperation of CO<sub>2</sub> shippers***

Unfortunately, none of the companies I approached for this research were willing to cooperate. According to them, the issue of governance and financial organization of the CO<sub>2</sub> infrastructure is sensitive strategic information. At the same time as I am conducting this research (January-August 2007) concrete CCS project proposals are being negotiated. The contents of these negotiations and the resulting contracts are kept confidential by the involved companies.

This leads me to two conclusions:

- There is a prospect for concrete projects on the level of CO<sub>2</sub> infrastructure;
- There are strategic advantages by being a first mover. By being the first investor, it becomes possible to seize the natural monopoly in CO<sub>2</sub> infrastructure network. Access to CO<sub>2</sub> sources and sinks, network effects and learning can provide critical advantages over competing companies.

From the perspective of the CO<sub>2</sub> shippers and from indirect information on their strategic considerations I can add the following observation on the issue of estimation for pipeline capacity to the analysis.



CO<sub>2</sub> shippers make capacity calculations based on secured supply and demand of CO<sub>2</sub>. The dimensions of the pipeline are determined by the first two contracts. This works well for one on one pipelines, but a pipeline network requires a larger capacity. The calculations leading to the correct pipeline diameter are hard to make and involve investment under uncertainty. Therefore, CO<sub>2</sub> shippers are inclined to underestimate the required capacity to reduce costs. Apart from a market failure, such underinvestment creates a critical lock-in for the development of the network. The bulk of the costs for pipeline construction are in the acquiring of land and rights of way. Secondly, to increase capacity during planning is a fraction of the costs compared to the operational phase. As the circumference of a pipeline increases with the power of two and volume with the power of three, the material costs of scaling up fall with size. Combine this with the lifetime of a pipeline (20-30yrs) it becomes clear that an adequate estimation of required capacity is critical for the success of a CO<sub>2</sub> network.

Another angle is provided by the Dutch state owned natural gas transportation company Gasunie. Gasunie is also interested to become active in CO<sub>2</sub> transport (De Wolf, 2007). Their main advantage lies in their experience with the planning, construction and operation of pipeline infrastructure. They have no experience with the product CO<sub>2</sub>, but consider it an interesting extension of their business.

Worldwide, there are many companies active in the shipping of CO<sub>2</sub>. Oil & Gas companies and their subsidiaries are prominent among these. Others include U.S based Kinder-Morgan, the earlier mentioned Lindegas from Germany, French Air-Liquide, and U.K.'s Airproducts. Also VOPAK has experience with pipeline operations.

### ***Oil & Gas industry***

Oil and gas companies are critical stakeholders because they understand all the aspects of the CCS value chain. Oil and gas companies have:

- experience with capturing CO<sub>2</sub> at oil or gas wells;
- an easily accessible CO<sub>2</sub> source: H<sub>2</sub> production at refinery
- access to CO<sub>2</sub> storage sites, combined with the possibility to generate extra revenues through Enhanced Oil Recovery or Enhanced Gas Recovery
- experience with gas shipping, handling and other operations such as monitoring geological reservoirs
- knowledge: of possible storage sites, can assess potential storage sites
- excellent safety regulations and related organizational structure which can be transferred to CCS

But there are disadvantages. Oil and gas companies have limited assets with high opportunity costs. Especially in exploration and production human capital directed to the assessment of CO<sub>2</sub> storage sites competes with the exploration of new oil and gas reservoirs. Human capital has high opportunity costs (ZEPP, 2006a).

Also the risk/reward structure does not fit the exploration and production business. Storage of CO<sub>2</sub> is a low risk, low reward service. In contrast with exploration business which is high risk, high reward business (Kuijper, 2007).

But the oil and gas companies also recognize that to maintain the long term use of fossil fuels, something must be done about emissions. CCS offers an opportunity to continue the use of fossil fuels, while limiting the emissions (Kuijper, 2007). Furthermore, the opportunity to increase field production lifetime with EOR/EGR technologies provides the outlook of extra revenues for oil companies. All the oil majors (BP, Shell, Statoil, Chevron, ConocoPhillips, Total) are involved in developing technology for CCS projects (Rohner, 2006), indicating that indeed CCS projects are considered, provided of course that the revenues of a CCS project are sufficient to cover the incurred costs. Depending on geological spread, together with the estimations of available capacity, the number of companies also indicates that competition among storage sites is possible. The relations among companies, subsidiaries and the amount of vertical integration is however unclear. This will be further discussed in chapter 3.

The ability to handle high risk/high income business might give the oil & gas companies the opportunity to play an important role in a CO<sub>2</sub> regulatory framework. This will be dealt with in more detail in chapter 3.

#### **2.2.4 Public Acceptance & N.G.O's**

A first research of the public perception towards CCS has been done by Senternovem and the NWO (Best-Waldhober, Daamen, 2006). This research shows that the Dutch public is 'likely to agree with large scale implementation' of a CCS system. The respondents did not indicate a clear favourite CCS technology, all presented options were judged adequate.

Also the research has shown that the public opinion tends to follow the view of Non Governmental Organizations (NGO) on CCS. The message on CCS can be best conveyed in a cooperative between energy companies and environmental organizations (Best-Waldhober & Daamen, 2006). Therefore, to generate sufficient public acceptance the cooperation of NGO's is critical.

The public is a powerful actor. Their opinions count for politicians, who in turn determine the budgets for policy makers. Their influence may be indirect, but a massive public outcry against CCS may well stop all progress in its tracks.

#### ***Environmental NGO's***

Doubts on CCS are present with the environmental NGO's. They point at the unresolved issues of storage: leakage. The NGO's emphasize the need for research to determine the probability of leakage from storage sites (Audus, 2006).

Furthermore the NGO's indicate the necessity of clear liability allocation. The liability can lie either with the owner of the storage location (i.e. government) or with the operator. In any way, strict and clear liabilities need to be defined (von Goerne, 2006).

Very recently (during the writing of this report) an interesting coalition of labor unions and environmental NGO's has presented their vision in a report called Green4sure. In the report the

unions and NGO's sketch a scenario where the Netherlands can reduce 50% CO<sub>2</sub> emissions in 2050, where a substantial part of the reduction is realized by a CCS system. As one of the commissioning parties is Milieu Defensie, notorious for their non-participation and radical views, it can be deduced that a move towards the acceptance and legitimization of CCS as a greenhouse gas mitigation instrument has been started by the NGO's.

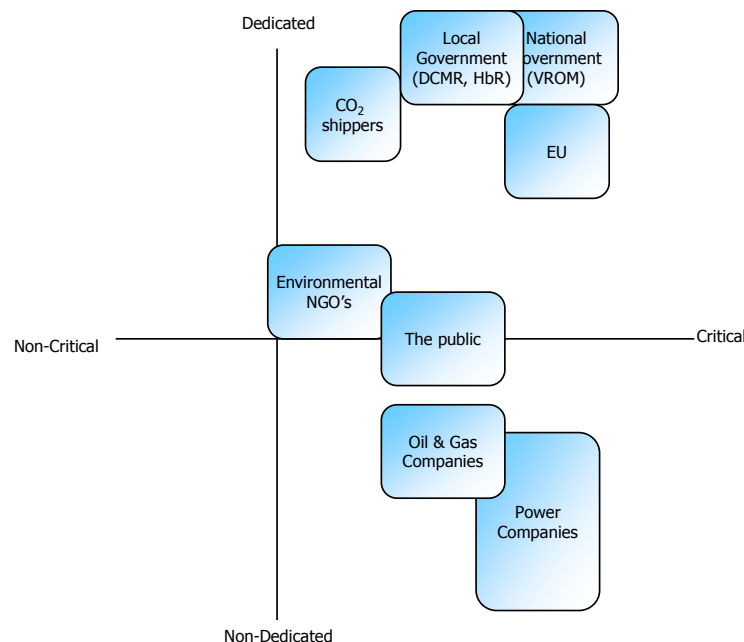
### 2.2.5 Conclusions stakeholder analysis

It can be concluded that commitment exists for the implementation of a CCS system in the Netherlands with private, public and non-governmental stakeholders. Uncertainty about future policy and uncertainty about costs are the main barriers. Focusing on infrastructure, the bearing of high up front costs in the construction phase are a particular barrier.

The starts up of demonstration projects funded with government aid are considered across the value chain. The refusal to cooperate to the research by CO<sub>2</sub> shippers indicates that important decisions will be made in the short term. The theme of the CATO congress 'van plannen naar projecten' [from plans to projects] held in November 2006 underlines the current status.

An overview of the actors and their position is presented in Figure 12: Stakeholder diagram. The figure divides the stakeholders in four groups. The first distinction is based on the dedication of stakeholders to the implementation of a CCS system. Those stakeholders that are dedicated to build a system are positioned on the positive vertical axis, those who oppose it are on the negative side of the vertical axis. The second distinction is based on the criticality of the stakeholders in the process. If the participation of stakeholders is critical, so if their participation is required in a CCS system, they are positioned accordingly on the horizontal axis.

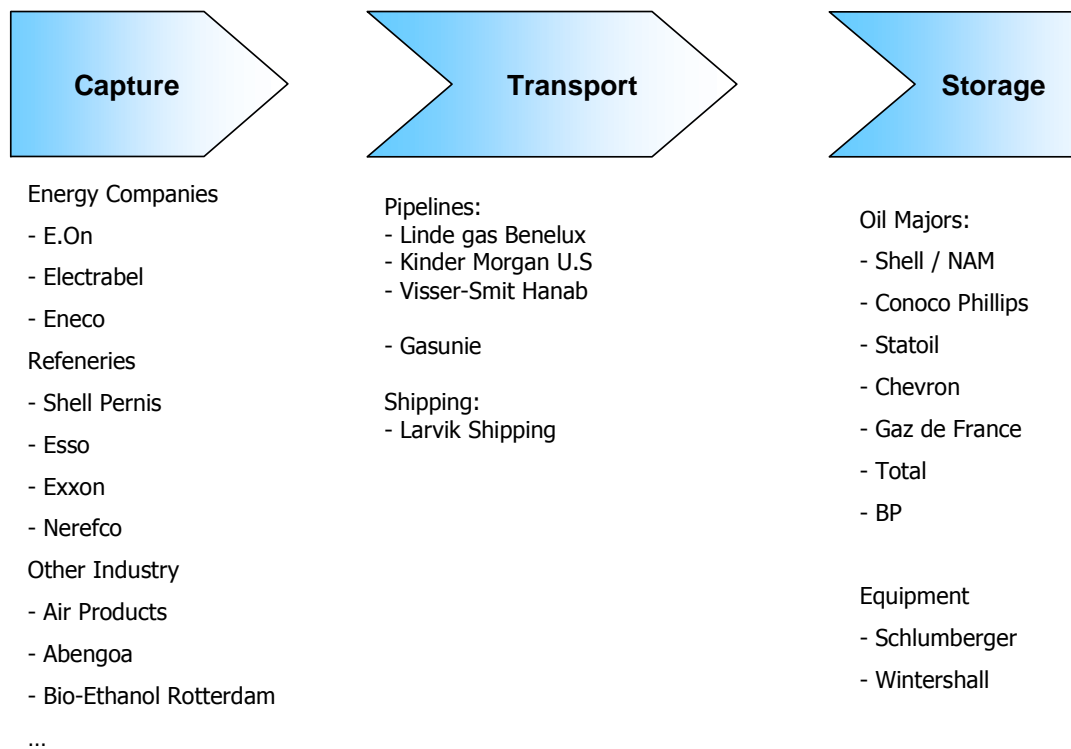
It is important to note that this figure gives a static overview. Stakeholders can switch positions and change from non-dedicated to dedicated actors when perceptions change, or compensation is offered.



**Figure 12: Stakeholder diagram**

The figure indicates which stakeholders need to move up to the first quadrant, to start up the value chain. The oil & gas companies and the power utility companies need to become dedicated, as they are critical actors. Furthermore, care must be taken to maintain or improve the position of the public and the environmental NGO's. They are critical, as major opposition might break a project, or induce extra costs.

Another method to identify the stakeholders and their power is by looking at the value chain. Figure 13 shows a number of companies active in the value chain. It must be noted that of the transportation companies, Kinder Morgan is not active in the port of Rotterdam region.



**Figure 13: Stakeholders in the value chain (M. Barrio et al., 2004; Knippels, 2007; Rohner, 2006)**

The figure shows that for capture, many CO<sub>2</sub> sources are available. They can compete for access to pipeline capacity. The companies that can build, operate and maintain a transportation system are relatively few. They have a strategic position in the value chain. For Storage, all oil majors can supply storage capacity. The location of suitable of storage reservoirs remains unclear.

For the rest of the report, the stakeholder analysis has provided requirements, constraints, performance criteria and possible design options; these are presented below in Table 3.

**Table 3: Requirements, criteria, constraints & design option Stakeholders**

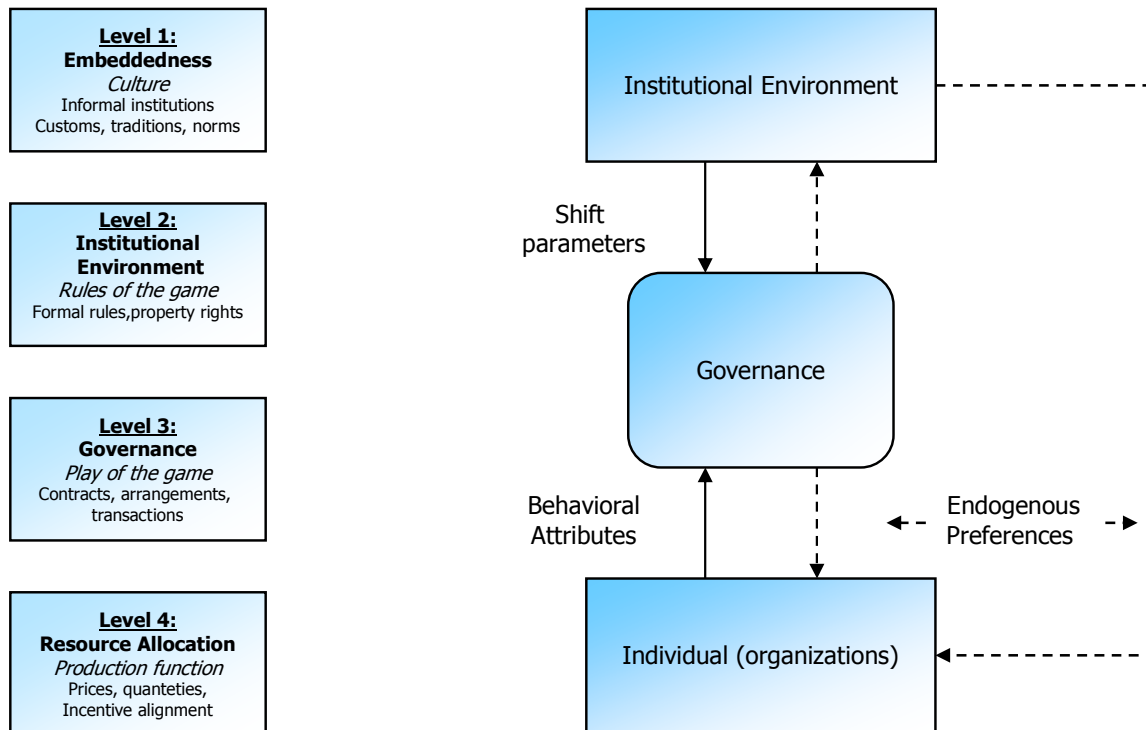
<b><u>Requirements</u></b>	<b><u>Criteria</u></b>	<b><u>Constraints</u></b>	<b><u>Design options</u></b>
The institutional arrangement between companies in the value chain should be efficient.	Efficiency in allocation of risk  Minimal transaction costs	The strategic importance of the control of capture process. Ownership of potentially usable assets (e.g. offshore infrastructure)	Restrictions to Vertical integration  Ownership of the network.  Contractual possibilities
The returns should be correspondent with the risks taken.	Risk/reward matches market situations	-	Options for Price & Return regulation
The regulatory framework should allow for cost recovery	Return on investment	No below cost service	Options for Price & Return regulation
The regulatory framework should ensure that the system stores at least 18 Mton in 2025	18 Mton in 2025 Capacity of: connected capture connected storage	-	-
The regulation and governance should encourage to connect as many sources and sinks as economically feasible	Volume of connected capture  Volume of connected storage	Capture cost, Storage capacity, Eu-ets price	Network expansion incentives
The regulations should be stable and predictable	Uncertainty (in IRR)		Design of a regulatory institution
The institutional arrangement should stimulate innovations	Cost decrease in time		Options for price & return regulations

### 2.3 INSTITUTIONAL ANALYSIS

The existing institutions put requirements, constraints and performance criteria on the regulatory framework to be designed. The new institutions need to fit the existing ones, as explained in the concept of institutional embeddedness.

The idea of embeddedness of institutions is explained by Oliver E. Williamson (1979), who defines four layers of institutions and argues that the different levels of institutions are connected and dependent. Koppenjan and Groenewegen (2005) use this concept as a tool to provide insight

in the field of institutional design. Figure 14 shows the concept with the interactions. The institutional environment made up of the culture and formal laws determines the modes of governance below. On the other side, the motives and behavior of individual organizations influence the governance modes from the bottom up. The cultural elements of the institutional environment shape the preferences of individual actors and individual organizations. The institutional environment refers to levels 1 and 2 of left figure. Recall that at these levels of institutional analysis the informal institutions such as culture and values (level 1) and the formal regulatory framework (level 2) are the subjects of concern.



**Figure 14: The concept of institutional embeddedness (Williamson, 1979)**

The dotted line of governance upward to the institutional environment indicates that by pointing out strategic benefits governance structures can also shape the institutional environment. That feedback is a critical aspect of this research. To come to efficient and effective outcomes the regulatory framework determines the emerging governance structure. And in the governance structure lays the key to an efficient market ordering. Holding this view, the central position of analyzing the stakeholder interests becomes apparent. The stakeholders' objectives and requirements determine the outcome of the governance structure. It is important to keep in mind that the process determining the outcome goes both ways, top-down and bottom up. The dynamics of this process of interaction poses a challenge for the designer of regulatory frameworks.

The institutional analysis is build up starting with a description of

**Design Requirement:**  
The designer should focus on the dynamic interactions between regulations and governance

institutional issues connected to infrastructure in general. The liberalization of infrastructures is treated in 2.3.1, the issues surrounding ownership and risk are treated in 2.3.2 and an analysis of market power is provided in 2.3.3. In 2.3.4 the analysis turns to rules and regulation specific to CCS. And in 2.3.5 the recent developments in policy are described.

### **2.3.1 Liberalization of Infrastructures**

The institutional analysis starts of with a general scope. The liberalization of infrastructures is a movement in infrastructure regulations that has shaped the institutional environment for infrastructure regulation in Europe. Two European Directives (Directive 2003/54/EC; Directive 2003/55/EC, 2003) formalize the liberal movement in rules and regulations. The following section treats the general arguments for liberalization.

Before the 1990s, infrastructure utilities were owned and operated by government or government entities. The utilities were vertically integrated and as such operated under as a state owned monopoly. Concerns on two levels were the main reason to uphold the monopolistic system. First, that such important services as water, communications and energy would befall to market parties who could not bear the costs and second, the need to protect captive consumers from a monopolistic market party. However, this model of governance leads to inefficiencies such as low productivity, short investments, poor quality and revenue shortages (Kessides, 2003, pp. ii-iv).

A new regulatory structure with a liberal policy has been adopted since based on European union regulation on liberalization measures (Directive 2003/54/EC; Directive 2003/55/EC). Through the mechanism of increased competition innovation, customer orientation and improved innovation can be realized (OECD, 2002).

Other elements of infrastructure liberalization are privatization of state-owned enterprises, the creation of competitive markets where this is possible and the application of performance based regulatory mechanisms (Joskow, 2003; Kessides, 2003).

The move towards a more liberalized sector with increased competition led to a series of policy changes. Countries who have gone through this change have mostly applied the following changes:

- Reorganization of state-owned utilities into autonomous enterprises that run on a commercial basis.
- Unbundling structurally competitive or contestable activities from natural monopolies.
- Removing restrictions on entry into the potentially competitive segments.
- Privatizing some or all assets, especially in the competitive segments
- Establishing institutional mechanisms to regulate activities where competition is not feasible.

(Kessides, 2003)

The liberalization movement in infrastructure sectors is important for the design of a regulatory framework from the embeddedness of institutions perspective. The embeddedness requires

institutions to match with the institutions already in place. This means that the regulatory framework of a CO<sub>2</sub> infrastructure should include elements of liberalization. In the following section we will analyze the institutional issues on vertical integration, monopoly and market power, and the efficiency of institutions. Note that vertical integration has also been a topic in the technological system analysis. The relation between the two will come forward in the discussion of the design options.

What should be noted here is that direct state-aid by member states of the European community directly aiding. Article 87(1) states that 'aid granted by a Member State or through State resources in any form whatsoever which distorts or threatens to distort competition by favoring certain undertakings' is incompatible with the common market and therefore prohibited (EC Treaty, 2002, p. 67). This poses a constraint for the public involvement and investments.

### ***Vertical Integration: Neoclassical arguments***

Vertical integration refers to the integration of subsequent activities in a value chain. It can be either forward vertical integration, where for example a producing firm gets involved in transportation of his products, or backward vertical integration where a for example a retailer starts producing and selling his own product line. This section provides an analysis of vertical integration in relation to the liberalization policy seen in infrastructures. The two issues are linked through one of the basic principle of liberalization: the unbundling of competitive and natural monopoly activities (Joskow, 2003).

Other liberalization issues such as the introduction of competition in monopoly markets and performance based regulatory incentives will be treated in the design options chapter. The issue of privatization, or more fitted to the case, private participation, is linked to the arguments for efficiency of institutions in section **Error! Reference source not found.** The following treats first the neo-classical arguments for vertical integration. Then, arguments related to the field of transaction cost economics and vertical integration are presented.

Neo-Classical Economics focuses on optimization issues and discusses these in terms of static equilibrium. It presupposes fully rational actors and zero cost transactions (Groenewegen & Lemstra, 2007).

Vertical integration creates market power. The firm which has integrated forward can charge downstream firms with no alternative or high switch costs (in economic terms: a high price elasticity) a price far above marginal cost. When the firm has access to an essential facility, it charges itself a lower price than its competitors. This causes the price in markets further downstream to rise (Joskow, 2005). Such an artificial price rise is not desirable from a general welfare perspective.

Furthermore, when the monopolistic firm gives access to a competitive market downstream where the he is also active, the monopolist can restrict access to exclude possible competitors in a downstream contestable market (Joskow, 2005).

In the case of a CCS value chain the downstream market is the market for storage capacity. There is sufficient capacity available on the North Sea basin to presume a competitive supply



(see section 2.1.3). There is even competition between storage types: aquifers, EOR or depleted reservoirs are available at different costs to the suppliers of CO<sub>2</sub>. The revenue for each type is different, owners of CO<sub>2</sub> want to sell their Mtons to EOR sites, where they can fetch the highest market price for their product (see section 2.1.3). Access to these sites can be restricted based on available pipeline capacity. The analyses of technology and stakeholders in sections 2.1 and 2.2 justify the conclusion that a CO<sub>2</sub> network is indeed an essential facility, connecting sources and sinks of CO<sub>2</sub>. The neoclassical argument against vertical integration holds. This will be shown extensively in chapter 4, with a worked out example.

There are more arguments for and against vertical integration. The body of knowledge concerned with transaction cost economics and their view on vertical integration is treated in the next section.

### ***Vertical Integration: Transaction costs economic arguments***

The argument of vertical integration and the size of firms draws back to Ronald Coase (1937). Coase argued that the size of a firm is dependent on the efficiency of transactions. If a certain product or service can be acquired at the market place for fewer costs than producing the product or delivering the service yourself, it makes sense to go to the market. However, the costs of making such a transaction should also be taken into consideration (Coase, 1937). These transaction costs are the crucial factor when making the decision on integrating into a hierarchy, or remaining a market consumer (Williamson, 1998).

The object under study is, bluntly put, the cost of a transaction. The formulation of contracts, the negotiations, and other transaction specific investments need to be incorporated when making a decision on purchasing a good or service (Groenewegen & Lemstra, 2007). In this sense, transaction cost economics is about the make or buy decision (Joskow, 2005).

Consider the situation where two firms have been transacting for a while and have created a 'lock-in'. For some reason, costs have become associated with switching to another buyer or seller. Because of the investments specific to the transaction, switching costs have created a tight relationship between buyer and seller. Either of the two can start behaving opportunistically by re-bargaining the contract on the new terms. Joskow terms this opportunistic ex-post bargaining (Joskow, 2005). To protect oneself against ex-post bargaining firms have the option to integrate the 'buy' relationship into their own activities, transforming the purchase or sale to a 'make' decision.

The specificity of assets to the transaction is a crucial determinant in the make/buy decision. The integration of the transaction into the own hierarchy can provide more certainty and harmonize conflicting interests. Investments made prior to the transaction can thus provide administrative controls under control of the firm, and conflicts of interest can be dealt with internally, without the need for settling disputes in costly court hearings (Williamson, 2002).

Asset specificity arises in five different contexts (Joskow, 2005; Williamson, 1983). We will briefly describe each here, and discuss how the attributes of a CO<sub>2</sub> infrastructure network fit the five types of asset specificity.

1. Site specificity: often termed a “cheek-by-jowl” relationship, described with the example of a coal fired power plant next to a coal mine. Once the investment in the assets is done, they can no longer be moved. This can be applied to a CO<sub>2</sub> network: once in place, the assets cannot be moved. The sites connected to the CO<sub>2</sub> network become more valuable, as it offers the possibility to easily avoid CO<sub>2</sub> emissions. A network can however be extended to include other sites. This makes it less site specific.
2. Physical asset specificity: when partners to a transaction make investments specific to that transaction. For example in equipment or machinery dedicated to the exchange. In CCS systems this can be recognized in the investments in capture or injection equipment.
3. Human asset specificity: experience or training needed to produce goods and services related to the transaction accumulate in company workers. Such knowledge and experience is of use to the firms in the transaction, but is hard to extend to other areas. This occurs for instance in complex technical relationships between firms who design and construct aircraft parts. In CCS systems it can play a role in the relationships between companies in the value chain. Each will have to invest in training its personnel to be able to participate in a CCS system.
4. Dedicated assets: refer to investments made that would not have been made without the prospect of the transaction. The typical example is the development of a natural resource deposit in a remote location with the intention to supply a large upstream user. With respect to CO<sub>2</sub> value chains this type of asset specificity can be recognized in the reservation of a geological reservoir. An empty reservoir can be either closed off, dedicated to natural gas storage, or used for CO<sub>2</sub> storage.
5. Intangible assets: intangible assets are typified as brand names or loyalty. Being green becomes more important for companies and this is expressed through their brands. In this sense, it can be connected to CCS. The relationship with transactions and asset specificity can return through claims on the responsibility for the emission reduction. at this point in the development of CCS value chains it is hard to envision how intangible asset specificity can play a role in the transactions.

A general conclusion Williamson and Joskow make regarding asset specificity is that the more specific the investment, the more prone it becomes towards integration into an hierarchical relationship.

But hierarchies have their downsides. Growing organizations contain diseconomies of scale. As organizations get larger the need for more bureaucracy grows. It becomes more difficult to control costs and adapt to changing market conditions (Joskow, 2005; Williamson, 2002). This has been empirically proven for several utility sectors to be the case (Shirley & Walsh, 2000). Joskow adequately summarizes the discussion: “The decision whether or not to vertically integrate then becomes a tradeoff between the costs of alternative governance arrangements” (2005, p. 22).

### ***Conclusions Vertical integration***

The analysis of the arguments of vertical integration and this final statement of Joskow lead to an important conclusion for the design of a regulatory framework. The regulatory framework can influence the governance arrangements by allowing, regulating, or restricting vertical integration. By influencing the costs of the transaction the regulatory framework has the power to constrain the possible outcomes of the governance structure.

The issue of vertical integration plays a prominent role in the current discussion on the implementation of CCS systems. The fear of ex-post bargaining withholds firms to invest in specific assets. Do firms want to invest in forward or backward vertical integration to gain control on transactions? Interestingly, it is not a question of economic trade-offs alone. Since a CCS system is also a technical system, requirements raised by technology play an important role: cost reductions are associated with coordination between subsystems. The discussion on vertical integration will play an important role in this study, the topic will return in chapter 3 where the option to allow or restrict vertical integration is discussed.

### **2.3.2 Institutions, Ownership and Risk**

The efficiency of the regulatory framework is one of its key performance indicators. The liberalization movement in infrastructures has claimed that private ownership is a way to reach efficiency in the management and operation of infrastructures (Joskow, 2003; Kessides, 2003). This is supported by empirical evidence showing that in general performance of competitive activities in infrastructure sectors has improved when ownership changed from public to private (Shirley & Walsh, 2000).

When indeed the private sector participates the distribution of investment risk becomes an issue. Since none of the market parties want to bear any risk they cannot control, the adequate distribution of investment risks becomes an important element of the governance structure. The efficiency of a cooperative agreement between companies in an infrastructure dominated value chain is partly determined by the distribution of investment risk. Investment risk is a complex feature of decision making. It is made up of many factors, for example general economic developments, fuel prices, feedstock prices, available financial capital, debt rate etc... (Higgins, 2003). Some of the factors can be influenced by the regulatory framework. Based on interviews two factors important for the design emerge: the distribution of risk through contracts and risk arising from regulatory instability.

#### ***Contracts and Risk***

If a company takes an investment risk, this risk needs to be offset by the outlook of a return. The degree of risk and of return need to be correspondent: a higher risk requires a higher return. It depends on the attitude towards risk of the involved company whether or not it is willing to make the investment (Higgins, 2003).

Another aspect of investment risk is the relation between control and risk. Companies contemplating investments need to make a trade-off between obtaining a controlling position over part of the project and bearing risk. It is not always straightforward that the company that

is able to control the system should also be the main investor. However, where possible, this is the preferred option, as the operator is also financially involved, he will have the incentive to reduce cost (Brealey, Cooper, & Habib, 2000).

The allocation of risks is included in an agreement on the distribution of rewards from a project. Companies along the value chain are all involved and try to shift risks to others, or attract risks if they are able to control them. To create an efficient arrangement in the value chain, the notions of responsibility, reward and risks need to be connected. To come to efficient governance structure two conditions need to be satisfied: 'firstly, responsibilities are allocated to the parties best able to undertake them, secondly risks are borne by the parties best able to manage them. Allocating risk to a party, generally, gives the party an incentive to alter its behavior to minimize its costs. Risk allocation therefore affects the parties' incentives to improve efficiency' (Correljé, de Jong, van der Linde, Snijders, & Thönjes, 2003, p. 15).

Firms invest in projects that are expected to yield a return in excess of a required or 'hurdle' rate. Observers of business practice find that such hurdle rates are typically three or four times the cost of capital.' (Dixit & Pindyck, 1994, pp. 6-7) In other words, private firms do not invest until price rises substantially above long run average costs.

When investing in pipeline infrastructure, the interesting aspect occurs that increasing capacity at the start of the project is less expensive than scaling up once the pipeline is in operation. There are many technical factors involved, for example material costs only increase to the 2<sup>nd</sup> power (circumference) while capacity increases to the 3<sup>rd</sup> power (volume) per unit volume added. Furthermore, from an institutional perspective there is an upside risk of demand increase. Extra additions to the network caused by for instance a regulatory change, or a high price on the ETS can result in increased demand for network capacity. This upside risk can be taken into account in financing techniques, such as real options financing. In real options financing, the probabilities of future developments and the related opportunity costs are transferred to the present through calculations with probability mathematics (Dixit & Pindyck, 1994)

Risk therefore does not only have a negative undertone. The willingness of private parties to invest in a project which has an investment risk signifies that there is a demand for the infrastructure and that it will be used. Secondly, risk based financing will lead to a increased involvement by lenders 'during the final design, construction and operation of the project, and more effective monitoring' (Flyvbjerg, 2003, p. 141).

When a project is characterized by uncertainty, and thus risks, it can become very costly to include all terms in a contract (Estache & Martimort, 1999). To reduce cost, next to contracts other forms of arrangements between companies can be applied. The scale ranges from hierarchal arrangements with elements of vertical integration to one-off market transactions. The

**Box: *Types of Risk***

The allocation of risks requires a characterization of risk types. One can distinguish technological risk, related to system failure, economic risk, related to demand and supply risks, and regulatory risk, related to changes in policy or regulations.

Companies are generally specialized in handling one of these risks. Banks can hedge economic risks. Engineering firms mitigate or adapt to technical risks. Regulatory risk remains hard to handle, and is therefore a topic of debate, which is treated in this section.

field of transaction cost economics has resulted in scientific literature on the range of institutional arrangements and what factors influence the preference of an arrangement in a certain environment.

The regulatory framework should make sure that the risk is distributed such that it leads to minimal costs. This subject will return in section 2.3, where stakeholder interest also covers risk issues and in chapter 3, which will explore different mechanisms used to deal with investment risks.

### ***Regulatory risk***

The stability of regulations is an often heard requirement (see also stakeholder analysis 2.3). Changes in policy leading to a change in the regulatory regime influence the investment decisions made by market parties. Companies base their decisions on a term based on the expected life time of the project. Since in infrastructure investments, the considered life time is long (20+ years) investors need to have a clear picture of the regulations in the long term. On the other hand, governments find it hard to commit themselves for such a long term. This leads to requirements of robustness of institutions.

At the same time, institutions should be able to adapt to new situations. A technology change, economic developments or other transitions can outdate the institution. "Revisability" is an important requirement for institutions, but should be applied proportionally (Goodin, 1996).

Kessides is more concrete in stating to what changes a regulator should adopt: "changes in demand and supply, in industry technology, and in competitiveness of the directly regulated adjacent markets" (Kessides, 2003, p. 62). So regulatory flexibility and adaptability is especially important in sector which are experiencing technological innovations and market changes. The market for CO<sub>2</sub> emission reductions can be very well categorized as such.

The risk of a system of regulations (possibly accompanied by a regulator) is apparent in the abuse of regulatory changes by government or regulators to further their own goals. If outcomes turn out to be 'best case' rather than 'worst case', it appears as if a company has made excessive returns. In such scenario's policy makers are pressed to "claw back" the higher returns, as supposedly, the companies operating under regulation were allowed to make too much profit at a cost to society.

However, by failing the commitment, the risks for projects rise, and cost of capital will increase (Berg, 2001). The requirement that arises from Berg's analysis pleads for the independence of a regulator from the state authorities. This requirement is found in many places in literature, for the same reasons as Berg has sketched. Therefore, when a regulator is considered in the regulatory framework for a CO<sub>2</sub> network, it should be independent from elected government officials.

Companies take regulatory risk into account when calculating their required return on investment. Moreover, when regulatory instability is perceived, the opportunity cost of delaying action, waiting to see what happens with regulation, becomes a option for potential investors

#### **Design Requirement:**

The designer should be independent of both government and private stakeholders

(Dixit & Pindyck, 1994). According to Dixit and Pindyck, policy makers can create a situation of investment delay, by starting a procedure designed to promote speedy investment.

Literature on the design of regulatory institutions is widely available, mostly from reports and working papers by the World Bank. We have included requirements on regulatory institutions from these documents in an appendix dedicated to this issue (see Appendix C.5)

With respect to CO<sub>2</sub> value chains, the exogenous developments to which a regulator should be able to adapt can be generalized in changes in technology, European policy and world economics. Examples of technological developments include radical innovations in CCS or other carbon reducing technologies; a change of European policy towards CCS, for example the obligation to capture and store CO<sub>2</sub>, and; changes in geo politics resulting in increased scarcity of fossil fuels and the related changes in fossil fuel price.

### ***Conclusions Risk Distribution***

A general conclusion related to risk, is that risk should be allocated to those who can control it best, or in other words, against the lowest costs (Correljé et al., 2003). Involving private investment leads to efficient distribution of risks, both technical and economical. This is because parties with knowledge of technical system are superior in managing risks, therefore are able to provide a cheaper service, or an improved design. A similar mechanism arises with economic risk. Private actors who are able to adopt or hedge economic risks can provide capital at the lowest rates. If no private financing can be found at reasonable rates, combined financing with debt and equity capital is possible.

Private investors only take private values into account; public good values are not calculated in the investment. With respect to CO<sub>2</sub> pipelines, this issue comes to the fore with respect to pipeline design and the related investment costs. Increased pipeline diameter creates the opportunity for companies to join the network in the future at limited costs. The costs for the extra diameter however need to be borne during construction. This issue is linked to competition and vertical integration. Firms active in a CCS value chain may want to block entry from others if it gives them competitive advantage. Therefore, it is hard for private investors to assess the need for a pipeline design of sufficient capacity to achieve public goals: effectiveness and efficiency of the CCS value chain. This argues for public involvement in the design and investment of the pipeline network.

With respect to regulatory risk independence of politics and regulation is important. Although the regulation serves a political goal, it needs to be secure against political influence. Flexibility of regulations need only occur when necessary. How this is achieved in practice remains an unresolved issue, and in reality, looking at other sectors remains a tough nut to crack (Alessie, 2007; Correljé, de Jong, van der Linde, Snijders, & Thönjes, 2003).

### **2.3.3 Analysis of Monopoly and Market power**

Market power is a concern for all participants in an infrastructure dominated sector except for the entity that holds the market power. Market dominance can result in price levels that are much higher than efficient price levels. This happens when prices are above long run marginal

cost. Market power can also be observed when consumers have low price elasticity. Or in non-economic terms: producers with market power can raise their prices without losing customers (Khemani & Shapiro, 1993). If public goods are concerned, such inefficiencies can present substantial social cost (Correljé, François, & Massarutto, 2006).

Market power has been studied, especially in relation to the electricity sector, where market power can have adverse technical consequences, leading to black-out, as happened in the California case (UNDP / Worldbank, 2001).

Barker, Tenebaum and Woolf have researched market power in the electricity sector and found a list of conditions which indicate market power exertion. The list is adopted for the CO<sub>2</sub> case:

- Significant and sustained departures of market clearing prices from estimates of long run and short-run marginal costs
- Capacity withholding
- Unexpected low availability
- Scheduling of maintenance at times of high prices
- High bid prices by generating units that "must run" for reliability reasons
- New and unexpected congestion on transmission lines
- Opposition by one or more capture plants to transmission investments that would relieve congestion

(Barker, Tenenbaum, & Woolf, 1997, p. 37)

It will be difficult to assess *ex ante* if market power will occur or not. Based on Herbert Simon's ideas on 'frailty of motive' and 'bounded rationality' (Simon, 1985), Williamson (1998) has argued that if there is a risk of market power, and kind and caring actors cannot be expected. The design of the organization should contain mechanisms that limit market power. And transaction costs economics is the study of choice:

"If candid reference to opportunism alerts us to avoidable dangers, which the more benign reference to frailties of motive would not, then there are real hazards in the more benevolent construction. Attenuating the *ex post* hazards of opportunism through the *ex ante* choice of governance is central to the transaction cost economics exercise."

[italics in original] (Williamson, 1998, p. 31)

It is an important question to find out if market failure could be a problem in a CCS infrastructure. It also needs to be assessed if this market failure is large enough to justify investments in a competition authority or other regulatory organization.

To answer this question, we take two steps. First we look at the issues in a network of industrial waste heat. Then we look at the situation of the CO<sub>2</sub> network to the Dutch horticulture sector.

### ***Heat networks***

A waste heat network is comparable to a CO<sub>2</sub> network in several respects. Like CO<sub>2</sub>, heat is a by-product of industrial activity. Industries need to discard their heat one way or the other. Efficiency can be increased if the low quality heat can be used effectively at other locations. Another similarity with CO<sub>2</sub> networks lies in the absence of a regulatory framework laid down in law.

The heat from is transported over a network and is sold to consumers (households, companies, other industry). Of interest in the analysis for market power is the price for which the heat will be sold. Currently, the mechanism that is applied is the so-called NMDA (*Niet Meer Dan Anders*) principle. NMDA implies that consumers of waste heat will never pay more than if they would have used natural gas (De Wit & Traversari, 2005). The heat is priced according to the substitute product, not according to the cost, a clear departure from competitive behavior and a signal of market power.

Consumers have organized themselves to protest against these prices and have been successful in some court cases (Actie Gigajoule, 2007). Politicians want to protect the interest of consumers as growth of the heat networks is expected. They want to include a supply obligation for heat suppliers, guarantees on service quality, a conflict resolution mechanism and monitoring by the Dte. Furthermore, a cost-based tariff is preferred, while maintaining the NMDA principle as a price ceiling (Köper, 2007).

From the situation in the heat networks it can be concluded that market power exists. Consumers are faced with high switching costs, prices are above costs.

### ***CO<sub>2</sub> networks and horticulture***

As mentioned in section 2.1.3 on storage options CO<sub>2</sub> is currently sold to horticulturists who use it to enhance crop growth. The OCAP project distributes CO<sub>2</sub> from the Shell refinery in the Rotterdam Botlek area to greenhouses in the region north of the port (OCAP, 2007). The prices horticulturists pay are nontransparent. According to the DCMR these are around €45,- /ton CO<sub>2</sub>, compared to cost estimations in the IPCC report, which are confirmed by the DCMR research, the costs for capturing and distributing the CO<sub>2</sub> are only €17,- (Hanegraaf, Santen, & Knippels, 2007).

As discussed in the technology section, uncertainty about the costs and rewards for Enhanced Oil Recovery (EOR) plays an important role in the feasibility of starting up the CCS value chain. The possible revenues achievable from CO<sub>2</sub> injection in nearly depleted oil fields ranges from a cost of €10,50 (Hendriks, Graus, & van Bergen, 2004) to a reward of €60,- (Hanegraaf, Santen, & Knippels, 2007), see also section 2.1.3 on storage technologies.

Strategic interests on concealing the actual costs and income play a role. The negotiations on CO<sub>2</sub> delivery to the oil rigs can create large revenues for both supplier and consumer. EOR is therefore considered as an important start up application for CO<sub>2</sub> value chains (Warmerhoven, 2006). The value of strategic information on actual costs plays an important role. Companies with strategic assets can try to inflate their costs to justify higher prices. Such behavior is common and reasonable. Markets and competition are the most suitable mechanisms to create efficient



pricing, the amount of information that can be condensed into a single number, price, is the crucial strength of the market (Williamson, 2002).

From the above sections on vertical integration and market power, the possibility of introducing competition appears useful. In chapter 3, the options for introducing competition in infrastructure sectors are treated. This is closely related to the possible restrictions on market power and vertical integration.

### **2.3.4 Rules and Regulations concerning CO<sub>2</sub>**

The regulations common in CCS literature concentrate on the required adaptation of existing laws to pave the road for CCS systems. The focus lies with integrating storage in existing regulations. The inclusion of CCS in the ETS is interesting, as the scope of economic regulation can provide handle points for integrating the required regulation.

#### ***EU Directives***

Pietro Di Zanno and François Giger have compiled the work of the group on legal issues and regulations of European Union Research group on Zero Emission Power plants (ZEPP). The following directives have the highest priority to be amended:

- 96/91/EC Directive on Integrated Pollution Prevention and Control: Is CO<sub>2</sub> a waste or a product?
- 99/31/EC Landfill Directive: storage of CO<sub>2</sub> in geological formations should be exempt from the landfill Directive
- 00/60/EC: Water framework Directive: storage in aquifers is prohibited under this Directive

More interesting, these directives are involved in a discussion on the classification of CO<sub>2</sub>. Currently, CO<sub>2</sub> is traded as a non-flammable, non corrosive, non poisonous gas. When CO<sub>2</sub> is captured from flue gases (in post-combustion) and liquefied to be stored, it can be 'regarded as waste in the context of EU legislation, as is governed by the provisions of the EU Directive of 15 July 1975 on waste' (Di Zanno & Giger, 2006, p. 44). However, when CO<sub>2</sub> is captured in a pre-combustion system where hydrogen production is the objective, the CO<sub>2</sub> can be seen as a raw material input for processes such as urea and methanol production or for application in ECBM, EGR or EOR.

If waste law is applicable, another obstacle arises. The Directive 1999/31/EC on landfill of waste is unclear on the underground storage of liquids or gases, but in the opinion of the ZEPP the landfill directive could be used to forbid storage of CO<sub>2</sub> in geological formations (Di Zanno & Giger, 2006).

The water framework directive also requires consideration in the context of CCS. Particularly when the geological storage in aquifers is concerned, the regulations on groundwater may

provide an obstacle for CO<sub>2</sub> storage projects. It is recommended that the directive contains a similar amendment as is available for the storage of natural gas (Di Zanno & Giger, 2006).

Similar recommendations can be found with other groups, such as Eurelectric (an organization for power producing companies), the DCMR and the NAM. It is widely expected that the necessary changes to remove barriers to CCS will be made by the European Union (Eurelectric, 2007; Hanegraaf, 2007; Kuijper, 2007; Strömberg, 2006; ZEPP, 2006b).

Barriers in international law, most notably the 'London Protocol' on international waters has been recently adapted to include offshore storage of CO<sub>2</sub>. Offshore storage of CO<sub>2</sub> in international waters is now allowed.

### ***Ownership & Responsibility for Storage sites***

Another issue that is prominent in the discussion on CCS is the responsibility for monitoring and controlling leakage at storage sites. The concern here is that storage operators will neglect their stewardship of the storage site and avoid costs of monitoring and controlling the site. The following option is considered the most plausible to be put into regulation.

The operator of the injection of CO<sub>2</sub> in a storage field is responsible for monitoring and controlling the site during the period of his activity. Once the injection is ended the storage operator hands over the responsibility for monitoring and control to the state on which the storage site is located (Roulet, 2007). The timing of the handover and the prolonged responsibility of the operator over the storage site can be subject of the negotiations with the government. A detailed and clear description of such a procedure is necessary to provide adequate transparency (Spiegeler, 2007). The oil and gas industry have experience with similar conditions, and a lot can be learnt from their experiences.

In the research by DCMR, Hanegraaf et al. (2007) make a noteworthy comment on the current system of allocating concessions for the exploitation of oil and gas fields. In the old system the national government has almost no influence on the usage of empty or nearly depleted oil and gas fields. The DCMR recommends changing the procedure and giving the government more leverage in allocating or reserving fields for CO<sub>2</sub> storage.

### ***Inclusion of CCS in the EU-ETS***

The European Union Emission Trading Scheme is a market where companies can trade CO<sub>2</sub> emission certificates. In short, it works as follows: Companies are allocated a number of emission allowances corresponding to their historical CO<sub>2</sub> emission. A company is allowed to trade a certificate when he has achieved a validated emission reduction. Other companies, who have increased their emission beyond the allocated amount, need to buy extra certificates to compensate the increased emissions. Through this system, a value is given to a CO<sub>2</sub> reduction at a certain moment in time. The market mechanism can produce an efficient outcome: emissions are reduced when and where this can be done at the least cost (Point Carbon, 2007).

The inclusion of CO<sub>2</sub> stored through CCS as tradable emission reduction is a crucial requirement for the financial feasibility of a CCS system (among others: Warmerhoven, 2006). The organizations supporting the technology agree on this issue, whereas opponents resist the inclusion. The general expectation is that once certain specific (long-term) conditions for leakage of storage sites are guaranteed (see Box), a compromise will be reached. Under strict conditions the CO<sub>2</sub> stored in geological formations or aquifers can be considered as a tradable emission reduction starting from the next regulatory period post 2008 (Drenth, 2007; Hanegraaf, 2007; Spiegelger, 2007).

But inclusion of CCS in the ETS alone is not enough, especially to realize CCS projects in the short term. There also needs to be a guarantee that the price level of CO<sub>2</sub> emission reduction is sufficiently high to cover the costs of the entire value chain.

The objective of the ETS is to create a behavior change of both consumers and producers of energy (and other CO<sub>2</sub> producing products). To achieve a high enough price, three conditions must hold:

1. There should be sufficient scarcity of emission allowances.
2. There should be an enforced fine with a high enough level.
3. The costs involved with the emission reduction cannot be avoided or passed forward to consumers.

(Haar & Haar, 2006)

Trading at the EU-ETS creates uncertainty about the exact value of carbon certificates in the future. Therefore, it is not only a risk to start the capture, also the counterparties in transport and storage will need to base their investments on the unsure, volatile value of CO<sub>2</sub>.

Concluding section 2.3.4 Rules and Regulations concerning CO<sub>2</sub>, it can be said that these regulatory changes are broadly endorsed by various stakeholders. Getting the legislation right is a necessary barrier before implementation of a CCS system. Many of the concerns of existing and

**Box: inclusion of CCS in the EU-ETS**

"Consequently the following boundary and completeness criteria are considered for CCS under the EU-ETS:

-All CO<sub>2</sub> produced at each installation should be calculated according to the existing guidelines for that installation as outlined in Decision C(2004)130.

-Energy used for powering the CO<sub>2</sub> capture equipment and for initial pipeline compression at the installation will be incorporated into the net calculation for each installation.

-Any fugitive CO<sub>2</sub> emissions occurring at each installation through inefficiencies in the capture process as any stack emissions of CO<sub>2</sub>, should be reported and reconciled with the installation.

-Any fugitive emissions arising from the transport of CO<sub>2</sub> to the storage site should be reported and attributed to the Transport system that should be considered as an installation under the EUETS.

-Any emissions during injection at the storage site should be attributed to the transport (??) system

-Any fugitive emissions occurring from the storage site (post injection) do not need to be reconciled with, but should be dealt with specifically within the permitting regime."

*p49-50 EU Research Platform on Zero Emission Fossil Fuel Power Plants – Strategic Deployment Document (ZEPP, 2006b)*

proposed legislation have links with market related mechanisms. It would be of value to integrate concerns, safety and economic performance, into one regulatory framework. This subject will return after the analysis of the other institutions, in section 2.3.6 *Conclusions Institutional Analysis*.

### **2.3.5 Recent Policy Developments**

One of the factors against which a CO<sub>2</sub> regulatory framework should be robust is policy developments from levels outside the scope of control of the responsible government authority. Most notably, these are policy and regulations drafted at the EU level. This section contains an overview of exogenous policy developments with a degree of uncertainty whether or not they will be implemented.

The European Commission has put out a communication where they consider obligating capture for coal fired power plants after 2020 (European Commission, 2007). Such an obligation would have consequences for the market position of power plants in a CO<sub>2</sub> market. It becomes much weaker as they no longer have the choice between emitting CO<sub>2</sub> or transferring it to the pipeline system. The power plants become completely dependent on the other parts of the value chain. To get an improved strategic position in the value chain the power plants need some protection. They can either vertically integrate with transport, or the transport market can be regulated. This will be further discussed in the design phase with the help of conceptual designs.

A further policy development concerns the future of the EU ETS. That CCS will be included after 2008 is broadly expected and the regulations of the ETS period 2008-2012 are reasonably clear. The EU is in negotiations with member states to rigorously bring down the national allocation levels. This has a positive impact on the price of emission allowances at the trade floor. Contrary to the price level of the current ETS period, the prices for allowances in 2008-2012 have risen on the expectation of further cuts of emissions (Point Carbon, 2007). However, what will happen after 2012 is unclear. The EU is evaluating options to increase the use of the carbon market. One of the options that is considered is auctioning of the emissions allowances at the start of the regulatory period (Groeneneberg, 2007). This will no doubt have an impact on the revenues in a CCS project. Although its future is insecure, policy makers on all level should, and do, stress the continuation of the ETS in any form (Point Carbon, 2007). Since policy makers and politicians have committed themselves to the climate change issue, we do not expect that the interest for CO<sub>2</sub> emission reduction will wane. On the contrary, once it has been shown that CO<sub>2</sub> emissions can be dramatically reduced, the issue will remain on the agenda. This view is confirmed by a survey done by Point Carbon on its annual conference of industry experts (Point Carbon, 2007).

Apart from the level of the price of the ETS, it is also unsure which party of the value chain will be the one to be allowed to sell the reduced emission. Will it be the capture plant who prevents the emission, or the storage company who secures the removal from the atmosphere. Or will the involved companies be allowed to make the desired arrangements themselves. As this issue is still unresolved, we will try to make recommendations towards this issue in the final chapter.

This section has highlighted the importance of regulatory independence from policy makers. Secondly, the regulatory framework should be robust and flexible at the same time.

### 2.3.6 Conclusions Institutional Analysis

The analysis of the institutions has focused on the embeddedness of the regulatory framework in other existing institutions. This leads to six conclusions. The conclusions in their turn provide requirements, performance criteria and constraints for the design. Also they indicate design options from which the designer can choose to build his design. First the six conclusions are presented here.

Private investment involvement leads to a more efficient market in terms of risk distribution and transaction mechanisms. This holds for both economic and technological risk. The downside of private investment is that it does not consider public good values. Since there are public good values involved with effective and efficient CCS value chains public involvement in the investment is justified. From this trade-off a clear design option can be identified: a decision for public, private or hybrid form of investment.

The vertical integration in the value chain also has its advantages and disadvantages. The choice for production of a good or acquiring it in the market is a tradeoff companies need to make. The issue of vertical integration and market power is closely linked to this question of governance structure. A regulatory framework can use restrictions on vertical integration as an instrument to influence the governance structure. This makes restrictions on vertical integration a second design option for the design of a regulatory framework.

There is a clear body of literature on the design of regulations. Regulations should be stable, predictable and flexible. They need to deal with exogenous developments in such a way that the value chain participants can predict the outcome. Apart from these requirements, a regulatory authority needs to be independent of elected representatives of government. This is linked to a requirement on the design process. To come to a design that is accepted by both government and private companies' independence of both parties is needed.

Finally, the addition of regulations necessary for inclusion in the ETS to the economic framework of infrastructure regulation creates an extra function for the regulatory framework.

The institutional analysis has mainly provided design variables. The requirements, performance criteria, constraints and design options arising from the institutional analysis are given in Table 4.

**Table 4: Requirements, criteria, constraints & design option Institutions**

<u>Requirements</u>	<u>Criteria</u>	<u>Constraints</u>	<u>Design options</u>
The institutional arrangement between companies in the value chain should be efficient.	Minimal transaction costs	-	Restrictions on vertical integration Ownership of the network.

			Contractual possibilities
The institutional arrangement should fit the existing style of market based control	Investment participation of private companies	-	The ownership of the infrastructure; competition regulation
The investments made should be recovered	Minimal return on investment	No below cost service	Options for price & return regulations
Institutional arrangements need to be stable and predictable	Minimal uncertainty, minimal perceived investment risk due to regulatory capture		Design of a regulatory institution
When a regulator is considered, it should operate independent of elected government representatives	Independence of a regulator		Design of a regulatory institution
The institutional arrangements need to be flexible and adaptive	The speed and adequacy of adaptation		Design of a regulatory institution
The regulation of the value chain needs to fit the requirements of the inclusion in the EU-ETS	Inclusion in the EU-ETS	Specified by the EU-ETS	

## 2.4 MAIN CONCLUSIONS SYSTEM ANALYSIS

The analysis of the system has treated three perspectives on the system; technology, stakeholders and institutions. Besides generating insight in the mechanisms, dynamics and build-up of the different elements the analysis has focused on generating requirements, criteria, constraints and design options for the regulatory design. These are summarized in Appendix C Basis of Design. In this section, the conclusions related to the analysis are summarized and connected with each other.

### ***Conclusions Technology Analysis***

The analysis has provided a system boundary for the design of a regulatory framework. From a technological point of view, the framework can focus on the network alone, taking the capture and storage parts as black boxes with only cost, temperature and pressure requirements. The network requires coordination on temperature and pressure. A further important constraint is the need to have a network balance. There can be some slack in the network, but generally, the

amount of CO<sub>2</sub> produced at a given time needs to match the CO<sub>2</sub> injection capacity. The design takes technology as an exogenous variable. Therefore, section 2.1 provides an analysis of the technology and its consequences related to an institutional design. Technology is relatively static. Most equipment that is needed is available, and the predicted innovations are on the level of cost reductions, mainly in energy efficiency of the capture process.

That economies of scale exist in CO<sub>2</sub> pipeline networks has been confirmed by the analysis. Investments in infrastructure are enormous, creating a very high fixed cost and low variable cost,

**Box: Conclusions Technology Analysis Summarized:**

- The subsystems in the value chain put technical requirements on each other. This leads to the need for a network standard with regard to temperature, pressure and purity of CO<sub>2</sub>.
- Coordination of activities between subsystems can lead to cost reductions.
- CO<sub>2</sub> pipeline networks exhibit strong economies of scale
- Ships can provide competition for offshore transport
- The reaction of geological reservoirs to the injection of CO<sub>2</sub> requires more research, especially empirical research on large scale in the form of demonstration projects.
- It can be assumed that storage reservoirs are competitively available near the port of Rotterdam.

with a marginal cost close to zero. The natural monopoly character of the infrastructure is not only based on its extreme economies of scale, it is also regulated by the Harbor Authority that there can be only one pipeline for a substance per route. Next to the natural monopoly character of the network, public interests are involved in a CCS system. Based on the system analysis we can conclude that government involvement is justified.

***Conclusions Stakeholder Analysis***

Secondly the stakeholder analysis has shown that the public goods and external effects in a CCS value chain justify involvement of the government. The multi layered governmental structure of the Netherlands offers possibilities for the design of a regulatory framework and the required

**Box: Conclusions Stakeholder Analysis Summarized:**

- The intention to come to a CCS system exists with public, private and non-governmental stakeholders
- The high costs involved with starting up de the value chain generates a hold up problem, creating the main barrier for construction of the necessary subsystems.
- Start up through demonstration projects is widely considered as the next step in the implementation process.
- Many companies in both capture and storage can possibly be involved in the related subsystems
- For transport, only a limited number companies can offer the services required.
- The stakeholder analysis results are static. For the sake of the analysis we need dynamic results, about possible future positions of stakeholders. Therefore, the positions can be used as a starting point, but awareness towards changes remains necessary.

regulatory independence. The interests of the governmental bodies are aligned, where the local authorities besides having knowledge of the local conditions also have connection in the social networks. The position of the stakeholders is different from technology as it contains much more dynamics. Positions of stakeholders change over time. And, the design must consider the stakeholders' interests into the design. The movements of stakeholder positions are critical for a successful CCS system implementation.

### ***Conclusions Institutional Analysis***

The analysis has provided a design inputs from the concept of embeddedness of institutions, the new institutions need to be congruent with the existing ones. Another element the design needs to incorporate is raised by the need for the regulatory framework to support the inclusion of CCS in the EU-ETS. The requirements for inclusion focus on technical issues to secure storage and prevent leakage. Furthermore, the institutional analysis has shown that vertical integration in the value chain can have negative effects. The tradeoff between cost reductions for vertical integration and the cost increases through the resulting market power is one of the key issues in the efficiency of a regulatory framework. This element of the design will be further researched in the report. The design options and conceptual designs will further look into this issue, and relate vertical integration and the role of competition to the specifics characteristics of CCS.

#### **Box Conclusions Institutional Analysis summarized**

- The regulatory framework can influence the governance arrangements by allowing, regulating, or restricting vertical integration. By influencing the costs of the transaction the regulatory framework has the power to constrain the possible outcomes of the governance structure.
- Risk should be allocated to those who can control it best, or in other words, against the lowest costs. Involving private investment leads to efficient distribution of risks, both technical and economical.
- It is hard for private investors to assess the need for a pipeline design of sufficient capacity to achieve public goals. This argues for public involvement in the design and investment of the pipeline network
- Regulations should be stable, predictable and flexible. They need to deal with exogenous developments in such a way that the value chain participants can predict the outcome. Apart from these requirements, a regulatory authority needs to be independent of elected representatives of government.

### ***Design options***

From the conclusions on the institutional design three design options appear central to the design question. From the liberalization of infrastructures the need to arrange some kind of market mechanism for infrastructure governance is required. Chapter 3 will look into different



alternatives of regulating infrastructures with the introduction of competition and the market mechanism. A Second design option comes from the issues surrounding vertical integration. When vertical integration is restricted issues of market power can be prevented. However, when allowed, private investments will lower the societal costs and lead to more efficient distribution of risks. This design option is also treated in chapter three. Connected to this issue is the issue of ownership. Public ownership results in more control by public authorities on the design of the network. It becomes easier to include public values in the cost-benefit calculation in the design. On the other hand, the effectiveness realized with public ownership has a disadvantage with respect to efficiency. Private funds lead to more efficient investment and low cost operation. This third trade-off is also treated in chapter three.

The total list of design variables is shown below. These are:

- the ownership of the infrastructure
- the introduction of competition for network capacity
- restrictions or freedom on vertical integration
- the design of a regulatory authority
- the design of a price & return mechanism
- the design of network expansion incentives
- the design of regulation on entry barriers
- the design of added performance incentives

As the next chapter will show, the design options are interdependent. A choice made in the way to introduce competition for example is linked to the ownership of the infrastructure and the regulation on entry barriers.

### ***Requirements & Constraints***

The system analysis has focused on three areas: technology, institutions and stakeholders. Each has delivered four products: a set of requirements, a list of performance indicators, a set of constraints, and a set of design options. In this section, the most important ones are summarized.

The requirements and constraints of each part of the analysis are summarized in the tables at the end of each sub section, also they can be found in Appendix C Basis of Design.

### ***Performance Criteria***

From the analysis several performance criteria have emerged by which the designs can be evaluated. The views on the relative importance between stakeholders are different though. The criteria are:

- **The total volume of CO<sub>2</sub> captured and stored before 2025 should be at least 19 Mton**

- This is necessary for conforming to the Clinton climate initiative. The total volume is not dependent on the regulatory framework alone, but the regulations can play a crucial role in reaching this goal.
- **The regulatory framework should support an efficient operation of the total system**
  - The technical aspects of the system should be integrated in the regulatory framework in such a way, that the regulations support the technological system efficiency.
  - The regulatory framework should be able to adapt against changes in policy and technology in a predictable, (stability enhancing) manner.
  - The regulatory framework should contain options to encourage connections to other industrial areas to the network.
- **The market prices should be close to marginal cost**
  - For efficient markets, prices need to be close to long run marginal costs. This gives investment signals and secures fair pricing. (Static efficiency)
- **All those in the market willing to pay the market price must be served**
  - The network must connect all the parties who are willing to pay at least the market price. This leads to efficient network expansion. (allocative efficiency)
- **The regulatory framework should stimulate cost reductions through time**
  - The regulatory framework should contain incentives for reducing cost through innovations. This criteria is also known as dynamic efficiency.

The first two criteria are connected to the effectiveness of the system. The effectiveness of the system as defined here is not only dependent on the regulatory framework. There are many other factors present. When evaluating designs or proposals against this criteria.

Performance criteria can be directed at both the regulatory framework and at the performance of a CCS system in general. These are linked to each other as the regulatory framework is an institution that coordinates arrangements between actors in such a way that the most efficient system performance is realized.

### 3 DESIGN SPACE ANALYSIS

This section develops the design space. The design space analysis has the objective to provide insight in the range of possible solutions for the dilemmas spanned by the requirements, constraints and performance criteria. So first these dilemmas will be formulated. Then, the design options will be explained, divided into three levels, in structural elements, behavioral elements, and performance enhancing elements.

From the system analysis in the previous chapter we know the set of design options that the regulatory framework can consist of. For clarity, they are repeated here:

Chapter 2 resulted in a list of requirements, a set of performance criteria, a set of constraints and a list of design options. The design options are the main topic of this chapter. The list of options is repeated below, but this time a range is included.

**Table 5: Design Options and Range**

<i>Design Option</i>	<i>Range</i>
Ownership of the infrastructure	[public, ... , private]
The introduction of competition	[fully regulated, for, over, among]
Restrictions or freedom on vertical integration	[fully unbundled, ... , fully integrated]
The design of a regulatory authority	[none, single, multi-utility, local, national, supranational]
The design of a price & return mechanism	[none, pricecap, ROR, capacity auctioning]
The design of network expansion incentives	[none, per connection, per volume, auction, ...]
The design of regulation on entry barriers	[none, NTPA, RTPA]
The design of added performance incentives	[none, per volume, ...]

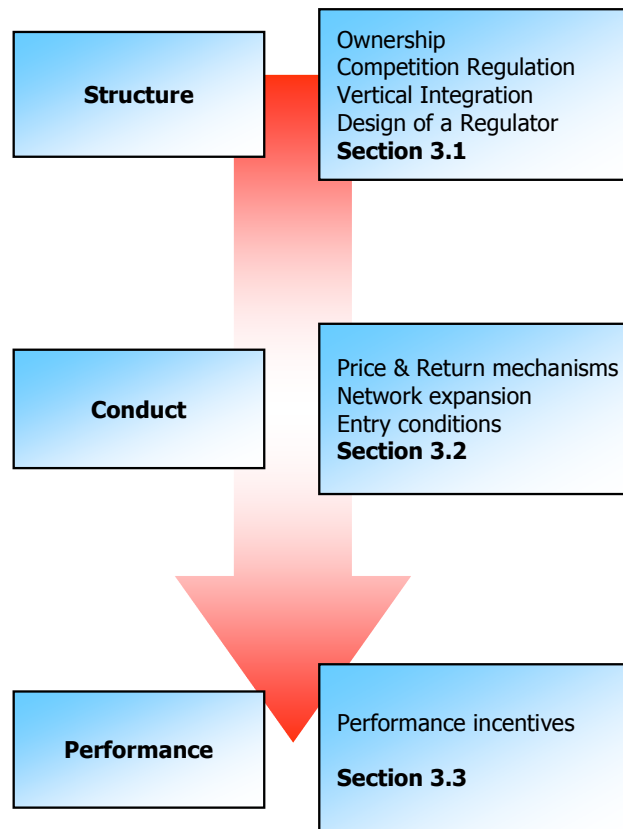
The possible range of solutions in this list can be condensed by using two insights. First, since the design space is seeking to support the design of an institutional arrangement in a technical environment, the constraints posed by the technological system limit the possible solution space. Second, some of the constraints put forward by the existing institutions or dominant stakeholders are so strong that they determine the design. Examples are the requirements posed for including CCS induced CO<sub>2</sub> reductions in the EU-ETS and the requirement that no service should be delivered below cost.

The chapter is structured according to the 'structure-conduct-performance' concept as presented by Berg (2001). The aim of the concept is to provide a framework for the design of regulatory governance systems. Let it be clear that the levels are not completely independent. A choice for a governance mode or regulation in one level can limit the options in another level.

**Structure** or market structure covers the basic elements of the market. Examples of important structural elements are the amount of firms in a sector, the ownership of the infrastructure, exclusivity of assets, vertical and horizontal integration and regulations, of both a technological and economic nature. The efficiency of both institutional arrangements and of risk allocation is one of the central requirements covered in this area. The structural part of the regulatory framework determines the pre-investment constraints.

**Conduct** or the behavioral layer of the design covers the actions of the participating parties once the infrastructure is built. It concerns mechanisms for network expansion, pricing rules for a transport service and regulatory options for entry conditions.

**Performance** regulation aims at influencing sector performance. Quality of service and cost reductions are important issues. In natural monopolies extra performance incentives are generally required as the owner of the infrastructure has no incentive to improve his quality level. Consumers are captive and may need to be protected. The section on performance regulation concerns the sharing of information, the incentives for innovation and extra incentives to motivate companies to focus on the main performance indicators: cost and volume of CO<sub>2</sub> stored. An important aspect of performance is determined by the possible business models of trading CO<sub>2</sub> over an infrastructure. These will also be discussed.



**Figure 15: Structure - Conduct – Performance (adapted from: Berg, 2001)**

This figure signifies the dependence of regulation between the levels. Interaction between structure, conduct and performance limit the total scope of possible designs. Each design option poses new or existing requirements on the regulatory framework. This chapter discusses not only the design options, but also provides an analysis of the options, resulting in further requirements, leading to constraints on the possible designs. The analysis will show that the design options related to the structural elements of the regulatory framework are the primary design options. The design of regulations on conduct and performance are the secondary decisions.

Chapter three discusses the three design options identified in chapter 2 as those of structural importance to the regulatory design. The design options at the lower levels are treated in the appendix C.7 on Design Options.

## 3.1 STRUCTURE

As said, structure refers to the basic elements of a market design. This is the level where the government or other public authority can wield the most influence.

The ownership of the infrastructure is determined by the composition of the investing parties. Ownership is determined by investment and can be either public, private (one firm), cooperation of firms and a form of public private cooperation. However, the different forms of cooperation can generate a variety of distributions for risks, responsibilities and rewards.

This section discusses the possible forms of ownership which can be fitted to a CO<sub>2</sub> network. First, I will discuss the issues of competition regulation. Connected to these design options are the issues of vertical integration. Thirdly a description of choices which arise when designing a regulatory agency are included. The section on structure ends with highlighting the interdependencies between the design options, and discusses the principal design dilemmas arising from this level. Also, the connection with the other levels is treated.

### **3.1.1 Competition regulation**

In infrastructure investments, investors face high costs in the early phase of the project and small returns over a longer period. To ensure that these returns are realized, owners of infrastructures can either try to secure the demand for their service through vertical integration (next section) or can try to control the alternatives services (horizontal integration or monopoly). The latter option is the topic of this section. As concluded in the technological analysis, it is uneconomic to operate two pipeline infrastructures next to each other because of extreme economies of scale inherent in pipeline infrastructures. Furthermore, in the port of Rotterdam, the harbor authority allows only one pipeline for a specific product on a single route. It is a hard constraint that there can only be one pipeline network (Port of Rotterdam, 2007).

None the less, opportunities for introducing competition remain. Applying a form of competition and market mechanisms to the regulatory framework is a requirement from the analysis, arising from the efficiency requirement (section 2.2).

The design can accommodate both requirements, although they appear conflicting at first sight. By considering certain constraints on ownership and abolishing exclusivity rights, competition can be introduced. The following sections describe two alternatives, based on a World Bank

publication by Michael Klein (1996) who has studied alternative market designs for infrastructures in different sectors around the world. The first one is competition for the infrastructure, where competing companies bid for a concession to operate the monopoly for a given period of time. The second one is competition on the infrastructure, where competition is artificially introduced by enforcing or incentivizing access to the network. Thirdly, competition among infrastructures is treated.

### ***Competition for the infrastructure***

The operation of the infrastructure is auctioned off to the bidder which offers the lowest price for consumers. Such an arrangement is also known as a concession. The terms of the concession can contain requirements which the infrastructure operator needs to fulfill.

A regulator is required for two reasons. First, to set adequate terms in a contract is a complex process. To make the contract complete, including all possible events, is complex and costly. A regulator can monitor and adjust the terms of the concession. Secondly, once in operation, the operator holds a natural monopoly. Although periodic re-bidding is an option, a regulator is still required to control prices and investments in maintenance and renovation of the infrastructure if necessary. The holder of the concession has the opportunity to neglect investment if he does not consider a second term. He can sweat the assets, by delaying investments to the last possible moment, preferably, by shifting the costs to the next concession holder.

In CO<sub>2</sub> networks, there is no incumbent party yet. Although some firms have more experience with CO<sub>2</sub> transport than others the main advantage will be with the firm who has constructed the pipeline. Transparency on the technical specifications of the infrastructure is a requirement for an efficient bidding process.

The company who would secure the first concession period has a considerable advantage in the next period. First, it has been able to learn while operating the infrastructure, leading to cost reduction, following the traditional learning curve. Second, a switch to a new company is a complex and costly operation. For these reasons, concerns for market power of the incumbent are justified, further building a need for a regulatory authority.

An important driver for fair and non-opportunistic behavior for the concession holder is reputation. The company will hold want to maintain a reputation of efficiency and quality of service to deter possible newcomers and to satisfy their consumers. Therefore transparency on the operation and investments of the concession holder can be an instrument to incentivize the concession holder to perform. Transparency and monitoring requirements can be part of the concession contract.

If similar networks are in operation in different regions, comparisons on price and service quality can be made. These benchmarks need to be corrected for local conditions. Benchmarking is a valuable approach to assess the performance of the concession holder and to set new terms at a new concession period.

A risk of this approach is underbidding by the applicants for the concession. When a concession is bid so low that the concession holder cannot return his investment, he goes bankrupt, leading in extremes to a possible interruption of service.

### ***Competition over the infrastructure***

Competition over the infrastructure basically means offering services over the infrastructure, where the capacity price of the network is included in the service price. Competition over the infrastructure can take three forms: open access, pooling or time-tabling.

**Open access** refers to the access to a bottleneck facility. For competition to take place, access to monopoly-type bottlenecks is required. Open access means that all competitors have access to the infrastructure or bottleneck on the same terms and for equal price.

The owner of the network can engage in 'predatory behavior', meaning that the network operator charges a price with the objective to harm or prey on a competitor. Incentives for predatory behavior occur when the network operator himself 'owns part of the competing supply facilities'. So to secure a fair open access regime without destructive market behavior a separation between capture and transport of CO<sub>2</sub> is required. A choice for an open access regime thus has consequences for the extent of vertical integration in the value chain.

Furthermore, open access has options to introduce 'pro-competitive' regulation, meaning that access rules and prices can be designed such to give advantage to new entrants.

In short, open access rules 'attempt to enable competition over the network by selling rights to network capacity to firms on a non-discriminatory basis' (Klein, 1996, p. 16).

**Pooling** of a market includes a centralized dispatch system that optimizes flows through the network. Suppliers bid for capacity and winning bidders will be able to transport CO<sub>2</sub>. A pooled market requires several organizations and institutions. An independent system operator is needed to control the physical flows, a pool market for capacity is needed and a regulator to control the independence of the system operator. Introducing a pooled market is a complex form of capacity allocation, although it is considered efficient in the U.S electricity markets. Furthermore, it leaves open the option to separate ownership and operation of the infrastructure.

**Time tabling** is based on scheduling the network capacity. This is a popular model when the transported good needs to be matched to a specific destination (airlines, freight, telecommunications etc...). For a CO<sub>2</sub> this is not the case, and time tabling is not a valid option.

### ***Competition among infrastructures***

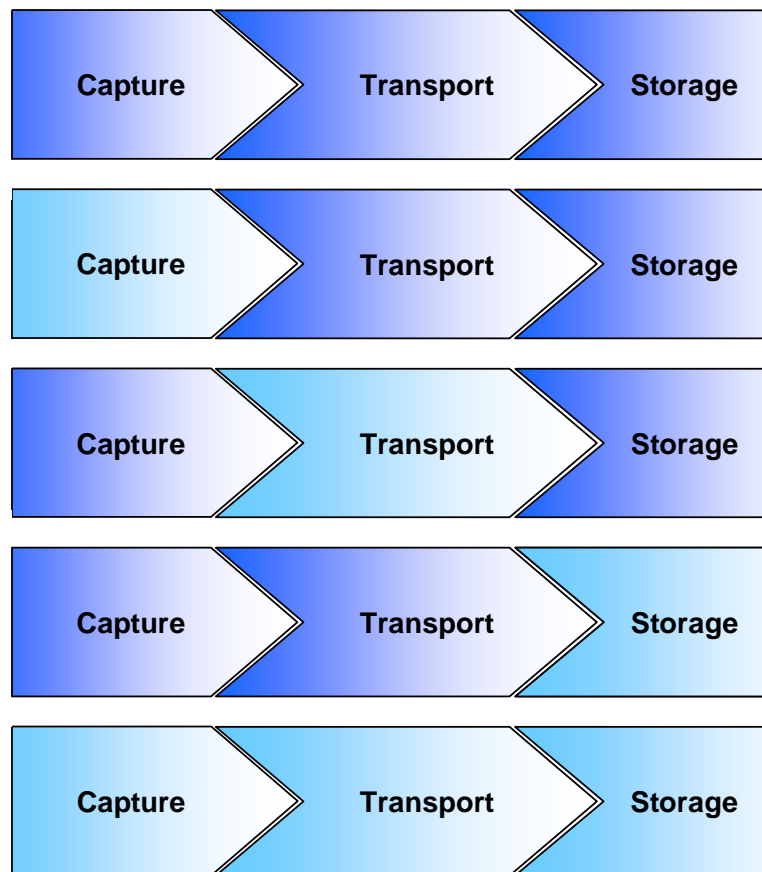
Competition among infrastructures arises from two perspectives. The first is between a CO<sub>2</sub> transportation service, CO<sub>2</sub> can be transported with pipelines, ships (barge or sea), rail and truck. Currently, costs of rail and truck are too high to compete with pipelines and ships see section 2.1.2. However, when looking at the CCS system at a larger scale, competition among infrastructures might well be possible.

When looking at a CO<sub>2</sub> network as a part of a CCS system, it functions as part of a CO<sub>2</sub> emission reduction system. As such, it competes with many technologies, both in the field of efficiency increases and of renewable energy. In this view, the traded good is not CO<sub>2</sub> itself, but a emission reduction. A power plant may switch to biomass, or other technologies that reduce CO<sub>2</sub> emissions. If innovation in solar cells leads to major cost reductions, CCS and centralized power plants in general has considerable competition. In all, many options are possible.

The structural elements of competition regulation contain the design options for ownership of the infrastructure. Where competition for the network entails government ownership, a competition over the network can include private ownership, or a public-private cooperative. Secondly, network entry conditions play a role in the competition on the infrastructure. As I will explain in the next section, regulation on vertical integration plays an important role in access rights as well.

### 3.1.2 Regulation on vertical Integration

Vertical integration refers to the integration of functions in the value chain into one company. In practice for a CCS value chain, this would imply that for example *capture* and *transport* services are executed by the same firm. Basically, there are five possible configurations of vertical integration in a CCS value chain, which can be both forward (from capture towards storage) or backward (from storage to capture). The dark blue arrows in Figure 16 indicate that the functions are performed by the same firm.



**Figure 16: Vertical integration**

The system analysis has provided requirements and constraints on vertical integration from all three perspectives. From a technological viewpoint integration can create economies of scale and



scope, especially between transport and storage. For storage facilities it is important to control the inflow of CO<sub>2</sub> in the field, as the pressure of the pipeline needs to be only a bit higher than the pressure in the field.

The institutional analysis has shown that vertical integration can lead to market power and entry barriers. This is a main concern, as it collides with the main objective of efficiency.

The stakeholder analysis has delivered the insight that power plants do not want that CO<sub>2</sub> becomes a concern for them. Their business is power production, and generally, the companies in the sector do not want to be distracted by CO<sub>2</sub> value chains. In the power sector, vertical integration in ownership is not expected. However, since investments in dedicated assets are made, the capture plants require strong and dedicated purchase agreements.

The oil & gas companies have a unique position based on their knowledge. They have experience in all elements of the value chain. Therefore some vertical integration from their perspective is possible.

Note here that vertical integration is the result of a regulatory framework. The decision to vertically integrate or decentralize is one that companies make. It is a governance issue which is constrained or allowed by the regulatory framework. So based on the system analysis it can be concluded that if vertical integration were allowed it would most likely occur between transport and storage in the case of power plants; and along the entire value chain for oil & gas companies.

So the likely vertical integration to occur is between capture and transport in the case of the oil industry as CO<sub>2</sub> sources, and between transport and storage. Engineering requirements and stakeholders interests argue for vertical integration, whereas the institutional arrangements can be less efficient. This conflict of interests will be further analyzed when making the conceptual designs. In the design exercise, decisions on allowing or restricting vertical integration lead to different outcomes of the design.

The technological analysis (section 2.1) has shown that vertical coordination of activities in the value chain can lead to cost reduction through increases in efficiency.

The integration of transport and storage can provide technological efficiency gains for similar reasons. In general it can be concluded that the motivation for firms to set up a vertically integrated value chain is twofold:

- Control over up or downstream facilities generates demand & supply security
  - Coordination between technological systems increases system efficiency
- (see chapter 2)

But vertical integration has drawbacks. The analysis in chapter 2 has also provided constraints limiting the possible configurations.

First, the capture process has influences on the operation of the emitting plants. CO<sub>2</sub> emitting industries want to control their own capture process, and it is therefore not expected that they

will let capture be carried out by another firm. So a transport firm cannot own a capture plant at the site of a power plant. It is however conceivable that a CO<sub>2</sub> source would want a stake in the transport, to control the pressure and temperature in the pipeline to match the requirements of his storage location and secure transfer of the CO<sub>2</sub>.

Secondly, the pipeline network is a monopoly where large economies of scale lead to potential market power. In a free market the owner of the network can determine the conditions for access to his infrastructure. Since it is uneconomical to build a second network, this gives the network owner considerable power. This will be shown in section **Error! Reference source not found.** As discussed in the section above, competition can be artificially introduced *over* or *for* the infrastructure. These regulations fit the paradigm of liberalized infrastructures and requires separate ownership of natural monopoly facilities from those that activities that are contestable to function efficiently (among others: Finger, Groenewegen, & Künneke, 2005; Joskow, 2005). The idea to combine a natural monopoly with competition incentives is inconsistent with yet another requirement: involve private capital. The outlook of monopoly rents is an important motivation for private companies to invest (compare R&D expenses substantiated by patent right in innovations).

The following section on contracts presents a range of possible solutions to create institutional agreements between parties, without including the neighbouring value chain activities inside the hierarchy, nor putting the transaction in the market at a distance.

### ***Investment Contracts***

The literature on governance of infrastructure projects contains a host of options. This section looks into these options from the perspective of two requirements taken from the analysis. First, to ensure sufficient private sector involvement, part of the project should at least be financed by private investment. Second is the requirement that a reward from an investment should be in agreement with the risks taken.

Private firms have multiple investment opportunities. Investment opportunities arise from a firms resources that distinguish it from another firm, being 'a firm's managerial resources, technological knowledge, reputation, market position and scale' all of which enable the firm to make investments others cannot make (Dixit & Pindyck, 1994, p. 9).

To finance a project, a company broadly has three options. A project can be financed based on corporate finance, on a non-recourse basis or with a hybrid form (Brealey, Cooper, & Habib, 2000). In the next section we will create some insight in these options based on the literature collected in Roger Miller and Donald Lessard's book on strategic management of large engineering projects.

In **Corporate finance** based contracts the financial risk is directly borne by the sponsor. The risk of the project executer is the creditworthiness of the sponsor. The project sponsor is not involved in the project itself, it is a external party making the funds available. The only concern of the sponsor is the financial return on the project. A corporate finance based contract gives some freedom to the content of the project. According to Brealey (Moulijn) such contracts are not

required to be very complete, as the sponsor is only concerned with the return of the project, and the project executer is only concerned with the creditworthiness of the sponsor.

In a **non-recourse financing** approach, a project is financed based only on the assets involved in the project itself. There is no external party who bears the financial risk. So when the project fails, debt collectors can only lay a claim on the assets involved in the project. Non-recourse financing requires the creation of a project specific legal entity who acts as the executor and liable party. The approach is more rigid than in corporate financing and requires more complete contracting. But since a separate organization is involved, parties participating in the project can negotiate the distribution of risks among themselves. Since none of the parties wants to bear any risk it can not control, non-recourse financing leads to an allocation of risks to those parties that are best capable of mitigating them (Conway & Kiselev, 2006). It is however difficult to set up a non-recourse project and it involves considerable transaction costs to set up all the negotiations and meetings.

The collection of **hybrid arrangements** is vast and contains a broad scope of arrangements. Basically, the owners of the project take up the project risk except for those risks that require support by an external party. Interesting options are *take or pay* contracts. This provides a guarantee that the product will be bought, regardless of the actual transfer. On the supply side of contractual arrangements can secure the supply of a feedstock. The ability to supply of the supplier is the main risk here. Other arrangements include those focusing on the risk during the construction of the project. Examples are numerous and options are many. Contracts such as Design-Build-Finance-Operate-Transfer DBFOT or other combinations are becoming popular arrangements for infrastructure project. Such constructions are popular when coordination between construction interests and operational interests are in order (Flyvbjerg, 2003).

### 3.1.3 Regulator Options

The first design option under consideration here is whether a regulatory institution is required in the first place. This section deals with the case when a regulatory institution is involved. The possible options and considerations of the design of a regulator will be discussed. The system analysis has provided a long list of requirements for a regulator (see Appendix C.5). The most important requirement is regulatory independence. The literature on the design of a regulator is broad. Here we focus on the issues regarding the scope of influence of the regulator. That some form of regulatory control is required is clear from the guarantees needed to trade CCS reduced CO<sub>2</sub> emissions on the ETS. The options and depth of regulatory responsibility are in part determined by the choices on competition regulation.

Ioannis Kessides of the World Bank has written a well known work on the options and decisions in designing a regulatory institution. According to Kessides, several important decisions need to be made regarding the design of a regulator (Kessides, 2003, p. 46):

- "A demarcation of regulatory responsibilities among the national and subnational tiers of government
- Industry-specific versus multi-sectoral regulatory agencies;

- Allocation of functional responsibilities (pro regulation of prices, licensing, quality, environmental effects); and
- Relationship with the sectoral ministries and with antitrust authorities.”

These choices can be categorized in two dimensions with two settings: ‘vertical location’ (centralized / decentralized) where the choice is between a regional, national or supranational regulation. The second design choice is on the ‘horizontal location’ where the scope (single or multiple sectors) of the utility is determined (Kessides, 2003).

### ***Vertical location of the regulator***

A decentralized regulator only has influence in a regional area. More centralized regulators contain a larger area of influence which can take the level of national or supranational regulation. The advantage of a decentralized responsibility is an easier adaptation to local conditions. The regulator can more easily collect information from firms and consumers.

A centralized regulatory institution has the advantage of making more effective use of scarce regulatory expertise. Human capital requirements are high for regulators and extensive knowledge of the market and related technologies is needed. The employees of a regulator therefore have a high opportunity cost, they are under pressure to make a change to industry, where the loans are generally higher. Centralization can be required when the regional jurisdictions are too small to create an efficient scale of operation (Kessides, 2003).

According to Kessides, the driving factors for a decision on vertical location of the regulator are:

- Country size, small countries are less suited for decentralized approach
- Nature of the industries. Electricity and telecoms typically have national regulators because of the required expertise. Water has regional regulators as local conditions play a substantial role.
- Regulatory capacity, the more delicate the constraints of regulatory capacity, the stronger the arguments for centralizing.
- When regulatory issues are multi tiered, so when some decisions made on regional level, and some on centralized level, the regulator can also be designed in a multi tiered fashion.

(Kessides, 2003)

### ***Horizontal location of the regulator***

Horizontal location refers to the scope of the regulator. A regulator can have authority over a single sector, or it can regulate multiple utilities in different sectors. Kessides offers five important Driving factors in the choice of the horizontal scope:

- In large economies, a wide scope of the regulator might lead to concerns on insufficient focus and potential diseconomies of scale. The narrower the scope of regulation, the less is the risk of insufficient industry focus or potential diseconomies of scale.
- If the products of multiple sectors can be each others substitute, the risk of economic distortions arising from inconsistent approaches to common issues in different sectors may be greater. So substitutability of products from different sectors is an argument for multi-utility regulation.
- Low availability of regulatory capacity (constrained by scarce expertise and vulnerability to industry and political capture) argues for a multi-industry approach. Benefits of industry specific agencies can be achieved through the creation of industry specific departments within an overall agency. So scarcity of regulatory expertise argues for multi utility regulation.

(Kessides, 2003)

Other considerations for a regulator the design of a regulator are more operational in nature. These include options on how to reduce regulatory uncertainty. Looking at the current style of regulation as practiced by the Dutch emission authority (NEA), a cooperative and advisory approach followed by strict enforcement if companies behave non-compliant appears effective (Alessie, 2007). The NEA operates in a turbulent policy environment, where policy changes from national, regional and supranational levels follow each other in short order. At the same time, emission reduction equipment is subject to rapid changes. The NEA receives targets with which companies need to comply. Instead of monitoring actual emissions, the NEA develops monitoring protocols. These protocols are technical documents stating the correct method of monitoring emissions. It is the protocols to which the industry needs to comply, not actual emissions. With this policy, the NEA has found a way to control the dilemma between robustness and flexibility (Alessie, 2007). How a regulator can walk the tightrope between robustness and flexibility is question for the detailed design.

## 3.2 CONDUCT

The conduct layer of the regulatory framework covers the actions of the participating parties once the infrastructure is built. It concerns mechanisms for network expansion, pricing rules for a transport service and regulatory options for entry conditions.

The choices for market structure have consequences for the regulation at the conduct level. I will discuss design options for price and return regulation, options for network expansion incentives and for entry condition regulation. Basically, the conduct level of the regulatory framework is all about getting the incentives in line with the basic goals: effectiveness and efficiency.

### **3.2.1 Price & Return**

As has come forward from the discussion on introducing competition in infrastructure sectors there are regulated pricing mechanisms available to create artificial market conditions. Both

competition *for* the infrastructure and competition *over* the infrastructure require pricing mechanisms. Of course it is also possible to choose not to introduce regulated competition and a pricing mechanism, and let the markets do its work. In this section we will describe a few common price and return mechanisms. We will also discuss the option of not applying a pricing mechanism.

The requirement of on a pricing mechanism from the system analysis is the ability for firms to recover their investments and cover their cost of operation. Gordon and Olson confirm this requirement and add a goal specific for pricing mechanisms from their research on pricing mechanisms in the electricity sector. First, a pricing mechanism should provide clear information for making economic decisions about consumption and investment. Second, it should cover the costs of the utility (Gordon & Olson, 2004). Both goals agree with the criteria of efficiency as we defined for the evaluation of the design.

### ***Price cap regulation***

In price cap regulation a formula determines the allowed price increase in each period. The formula is calculated based on changes in cost due to inflation, changes in productivity levels, changes in input price, costs related to changes in regulation, and other exogenous factors applicable to the industry (Norton, Sexton, & Silkman, 2002). So basically a price cap can be seen as a dynamic maximum price for the delivered service. The problem of price cap regulation is in calculating an adequate level of the cap. The information needed as input to the formula is hard to acquire. It resides with the firms under regulation. Therefore, they have an opportunity to behave opportunistically and inflate their costs. This allows higher profits, as the cap is set above the efficient cost level.

But when applied correctly, a price cap can create an efficient system. Research by Gordon & Olson has shown that a price cap model provide incentives for 'productive efficiency' and 'technical innovation' (Gordon & Olson, 2004).

A special form of price cap regulation allows price to rise according to the consumer price index (inflation of prices in the general economy) minus a special X factor for efficiency increases. The advantage of so called CPI-X regulation is that the formula is relatively simple. It is based on historical price level, inflation and an efficiency factor. The setting of the X-factor is the crucial action. However, when setting the X-factor in a cooperative setting with the regulated industry, efficient outcomes can be achieved. CPI-X cannot be applied when structural changes requiring investments are foreseen. In that case, the regulated industry needs to higher prices somewhat, to cover for the new investment (Bernstein & Sappington, 2000).

For the regulatory framework of a CO<sub>2</sub> network a price cap mechanism could be applied together with both forms of competition regulation (*for* and *over*). Also a price cap mechanism can be applied in both vertically integrated and vertically decentralized sectors. In a vertically integrated sector a price cap can be applied to lower entry barriers. But this will be discussed in section 3.2.3 *Entry conditions*.

### ***Rate of Return Regulation***

Rate of return (RoR) regulation is a more traditional form of cost plus regulation. It specifies the allowed rate of return on top of the costs incurred (De Vries, Correljé, & Knops, 2005). Companies under RoR need to specify all their investments, operational costs other relevant information to the regulator. The regulator then specifies an allowed rate of return and prices are set accordingly by the company at such a level that he does not exceed the allowed return (Thomas, 2003).

RoR has its criticisms. The foremost critique is that RoR does not motivate firms to reduce costs. Rather, companies under RoR have the incentive to increase investments, commonly referred to as gold-plating, since this allows them to make higher returns.

According to Thomas, price caps are similar to rate of return regulation. The main difference is in the timing of approving investments by the regulator. Under RoR regulation, the regulator has the possibility to check after the investment if it has been 'used and useful'. If utilities spend too much, the regulators can prevent them from adding excess expenditure to their rate base (Thomas, 2003).

In practice, with CPI-X regulation, the usefulness of investments haven't been monitored. Steve Thomas has done research on the merits of both cost-plus and price-cap regulation. It has turned out that companies under price-cap regulation have always invested less than they negotiated, arguing that investments were rendered unnecessary due to efficiency improvements. When rate of return regulation includes ex-post monitoring of the investments ('used and useful') it could provide sufficient incentive for companies not to make unnecessary investment (Thomas, 2003).

### ***Network capacity auctions***

To auction of network capacity is mostly applied at those parts of the network that serve as interconnectors between distinct parts of the network. Capacity auctions are for example applied on the interconnectors between the Netherlands and Germany. Demanding and supplying parties who want to sell electricity to each other over the border need to acquire network capacity, matching physical space on the connector with the exchanged amount. Since the interconnectors are congested, such capacity is scarce. By holding a daily (and yearly and monthly) auction, the system operators allocate the capacity to the highest bidders.

The hardest part of regulating network utilities is in determining the adequate amount of investment needed to fit the future growth. Rate of return regulation is notorious for supporting overinvestment, as the more is invested, the more profits are allowed. Price cap encourages minimizing investments, and reducing costs. Giving the right signals for network expansion in a regulated market is difficult. The network auction can provide a a market solution to a natural monopoly with regulated prices (Newberry, 2003).

The price level of the auction is an indicator for the demand on that part of the network. When prices have been enduringly high, the network operator has a basis for investment. He can use the extra income to expand the network in the congested areas. However, as with price cap and rate of return regulation, a capacity auctions also do not work perfectly. A network capacity

auction only works well 'if there are many potential participants, and if there are liquid spatial spot markets to reveal the value of capacity connecting these different markets' (Newberry, 2003, p. 28).

### **3.2.2 Network Expansion**

Network expansion is related to pricing mechanisms and performance incentives. Both options can result in expansion of the network. There are also more hierarchical ways to control network expansion. These will be treated in this section.

#### ***Mandated network expansion***

In mandated network expansion, the network company is obliged to deliver their service when a demand for it is apparent. If to geographically divided companies have a supply and a demand agreement of the good transported over the network, mandated network expansion prescribes that the connection is made.

This is the case with the natural gas network in the Netherlands. If a supplier and consumer of natural gas make a contract for the sale of natural gas over a sufficiently long period, Gasunie<sup>2</sup> is obliged to provide that service. At the same time, the users of the infrastructure have a use-it-or-lose-it agreement. Similar to the earlier discussed take-or-pay contracts. This means that once the pipeline is in place, its users pay for it, even if they do not use it. Since the costs of the pipeline is small compared to the costs of natural gas, companies are willing to enter in such an agreement (De Wolf, 2007).

This kind of network expansion mechanism is commonly seen in regulated environments. A higher authority is needed to mandate the expansion and lay it down in rules. Commonly, this is connected with a regulated price. It also fits well in a competition *over* the network. In the case of a CO<sub>2</sub> network in the port of Rotterdam, the port authority coordinates all planning and expansion of pipeline infrastructure. A role for the port authority in the network expansion is therefore necessary.

#### ***Planned network expansion***

In planned network expansion, there is a centralized approach to network expansion. A (regional) authority plans the connections. Such an approach requires complex coordination to avoid inefficiencies. The centralized planner needs to make sure that supply and demand are aligned when he plans the connection. The degree of centralization requires bureaucracy. It fits the competition *for* the network, where a tender is given out for the construction and operation of the planned links. Planning network expansion thus requires a lot of coordination by the regulator, even outside the scope of transport service.

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<sup>2</sup> After some organizational changes Gasunie is now the name of the network company where both Gas Transport Services (GTS), an in-house engineering consultancy Gasunie Engineering & Technology and a specialized pipeline contractor (Gasunie Bouw & Beheer) are housed. The natural gas trader GasTerra (formerly Gasunie Trade & Supply) is now placed more at a distance of the network company (Gasunie, 2007). Still it remains a complex organization for outsiders.



When looking at the Rotterdam harbor area, the routing of pipelines is heavily constrained. There is not much room left to plan and build infrastructure. Coordination by the Rotterdam Harbor Authority is already applied. Also because of safety regulations, since most pipelines contain hazardous materials (Port of Rotterdam, 2007).

The main part of the costs are not in the pipeline itself, but in the land that must be acquired or in trespassing rights. This means that in practice, the possible pipeline routes are heavily constrained (see the section on the port authority in 2.3).

### ***Network expansion incentives***

The more decentralized approach of incentivizing network connections has close relations with the other conduct level regulations. The pricing mechanism can contain incentives for network expansion. The issue is also related to the regulation on entry barriers.

The incentives for network expansion have been studied by World Bank researchers in the context of extending electricity networks to rural areas. Here network expansion has been successfully encouraged using performance based output incentives. Ray Tomkins has identified output targets which can be used to 'link performance to payment' (Tomkins, 2001). The one applicable to the context of a CO<sub>2</sub> network is to give a bonus for connecting all consumers who are willing to pay the market price of a connection. This is linked to the criterion of static (allocative) efficiency.

Commitment of the consumers who are to be connected is essential. To achieve this, users should take part in the investment. Thus, the capture and storage facilities should participate in a cost sharing agreement to ensure that they have sufficient commitment and actually use the network. And if any extra subsidies are involved, it is more efficient to direct them towards access to the network rather than to consumption (Tomkins, 2001).

The connection of other industrial areas to the CO<sub>2</sub> network plays again a role here. To connect other industrial areas is a goal for the port of Rotterdam, as it offers them with the opportunity to increase the volume of CO<sub>2</sub> transferred to the North Sea significantly. A design for a regulatory framework should at least contain the possibility to connect to other industrial areas, but it can also contain incentives to encourage interconnection.

### **3.2.3 Entry conditions**

Erecting barriers to entry is a strategy for the incumbents to deter new entrants and avoid competition. New entrants are a key factor in introducing competition. Therefore, to be able to have competitive arrangements between capture and storage companies, low entry barriers are crucial. The regulation of entry conditions is linked to vertical integration. Entry regulation is only required when vertically integrated firms are allowed. Because only when a firm has a stake in up or downstream markets (e.g. capture or storage) an incentive to exclude other from the network exists.

By introducing entry regulations, incumbents can be forced to allow access to their networks under regulated conditions. This issue is linked to the price & return regulation, as the entry conditions are for a large part determined by the price of service.

### ***Third Party access***

The access of others to the network is explicitly laid down in law in both the Electricity Directive and in the Gas Directive.

In article 18 of the Gas Directive, and article 20 of the Electricity Directive it is stated that system operator should allow access to their networks "based on published tariffs, applicable to all eligible customers, including supply undertakings, and applied objectively and without discrimination between system users" (article 20, Directive 2003/54/EC; article 18, Directive 2003/55/EC).

So the removal of entry barriers is seen as mainly applicable to a regulation of tariff based on a non-discriminatory basis.

The regulation on the removal of entry barriers is related to the pricing mechanism. Another regulatory strategy for encouraging entry is unbundling of vertically integrated companies. When companies are vertically integrated including a natural monopoly such as a network, they can use this to create entry barriers, by charging high prices for access to the network. This has been discussed before, but again, it is relevant to mention here that unbundling of the natural monopoly activities from the commercial activities is a solution to lower entry barriers.

A critical element is again the uncertainty on the outcome of the inclusion of CCS in the ETS. Whether storage or capture companies will be the ones to sell them at the ETS has a large influence on the incentive structure and bargaining positions. This issue will return in chapter 4 and 5 on the conceptual designs and tests.

#### **3.2.4 Interdependence of conduct with structure & performance**

The application of a pricing mechanism is related to introducing competition. In competition *for* the market the pricing mechanisms and the entry conditions are secondary decisions. In vertically integrated sectors a price and return mechanism can help in lowering entry barriers.

Network expansion incentives are linked to the role of the public authority. If the authority has sufficient knowledge of local conditions, he can plan or mandate connections. The design of a regulator can also play a role here. In the case of cost-plus regulation, the regulator needs to approve the new investments. If the regulator is placed more at a distance, at national or supranational level, the network expansion would rather be incentivized.

The regulations on entry barriers are connected to the structural elements of the regulatory design. Choices for a type of competition regulation or for ownership of the network and vertical integration determine the incentive structure for the network company. It might well be that the incentives are aligned with connecting and serving as many suppliers and consumers as possible. In that case, specific regulations on entry barriers might not even be necessary.

The analysis of the design options on conduct level has clearly shown that the structural elements are primary decisions, and that conduct regulation follows a choice for regulation on the market structure level.

### 3.3 PERFORMANCE

This is the level of regulation that is considered by the European Commission and its research platform on zero emission power plants, the ZEP. According to a member of ZEP, the regulations considered aim at finding incentives similar to feed-in tariffs which are used in renewable energy projects, such as wind and solar.

#### **3.3.1 Performance Incentives**

Renewable energy sources are more costly to implement than conventional energy sources. CO<sub>2</sub> free energy producers receive an incentive to create a market for renewable energy. Of course, energy produced in a CCS system is not renewable. However, it is almost CO<sub>2</sub> free. Therefore, it is considered to grant CCS systems similar incentives to create a level playing field for CO<sub>2</sub> free energy. Regulations that are commonly applied in Europe as performance incentives are feed-in tariffs and tax related incentives (IPCC, 2007c, p. 25, ch 13).

##### ***Feed-in tariffs***

Feed-in tariffs are regulated prices for electricity production from renewable energy sources. The feed-in tariff determines the price for which the utilities must purchase the electricity. By guaranteeing a high price for green electricity, investments have found sufficient basis to develop. As long as renewable energy delivers only a small contribution to electricity production, consumers won't notice an increase in their electricity rates (IPCC, 2007c).

These incentives may be effective, but they are also expensive. Especially when the industry gets used to the incomes, it can start to expect the extension of the instruments.

Similar incentives are considered for CCS, reasoned by the CO<sub>2</sub> free electricity that a CO<sub>2</sub> storing energy plant is able to produce.

##### ***Tax related incentives***

Another option to encourage investment in CCS projects is by giving tax-related incentives. This can draw in investments from other sectors. Companies looking for tax benefits with experience in complicated financing schemes will be attracted. An example where this worked was the financing of the Q7 wind park. A project involving Econcern (Ecofys' mother company) and a whole range of parties only interested in the investment opportunity, including Ikea and Rabobank (Econcern, 2007).

#### **3.3.2 Information and Monitoring**

To receive information, a special regulation on openness of the process and data can be set up.

Transparency of the system works well, but is a result in a weakened bargaining position for companies. A regulation at the performance level is required to monitor the CO<sub>2</sub> production and the amount of CO<sub>2</sub> put forward to the next link in the value chain. For some of the participants this kind of information is competitively sensitive.

### **3.3.3 Interdependence of Performance with structure & conduct**

The performance level of regulation is detached from the regulatory framework. It is the most flexible part, where special incentives can be applied to react to new conditions.

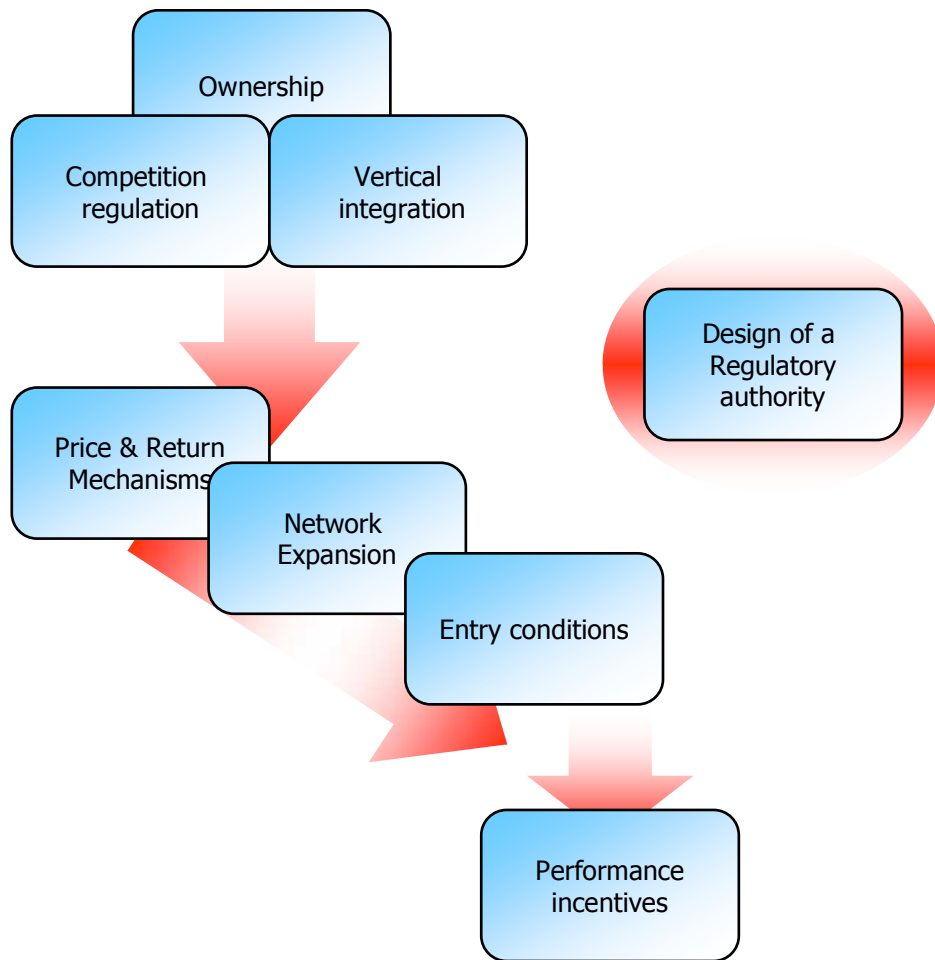
## **3.4 CONCLUSIONS OF THE DESIGN SPACE ANALYSIS**

Looking at all the options for the design there are many roads to travel down to when designing. The above analysis has shown that the primary design decisions arise in the structural part of the market. The conduct and performance regulation are secondary issues, to be filled in after the structural decisions have been made. This conclusion is in congruence with the findings of chapter 2.

Studies by researchers of institutional economics and regulatory frameworks supply a view of which type of conduct and performance regulation fit the structural decisions best. The secondary decisions can be optimized independently of the structural decisions. For a successful regulatory framework, the conduct and performance levels need to be in line with the structural level. A separate exercise is the design of a regulatory authority. After the market structure and fitting conduct and performance regulations have been designed, the regulator needs to be equipped with responsibilities and authority to monitor and control the market. The design of a regulator needs to take the special case of CCS and the requirements for inclusion in the ETS into account.

The design options on ownership [public, hybrid, private] and competition regulation [none, *for* the network, *over* the network] and the design of a regulatory institution are the most important decisions.

The following figure visualizes the conclusions of this chapter.



**Figure 17: Hierarchy of design options**

## PHASE II: DESIGN

### 4 CONCEPTUAL DESIGN

The conceptual design step is the step in the design procession which is added to the meta model as discussed in the introduction, see chapter 1. The function of the conceptual designs gives direction to the analysis. They are also a first step towards making a more detailed design. Learning by doing is a method for progressing in insight and gaining experience. The motivations for the design method as applied will be discussed in chapter 7. Important decisions on the basic design options are made here.

A further function of making the conceptual design is the identification of design dilemmas, gaps in the analysis, and the unresolved uncertainties. The designs are an exercise to find more requirements and directions for research, to learn by trial and error of making combinations. These will be taken up in chapter 6, where the analysis of the designs delves deeper details.

The chapter is built up as follows: first, the design method is described, and then each conceptual design is worked out. The lessons learned from the conceptual designs provide an input for the tests of chapter 5.

#### 4.1 DESIGN METHOD

The design space analysis of chapter 3 has shown that there is a great deal of interdependence between the design options. It was concluded that the design choices for the structural elements of the market make up the primary factors in the design of a regulatory framework. The primary importance of the structural design options limits the amount of available design options as indicated in the following Table 6.

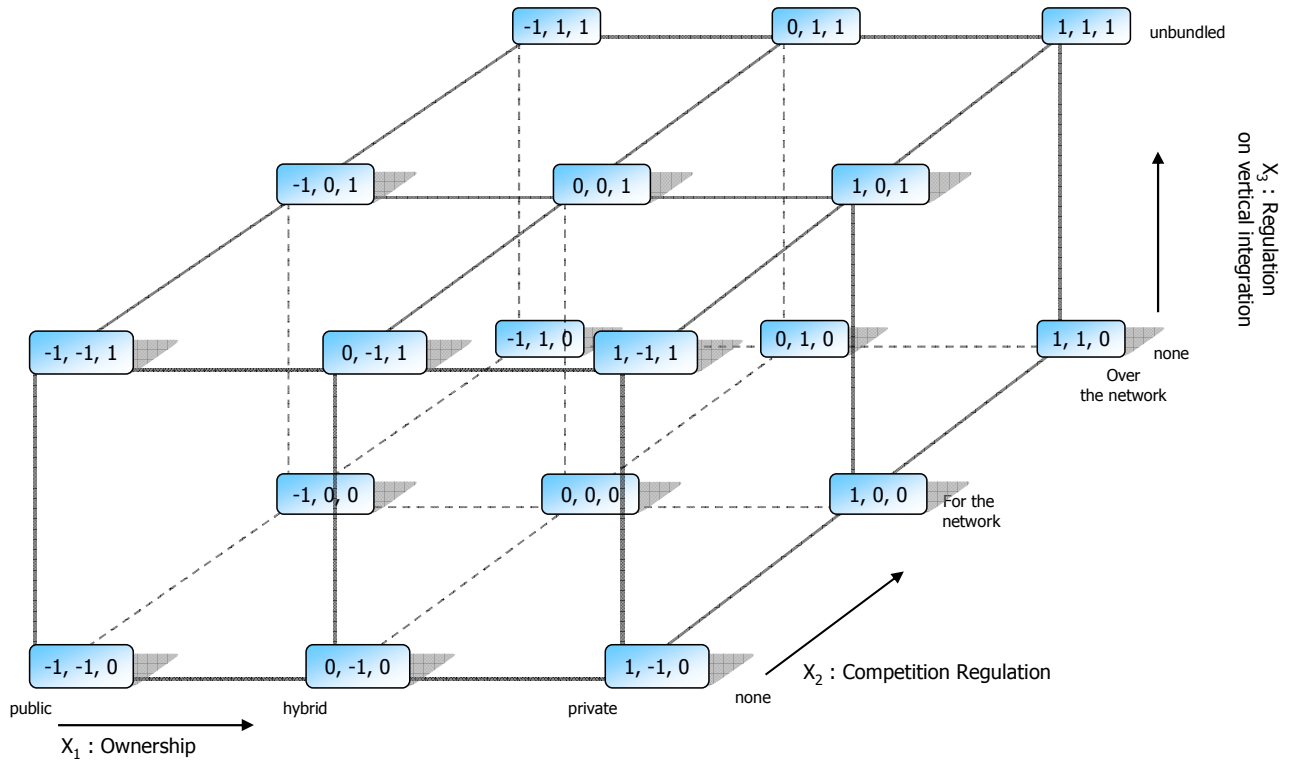
**Table 6: Structure design options and range**

Range	Design variable [ $x_i$ ]		
	$x_1$ Ownership	$x_2$ Competition Regulation	$x_3$ Restriction on vertical integration
-1	Public	None	-
0	Hybrid	<i>For</i> the network	None
1	Private	<i>Over</i> the network	Unbundled

In the hypothetical case when all these options were fully independent, and with three possibilities for competition regulation and ownership, and two possibilities for restrictions on vertical integration, the combination of the three options would lead to  $3*3*2 = 18$  conceptual designs. The total possible designs are depicted in Figure 18. The theoretically possible combinations are shown on three axes. The first axis  $x_1$  shows the possible options for the

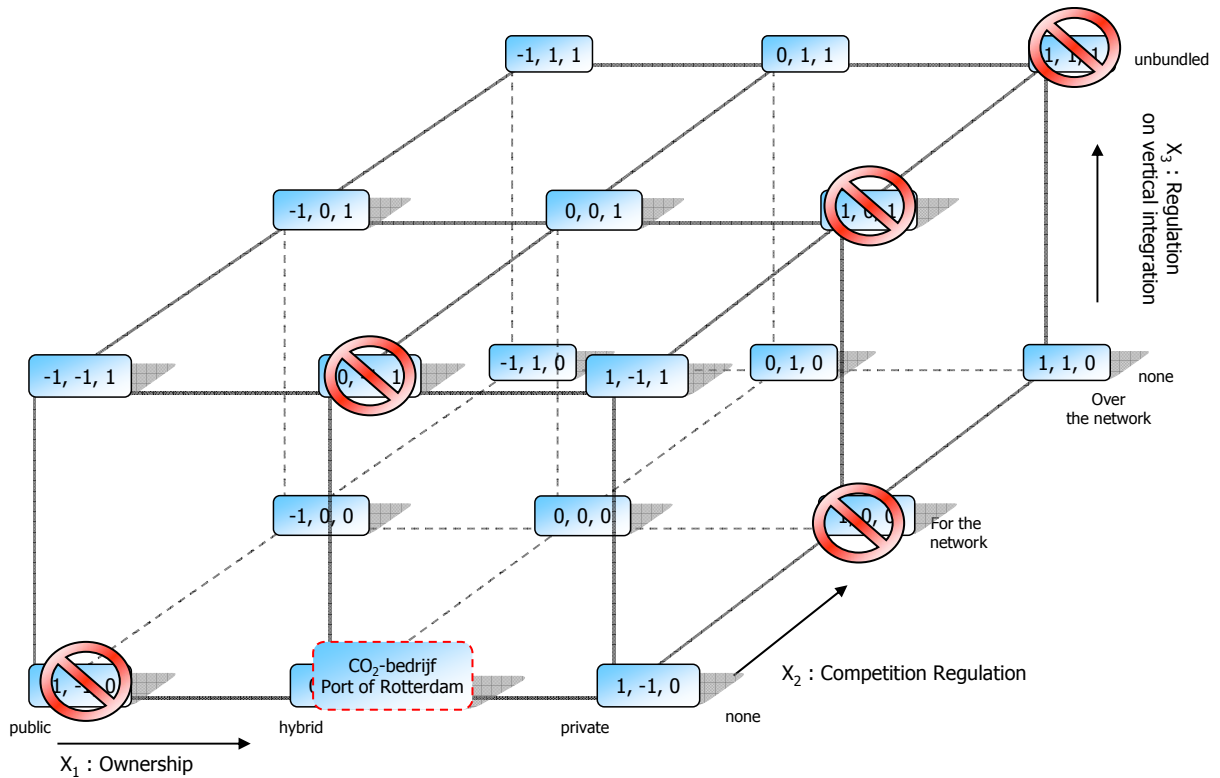
variable ownership. The second axis  $x_2$  shows the different types of competition regulation. And the third axis  $x_3$  shows the design option on restrictions on vertical integration.

The nodes indicate the designs with the settings corresponding to Table 6. The nodes can all be examined to evaluate their performance against the criteria.



**Figure 18: Design variables**

However, not all theoretically potential designs are feasible in practice. Based on the constraints and requirements of the system analysis, it becomes possible to eliminate several of the design options.



**Figure 19: Elimination of design options**

The following list indicates the reasons for excluding the blocked design options in Figure 19.

- Lower left corner, front face:
  - o Public ownership and not unbundled and no competition regulation, is the same as the sphere above, as a publicly owned infrastructure cannot integrate into a capture or storage plant.
- Top center, front face:
  - o The sphere in the center top position of the face of the box by is very similar to the Regulated Monopoly design. When regulations at the conduct level are applied, becomes undistinguishable from a Regulated monopoly.
- Center positions, right side:
  - o Private ownership combined with competition *for* the network is not possible as a starting position. The interests of a private company to invest and own the network do not match with the subsequent operation by some other party. Without vertical integration restrictions, this could be feasible in theory. Company and storage companies can invest jointly and let another company operate their pipelines through some kind of ingenious arrangement.
  - o This argument extends to private ownership, competition for the network, and with vertical integration restrictions. It is generally unlikely that a private



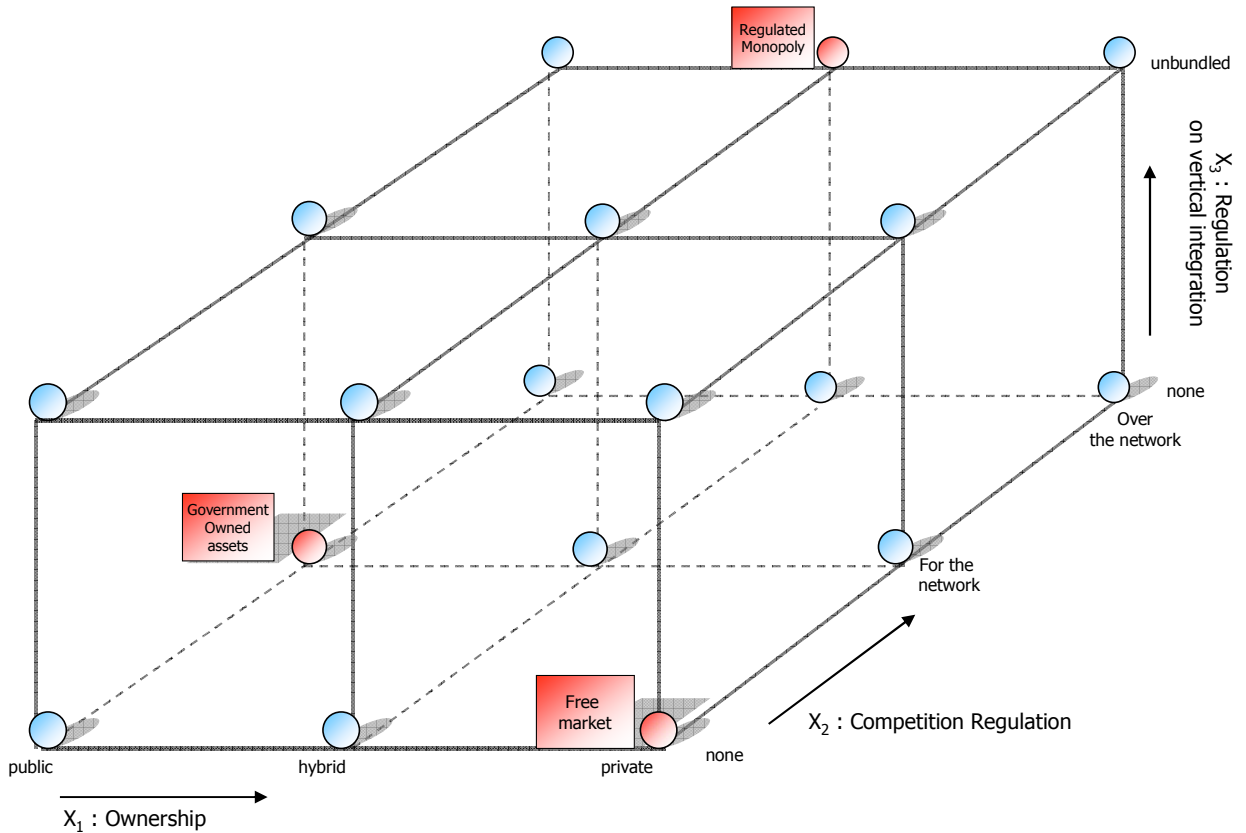
company would want to invest in a pipeline system where it cannot determine how it is used.

- Top right, right side:
  - o The argument is similar to the previous two. As a start up, it is unlikely that a private company wants to invest in a regulated monopoly, without support by the government. A private company needs to be able to control price and return itself, and does not willingly sets itself in such a dependent position. This position could however be possible when an integrated CO<sub>2</sub> source-sink system is forced to open his network to competitors.

A special case is taken up by the lower center front face. In an interview with the DCMR and the HbR was indicated that together with private parties the creation of a so-called "CO<sub>2</sub>-bedrijf" is considered. Although it is unclear at the time of writing what the exact content of these plans will be.

With the two exclusions on the center position at the right side of the box we must remark the following. It might be possible, theoretically, for private investors such as equity firms or pension funds to invest in pipeline infrastructure. However, the risk-return level required does not match the portfolio of these companies. It is not unconceivable that that will change in the future. But at the current time, the investments are just too big for a company to do a risky investment when it cannot control the risks. Generally, it must be noted that the exclusions are taken from a static perspective. Developments of the market and initiatives can change the environment influencing the decisions of stakeholders. Therefore, the exclusions made here serve the purpose of delineating the design space to look at start-up conditions of a CO<sub>2</sub> network. It should be clear that the exclusions do not lead to path dependent decisions in the design progression. If the conditions change, stakeholders shift positions, or other exogenous variables change, then the design space needs to be expanded again.

This chapter presents three of the possible design options in more detail. The contents of the design variables coupled to the characteristics of the technology related to CO<sub>2</sub>, the interests of CO<sub>2</sub> source and sink companies and the role of regulations is discussed. The three are chosen such that insights in the mechanisms involved can be extended to the designs in neighboring intersections of the design variables. The final section describes the current developments of creating a network company for CO<sub>2</sub> in the port of Rotterdam. The information on this endeavor are scarce. The interviewed respondents involved in the setting up of the network company claim that there is no clear picture yet of what this network company should look like (Hanegraaf, 2007; Port of Rotterdam, 2007).



**Figure 20: Design variables visualized**

**Table 7 : Conceptual Designs**

	<b><i>Free market</i></b>	<b><i>Regulated Monopoly</i></b>	<b><i>Government assets</i></b>
<b>Ownership</b>	Private	Hybrid	Public
<b>Competition regulation</b>	None	Over the Network	For the network
<b>Restrictions on vertical integration</b>	None	Unbundled	none

In the conceptual designs choices have been made for the regulations on conduct and performance levels. Each of these will be explained and substantiated in the next sections on the conceptual designs.

***Values in Conceptual Designs***

The values used in the following sections on the conceptual designs are based on two sources of information. Firstly, the IPCC special report on CCS and the recently published report by the DCMR on CCS opportunities for the Rijnmond area. The numbers and their origin are described in Appendix D Values used in the Design.

### ***Theory in the Conceptual Designs***

To link the theory discussed in chapters 2 and 3 to the case of CCS, the conceptual designs describe how the design variables operate when applied in a certain combination. Each design variable contains trade-offs. Before turning to the worked out version of these we briefly indicate them here, to clarify the link between theory and practice:

**Ownership:** public ownership leads to a stronger representation of public goals. Also, it brings with it the burden of bureaucracy. Private ownership is associated with efficiency. Especially when risk distribution is concerned, mechanisms result in an efficient allocation of the risks. However, private ownership is associated with strong risk averseness, resulting in little investments to reach significant CO<sub>2</sub> emission reduction.

**Competition Regulation:** in regulating competition there is the dilemma of providing regulatory stability to generate a stable investment climate opposed to the need for flexibility and adaptability of regulations in a dynamic sector such as fossil fuel based industry. The conceptual designs treat different forms of regulation to make clear the mechanisms underlying each and in that way provide insights for the regulatory design.

**Restrictions on Vertical integration:** restricting or allowing vertical integration both have its merits. Allowing vertical integration leads to a better coordination of activities between subsystems. As indicated in the technical analysis such coordination can lead to cost reduction. The institutional analysis however has resulted in the conclusion that vertical integration creates problems with the efficiency of the system, regarding the natural monopoly of the network.

The issues raised by the theoretical analysis will come to the fore in the treatment of the conceptual designs in the next sections.

## **4.2 CONCEPTUAL DESIGN 1: FREE MARKET WITH INCENTIVE REGULATION**

The statement of Ronald Coase is applicable to the first conceptual design of the free market. In this conceptual design the structural elements are dealt with in the following fashion.

There is no government participation in ownership, it is completely private. The full costs of the investment are borne by private parties. This means that also the risks are borne by private parties. Private parties is here written in plural as it is to be expected that an alliance of private parties is founded to be able to cover the investment. It is very unlikely that only one single investor would be able and willing to take up the full investment and associated financial risk.

In a free market, there is no interference of government in any way. Therefore, there are no restrictions on vertical integration or related conduct regulations such as pricing mechanisms, network expansion incentives and entry conditions.

Since there is no government involvement, trivially, the free market is free of competition regulation. There is no regulation on competition, apart from the standard national competition authority.

Note that in this situation the emergence of a network is not publicly coordinated. Because of the economies of scale and rules of the Rotterdam harbor authority on pipelines, it is to be

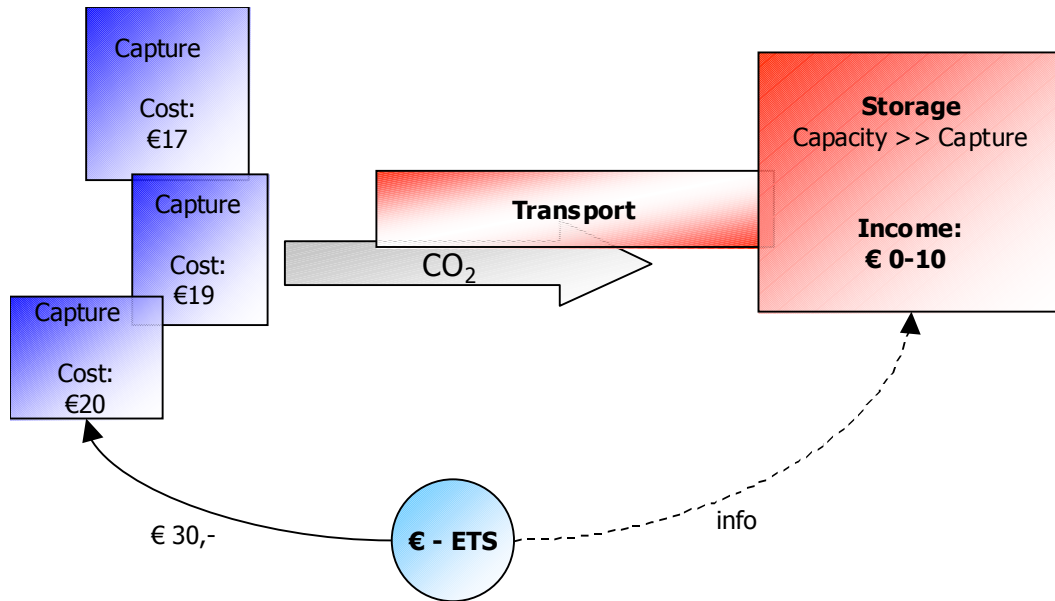
expected that even without coordination a network will emerge. Or, at least a starting pipeline to which other companies would like to connect, thus evolving into a network.

If these choices are made, what would occur in a CO<sub>2</sub> market? Let us first look at vertical integration. From the system analysis it has become clear that vertical integration between the transport and storage activities is likely. Also, when an oil and gas company is considered as a CO<sub>2</sub> source, the functions capture and transport, or a complete vertical integration is possible. Since there is no regulation on vertical integration, it is also unsure which option will emerge. Therefore, the following section discuss three options: integrated transport and storage (Transstor), integrated capture and transport (Captrans) and a thirdly a fully integrated CCS company.

### ***Transactions in a vertically integrated transport + storage: Transstor***

In this first option a vertically integrated transport and storage is considered, we call the company: Transstor. The natural monopoly for transport is held by Transstor. Transstor is originally a company with storage capacity who has vertically integrated backward in the value chain. Storage capacity is available or easy to connect once the network backbone is in place. We first look at an option where capture receives the ETS credits. Then, we look into the situation when Transstor trades the stored ETS on the ETS.

So in the first situation it is assumed that the ETS allowances are collected by the capture plants, below I will show the effects of the reverse situation. To be able to sell their credits, the capture plants need to make sure that the ETS is transported and stored. Since Transstor is their only option, they are in a weak position to negotiate a contract. The ETS price level is information available to anyone, so all involved parties know the value of the ETS in a point in time. Therefore, while negotiating a contract, Transstor knows what the capture plants last offer will be: just below the ETS price, or the cost of a ETS emission. Therefore, the Transstor can charge a price just below ETS to ETS emitting companies, based on the price that the companies are willing to pay.



**Figure 21: Vertically integrated transport & storage (I)**

If the ETS changes enduringly, Transstor can start renegotiations. The capture plants are economically captured by Transstor once they have made the investment in capture technology. .

The capture plants are charged by Transstor a price of the ETS minus a negotiated price, close to the ETS level. Because there is competition among capture plants to supply CO<sub>2</sub> and network capacity is limited, Transstor can play them off against each other. Also information on capture costs is available. Once the capture plant has made the investment in the capture technology he is vulnerable to renegotiation. Transstor knows the investment is made, and he can drive up the price up to just below the ETS level. The capture plant has made his investment and his costs are sunk, so he has no option but to accept Transstor's new offer.

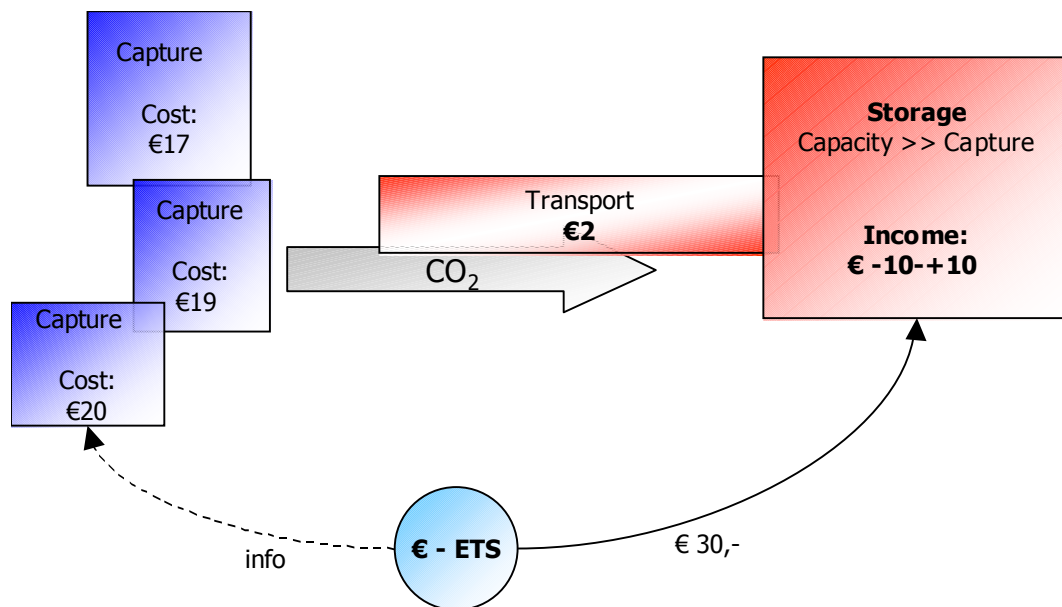
The high margin earned by Transstor attracts competition. Since there is only one network, competitors in storage will need to connect to that as well. Transstor will want to prevent that, and charge an entry price just so that entry will be unattractive. Concretely this means just above the earnings of storage plus the level of the ETS. Since Transstor has all the necessary information this is easily possible.

From the perspective of capture plants, there is an incentive to reduce cost. The costs incurred in capture are directly added to the operational cost of their production, be it oil refining or power generation. If all competitors are in the same kind of system, costs will be passed forward to consumers. If some competitors are in a different CCS system, where system costs are more evenly distributed the capture plants in a Transstor system have a disadvantage.

Concluding, a system with a Transstor will lead to a functioning CCS system where there is an incentive for all companies to invest in CCS equipment, however, the costs and benefits are not fairly distributed along the value chain. Therefore the requirement that a CCS system leads to economic development of the region is not met.

For new entry capture plants, there is no real incentive to participate. If the price they need to pay is so close to the ETS, they might just well pay the ets and not sell to Transstor. So if Transstor wants to increase volume, he needs to negotiate lower access prices to lure in new entrants. However, when Transstor builds a reputation of renegotiating contracts, this might become difficult and CO<sub>2</sub> emitters will look for other technologies to reduce emissions. Therefore, reputation might constrain opportunistic behavior by Transstor.

As it is still uncertain who will get the ETS credits consider the situation where Transstor is the trading party at the ETS:



**Figure 22: Vertically integrated transport & storage (II)**

Now, the incentive for Transstor to collect as much CO<sub>2</sub> as possible is apparent. Transstor needs to connect as many capture plants to increase volume. The capture companies now have the advantage that they can predict a large share of Transstor's income. This gives them a stronger bargaining position. On the other hand, the risk of renegotiation after emitters have invested in capture equipment remains.

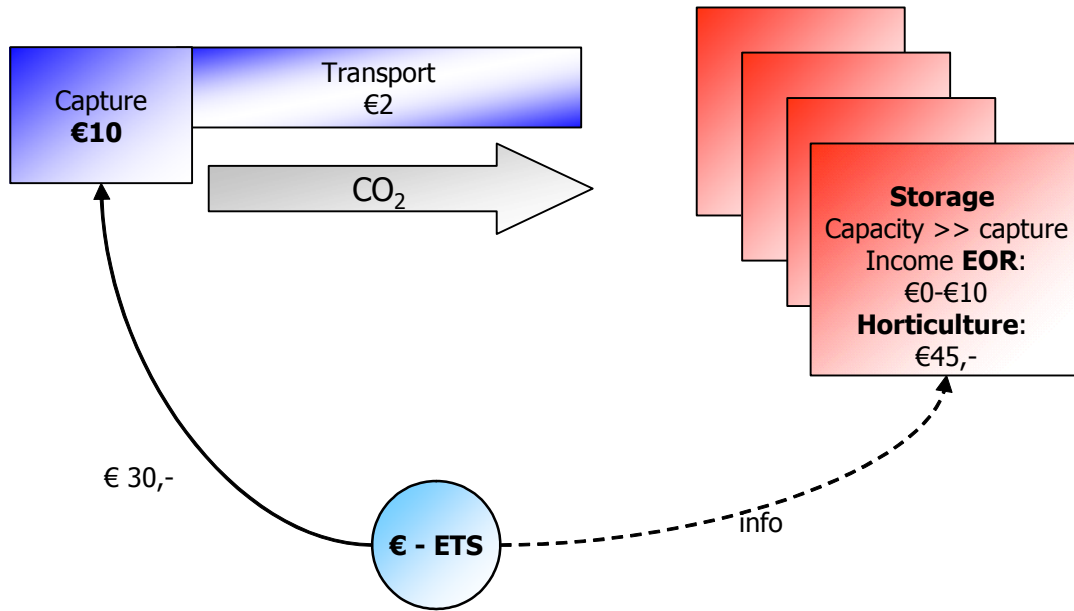
In this situation, the CO<sub>2</sub> resembles a product with economic value, where the monetary flow is in the opposite direction of the product flow. This makes efficient market based transactions more feasible in a unregulated market. Therefore, in a vertically integrated situation, I would recommend to have the storage party being the CO<sub>2</sub> trader on the ETS.

The design will be evaluated against the performance criteria in chapter 5. First we turn now to the description of a vertically integrated capture and transport company.

### **Transactions in vertically integrated capture & transport: Captrans**

This scenario resembles the current situation in the OCAP network. The horticulturists pay €45,- on average per ton CO<sub>2</sub> through a complex pricing mechanism.

In a scenario with Captrans, CO<sub>2</sub> is captured and transported by the same company. There are many storage operators bargaining for the CO<sub>2</sub>.



**Figure 23: Vertically integrated Capture & Transport**

When Captrans trades the ETS credits, the CO<sub>2</sub> is transferred to the storage parties who have an income of CO<sub>2</sub> from €0-10 for EOR or €45 when the CO<sub>2</sub> is applied for horticulture purposes. Note that for horticulture, a trade of ETS will probably not be allowed. The capacity for CO<sub>2</sub> uptake by horticulture is limited. Since income can be generated above ETS levels these sources are connected first. In the case of horticulture, Captrans receives €26 (=€45-17-2) for horticulture. When trading on the ETS the income for Captrans is €11 (=€30-17-2). In both scenario's Captrans has some power to control the price without losing customers. Since horticulturalists are either burning natural gas for CO<sub>2</sub> or buying it from the network, Captrans has seller power to price CO<sub>2</sub> to the highest price the horticulturalists are willing to pay.

When selling to EOR the storage parties have a better bargaining position. Their income is unknown to Captrans, unless Captrans is an oil & gas company itself. Then it knows the revenue and cost of storage operations. Since they will be reluctant to sell to their competitors for enhancing production they will increase price levels, effectively integrating the entire chain into one company.

The high prices and revenues achieved selling to horticulture can attract other CO<sub>2</sub> sources. This would be against the interest of Captrans, who can raise entry costs to increase costs for competing CO<sub>2</sub> sources who want deliver at a competitive price to horticulturists. Since the sales volume to horticulture is small, there is no incentive for Captrans to open up this market. Such

market opening would lead to lower prices, even to marginal costs if competition on both sides of the network exists.

### ***Capture obligation***

When capture is mandatory, the position of CO<sub>2</sub> emitters deteriorates. Their negotiation position with Captrans worsens. They are now in the position they would have been in when renegotiating.

When Captrans is dominant, the position of the capture plants competing for the network worsens as well. They are forced to buy network access at monopolistic prices.

In a situation with mandatory capture, the performance of the system is questionable. See chapter 5.

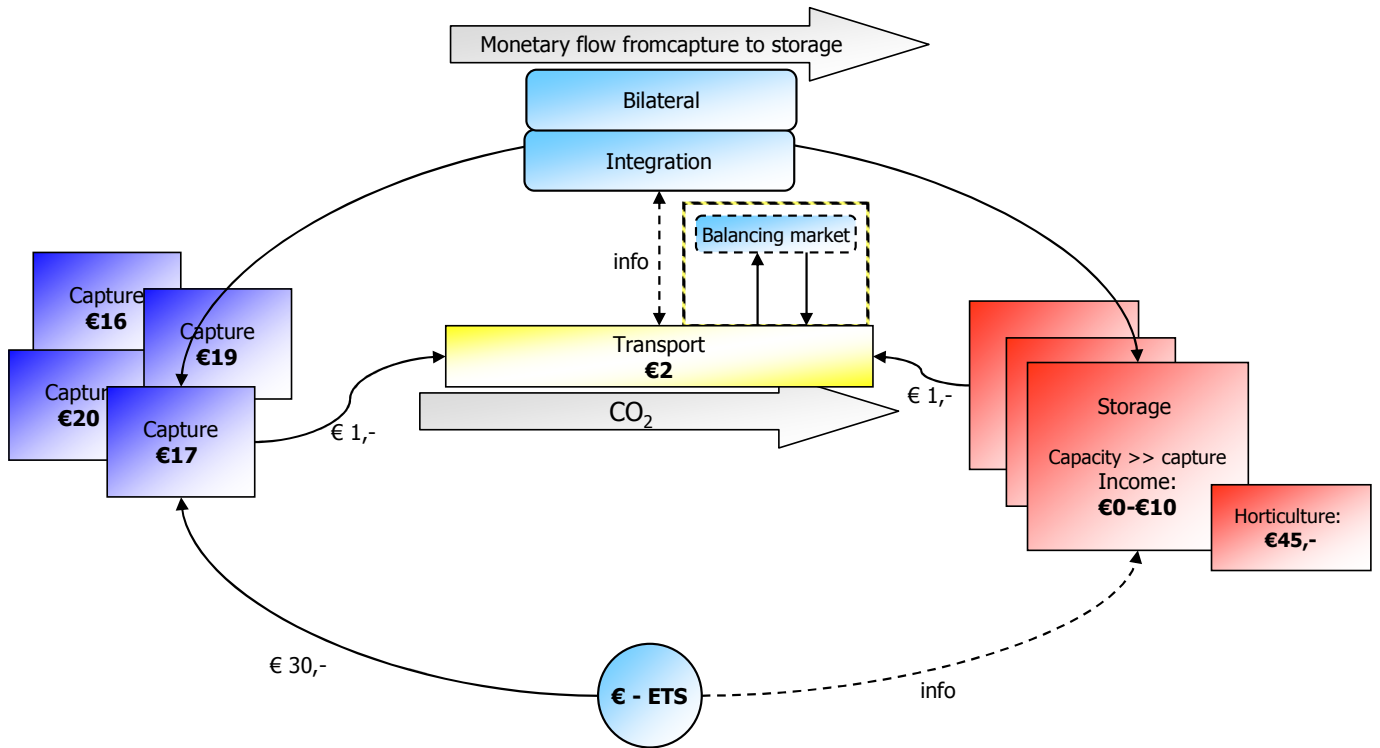
There is no regulator at the outset. But when companies feel mistreated by the integrated Captrans of transstor, they can appeal to the national competition authority. After a court ruling, this may lead to a juridical framework and a request for regulation and state intervention. This is an interesting form of bottom up design of regulatory governance.

## **4.3 CONCEPTUAL DESIGN 2: REGULATED MONOPOLY**

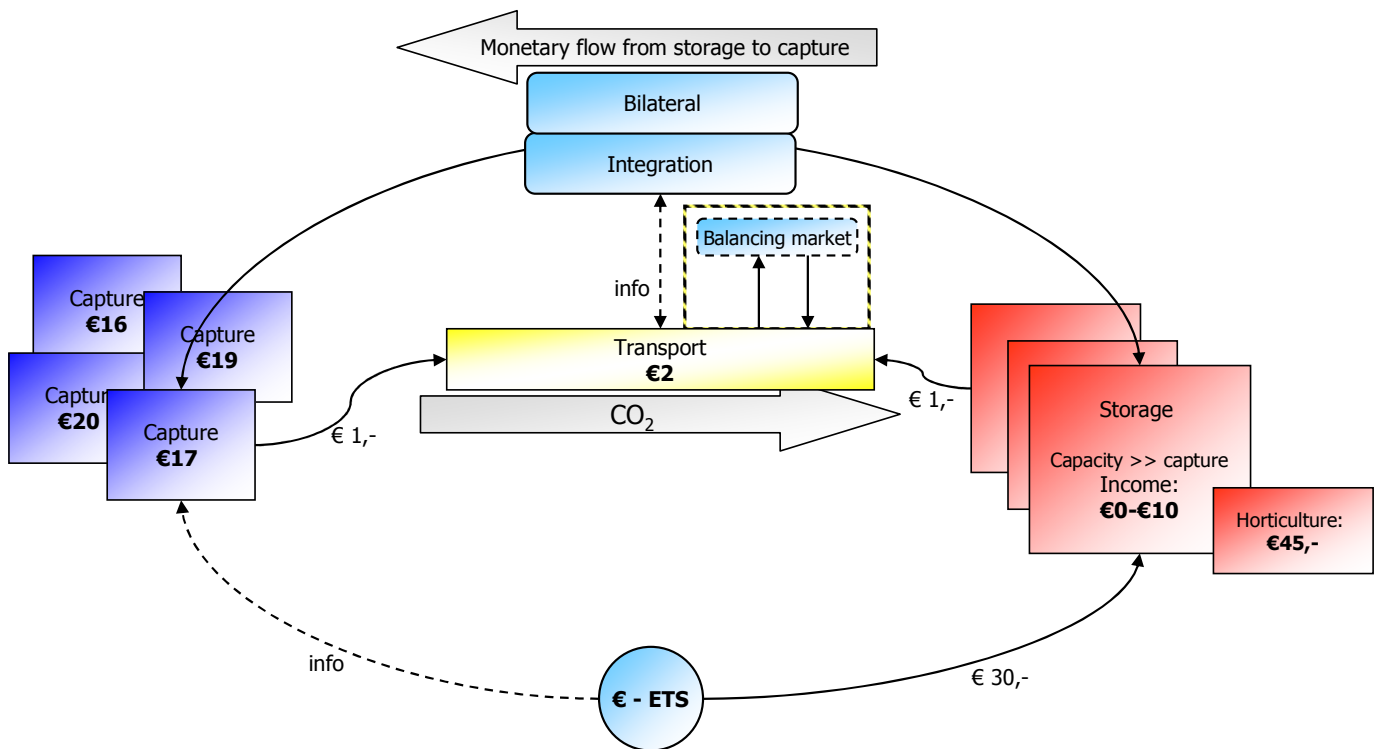
In a regulated monopoly, transport is unbundled from storage and capture in a specialized company owned by both public and private shareholders: Transco. This conceptual design is different from the previous one. The ownership is partly public, giving the public values in a CCS system a voice. The description of this conceptual design will develop several scenarios for different types of vertical integration. For all scenarios the ownership is in the hands of a public private partnership, there is competition regulation to facilitate competition between capture and storage.

The content of the choices on design options for the conduct and performance levels will be discussed below.





**Figure 24: Regulated Monopoly with capture as ETS trader**



**Figure 25: Regulated Monopoly with storage as ETS trader**

### ***The transportation company in Regulated Monopoly: Transco***

The transportation company in a regulated monopoly cannot be owned by company who is active in CO<sub>2</sub> capture or storage. In the design under inspection here, the transport company is owned by a partnership of public and private stakeholders. It could be privatized completely, but since the CCS system is still in its start-up phase, risks are too large to handle for a private party. The Regulated monopoly design considers a public private partnership where the public stakeholders hold at least 50%+1 of the shares. Because of the public participation the public interests inherent in a CCS system are at the forefront.

This means that in principle the network connects as many capture plants as economically feasible. It is possible that the public shareholders want to connect capture plants for which a connection to a CCS system is not economically efficient, motivated by their desire to reach publicly committed CO<sub>2</sub> reduction goals. If in the opinion of the majority of the shareholders it is considered that the economic interest is of less importance than the social interest of mitigating CO<sub>2</sub> emissions, decisions which are not economically efficient can be taken. The private participants of the CO<sub>2</sub> enterprise can be expected to object to such decisions. The constant discussion on decisions for public and private benefits of the CO<sub>2</sub> network will form as a check on the behavior of the transport company. This is one of the reasons private participation is necessary to generate economic efficiency (see 2.2).

### ***Balancing the network***

Since, the network connects multiple sources and sinks of CO<sub>2</sub> operated by different companies, there is a need for balancing. Transco is responsible for the balancing of the network. In the previous conceptual design (4.2) the integrated company was able to coordinate in and out flow of the network. In the case of an independent network company, balancing of demand and supply becomes an issue to prevent pressure drops, or pressure build-up. Apart from safety problems an imbalance can also have economic consequences as a supplier can be prevented to supply his CO<sub>2</sub>, or a consumer is unable to extract CO<sub>2</sub> from the network when he needs it. So an imbalance has economical as well as safety consequences.

The companies involved in the network need to supply data to Transco on their supply and consumption of CO<sub>2</sub> from the network. The network itself has some capacity to temporarily store the CO<sub>2</sub>, but in the case of enduring imbalance Transco needs to intervene. There are several options available. First, Transco can build intermediate storage facilities as a buffer system to cope with imbalances. Second, Transco can contract 'balance responsible parties', who can store CO<sub>2</sub> when asked to, this requires compensation for the involved storage companies. A third option is to create a balancing market as is in practice in the electricity market, this balancing market will be discussed later under the section focused on transactions. Added to this should be the observation that storage capacity contracted through Transco should be more expensive than storage capacity contracted through the market. This is a necessary incentive to alleviate the burden of Transco for contracting storage capacity. The penalty for contracting at Transco should be at least the transaction costs associated with setting up a bilateral contract with a storage

capacity supplier. In this way, it is less expensive for a capture plant to negotiate a bilateral contract for storage capacity itself.

Transco is also responsible for setting up a network standard for pressure and temperature of the CO<sub>2</sub>. Transco operates and maintains the pipelines, so they are in the best position to set an adequate standard. Capture companies are responsible for supplying the CO<sub>2</sub> to the specified standards. If it is technologically and economically efficient, Transco has the option to maintain different standards in different parts of the network. Interconnection stations between the different parts of the network will then be controlled by Transco. A network design with transmission and distribution pipelines can then be envisioned.

### ***Transactions in a fully unbundled Regulated-Monopoly***

In the fully unbundled situation, integration between capture and storage companies are also not allowed. In the first part of this description we will look into case when the capture company receives the ETS credits, and there is no capture obligation.

Since the capture plant can be connected to the network, he can be sure of demand of last resort for his CO<sub>2</sub>. However, as discussed above, contracting storage capacity through Transco will be less efficient than negotiating a bilateral contract. Therefore, the investment decision for capture equipment can be made based on the ETS level, the cost of capture and the availability of storage capacity. The system analysis has shown that there is more storage capacity available than there are CO<sub>2</sub> sources (see 2.1.3). For storage capacity to connect to the network they need an incentive, a compensation for their costs. In the case where capture receives the certified emission reduction this must be in the form of financial compensation from the capture plant.

If the financial compensation is attractive enough, the connected storage plant can start looking for other CO<sub>2</sub> sources to store CO<sub>2</sub> for. When the ETS trading rights are allocated to the storage party instead of the capture company, storage companies have a more clear incentive to increase the volume of CO<sub>2</sub> stored.

Also other ties between capture and storage companies exist in other markets: typically the fossil fuel market. CO<sub>2</sub> emitters typically consume fossil fuels. Fossil fuels are sold by the same companies who also own (through a subsidiary) or operate storage platforms. Therefore, multi product arrangements can be made between capture and storage companies. Such arrangements can become quite complex, but create a new area of package deals between consumers and suppliers of fossil fuels and CO<sub>2</sub>. The creation of such deals is not limited to this conceptual design. It is a transaction which is more likely to emerge in a system with an unbundled network, since this gives companies more freedom to engage in innovative business arrangements.

In both of the two settings, capture and storage companies have an incentive to capture and store CO<sub>2</sub>. Since the network is regulated, problems with connection charges and entry barriers do not arise.

Although under public authority Transco remains a monopolist requiring regulation. A regulatory authority needs to monitor Transco's operations and control if their decisions are harmful to

competition. Furthermore, specific regulation is needed for the monitoring of the flows in a CCS system to fulfill the requirement of inclusion in the ETS.

### ***The balancing market***

The balancing market for CO<sub>2</sub> can work in the same way as with electricity and gas markets. Transco is responsible for the efficient operation of the network. Therefore it cannot allow imbalances in the network. Since Transco monitors all the transactions between capture and storage plants, he knows where the main flows will arise. Still, actual flows can differ from the contracted flows. If this leads to congestion or imbalance, Transco needs to react and intervene by contracting production or storage capacity on a balancing market. The balancing market is created by balance responsible parties, those parties that have contracted capacity reserves which can be used when needed. Since the network is enclosed by capture and storage two types of imbalance can occur: a shortage and a surplus imbalance. When the pressure drops Transco has two options: increase CO<sub>2</sub> supply, or decrease CO<sub>2</sub> demand. This can create interesting situations. If the CO<sub>2</sub> balancing market has high demand (and related high value) for extra CO<sub>2</sub> it might become more profitable to increase production (e.g. in electricity plants) to cover the demand for CO<sub>2</sub>. The markets for CO<sub>2</sub> and electricity are then obviously connected. The second option in a CO<sub>2</sub> shortage is to force a storage company to shut down his operations. Engineered safety devices at the storage systems can also automatically shut down operations in case of underpressure.

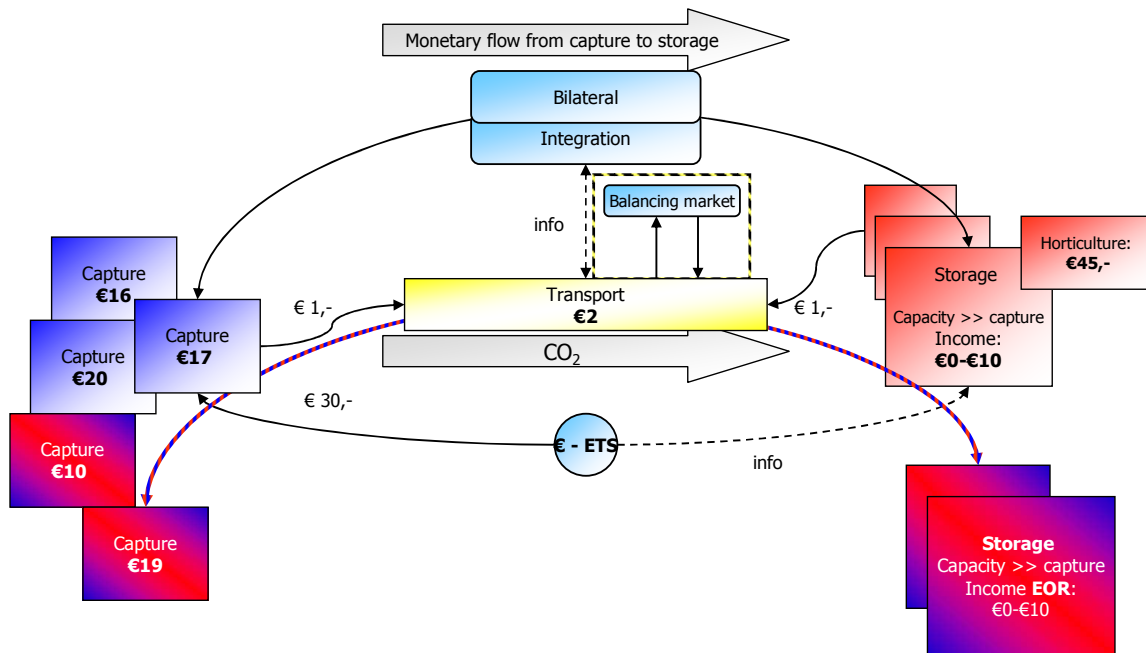
In case of a CO<sub>2</sub> surplus Transco has again two options: decrease production and increase storage. To decrease supply to the network is undesired; it would result in either interference with the process of the involved plants, or in venting of CO<sub>2</sub> to the atmosphere. Increase production capacity may not always be possible because of capacity constraints at the storage sites. Therefore, Transco needs to make sure that sufficient storage capacity is available. So some vertical integration is possible. Transstor should make sure that contracting this reserve capacity is more expensive than contracting capacity in the market by a sufficient margin (including transaction costs) so not to discourage investment by the market.

A balancing market thus needs to result in incentives for new investments, in capture equipment, in storage capacity or in pipeline capacity.

### ***Transaction in a Regulated monopoly with vertical integration***

If storage and capture are allowed to integrate, they might do so, if they are not already as is the case with oil & gas companies. This section describes the sphere in Figure 20 directly below the indicated position of a regulated monopoly.

Vertical integration between capture and storage in a regulated monopoly does not lead to inefficiencies. The plants need to supply Transco with information on the volume of CO<sub>2</sub>. In this case, it is no longer of importance which party receives the CER's as both capture and storage are part of the same company.



**Figure 26: Regulated Monopoly with vertically integrated capture & storage**

Since the natural monopoly is not part of the integrated company it has no market power, as long as it does not control a sufficiently large share of the storage capacity to control its prices. A regulator can control this, and monitor if it leads to exertion of market power.

Finally, the case when vertical integration between capture or storage and transport might be allowed, the incentives change as follows. The hybrid arrangement for ownership allows for 50% -1 share for private parties. To attain some influence in the decision making on the transportation network capture and storage parties may seek representation through ownership in Transco. Here, they can pursue their own goals and objectives and try to direct Transco towards their own cause. This is not inherently an unwanted situation, as long as the Transco board and the regulator secure that market power remains limited. It can even be a very efficient situation when well regulated. The transportation service is in principle facilitating the exchange between capture and storage. Representation of both interests in the transport service may lead to an efficient allocation of resources, to those positions where it can be of best use to both transport and storage. Care must be taken that Transco does not become the pawn of a market power wielding storage company, who uses Transco to limit competition: another task for the regulator.

### ***Capture obligation***

When capture becomes mandated for CO<sub>2</sub> emitters, the market conditions change considerably. The position of the capture plants who already invested in capture technology remains unchanged. However, the production of CO<sub>2</sub> in the network will increase as more capture plants come online. The demand for network and storage capacity will increase. It is easier to scale up the storage capacity. By adding aquifers to the network, the capacity can be increased. Such

decisions are however a departure from market based transactions as in the situation without capture obligations.

Network capacity needs to follow increases in volumes produced. The scale up of the network is much more expensive than a scale up of storage capacity. Recalling from the beginning of this section, the involvement of a public authority was rationalized for securing sufficient funds for upfront overinvestment to ensure sufficient network capacity. Therefore it can be anticipated that such a contingency was taken into account in the design of the project. Growth of CO<sub>2</sub> trades is an upside risk for network investments, which occurs when the regulation on mandated capture becomes reality. It is possible to include that upside risk in the investment decision (See analysis on investment under uncertainty in section 2.2.4) through real options financing techniques.

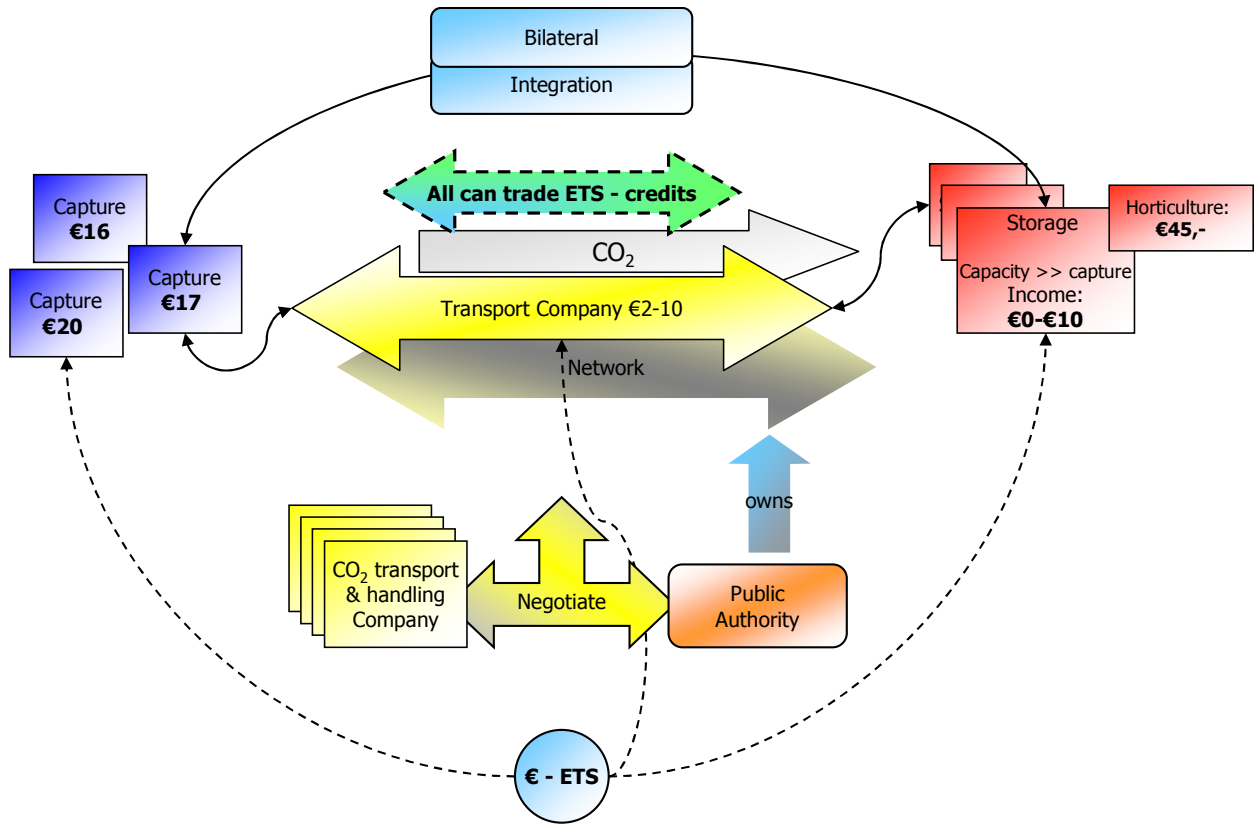
To change the regulations in the regulated monopoly design can be complex. Since the government has a stake in the network it starts to get conflicting interests. On the one hand the network supplies an income to the public authority, on the other, the public authority is supposed to control competition and issue regulations accordingly. These kind of conflict can lead to inefficiency.

#### **4.4 CONCEPTUAL DESIGN 3: GOVERNMENT OWNED ASSETS**

In this final conceptual design, the government owns the assets. It takes the initiative of constructing the infrastructure before capture and storage companies have explicated their willingness to join the network. A public authority coordinates the investment. The first step of the construction is similar in the previous design based a contract with a private party. However, the complete ownership remains with the government. The operation of the infrastructure is given out in a concession for a sufficiently long period (how long exactly will need to be determined, but say 10 years). In the first case, there are no limitations to who can enter in the tender agreement. Companies active in storage and capture can also join the competition.

The advantage here is that the amount of companies grows. The disadvantage is again the creation of market power through vertical integration, as explained in the Free-market design. Since in this case the ownership of the infrastructure remains with the public authority, a much stronger position for a regulatory body is created, for it to control the misuse of market power.

First we will discuss the general characteristics of this regulatory design, then we will go into the issues related to vertical integration in this model.



**Figure 27: Government owned assets**

Once the infrastructure is built, the public authority issues a tender procedure for the operation of the infrastructure. The terms laid down in the tender, and the final negotiations with the concession holder are crucial for the future performance of the network. The concession holder must be allowed to expand the network and invest in it, during the concession period. To expand the network, the costs of these expansions need to be covered by the concessionaire and the connected CO<sub>2</sub> source or sink.

The requirements of the tender and the crucial negotiations following it will need to contain the regulations on *conduct* and *performance* level. The regulations can change between concession periods, allowing some flexibility.

A pricing mechanism can be chosen depending on the need for network growth or for efficiency increase. To encourage growth of the network and increase the amount of connections Rate-of-return regulation can be applied. This will attract companies to the tender who also have experience in building pipelines, since they have the opportunity to use their learning and experience in pipeline construction and operation. Knowledge and experience with CO<sub>2</sub> handling is needed to make an estimate of the risk and costs involved in operating a CO<sub>2</sub> network. Because the estimation of risks and costs is so difficult to make, the value of the tendering arrangement for the public authority is in the transfer of this estimation to competing private companies.

When cost reductions are needed, and network growth has stabilized, a price cap is the regulation of choice. The companies attracted to the tender will then focus more on efficiency increases, and companies with experience in network operation will be attracted to the tender. Cost reduction and efficiency increase are types of operation which require less CO<sub>2</sub> specific experience. The focus can shift to balancing the network and achieving system efficiency.

It is clear that for the first phase, the concession should be at expanding the market.

The competition *for* the network introduces a second market, one for the concession. For functionality of that market it is required that there are several companies competing for the tender. The preparation for a tender creates costs for participating companies. They need to dedicate resources for preparing the bid. Therefore, they need to be compensated. After a short-list first round of the tender, the public authority can offer this compensation. The procedure and criteria used in the selection of a company needs to be carefully designed. The performance criteria need to be very clear, ranked and weighted properly, before an assessment of the concession contenders can take place.

### ***Regulating in a concession***

The pipeline infrastructure still remains a monopoly, so the need for a regulatory authority remains. Especially in connection with the trading on the ETS, a regulator is required to monitor the transactions and the flow of CO<sub>2</sub> to secure that the CO<sub>2</sub> is not traded twice.

A commercial operator of the CO<sub>2</sub> pipeline can itself also engage in transacting at the ETS, if it succeeds in securing deals with both capture and storage facilities. This is not unrealistic, as he controls the network connections and expansions. Therefore, the price for the transport service increases, as profits and risks are now partly shared by the transportation company.

Also, it should be monitored if the concession holder behaves as was agreed in the contract. The terms laid down in the concession contract should be monitored. Consequences of non-compliance should also be in the contract. This increases the cost of the contract, as it needs to be more complete, but it also provides a framework for conflict resolution.

In the case when a company engaged in capture or storage decides to bid for the contract, vertical integration of natural monopoly activities with competitive activities arises. The terms of the concession contract are the same for a capture or storage company are the same as for another company. He will need to serve his competitors at a non-discriminatory basis. Since he does not own the infrastructure, it is difficult to exclude his competitors from service. Strategic behavior with scheduling maintenance at inconvenient times or more often at his competitors and other opportunistic behavior can be expected. It becomes costly for a regulator to anticipate all possible opportunistic behavior. From that viewpoint vertical integration through a concession is undesired. However, it can also have benefits. When the vertically integrated firm is a storage company, he can create system efficiency, and since his incentives are aligned with the public goals (storing as much CO<sub>2</sub> at the lowest cost) it can be expected that such an arrangement is efficient.



## 4.5 REALITY: THE "CO<sub>2</sub> BEDRIJF"

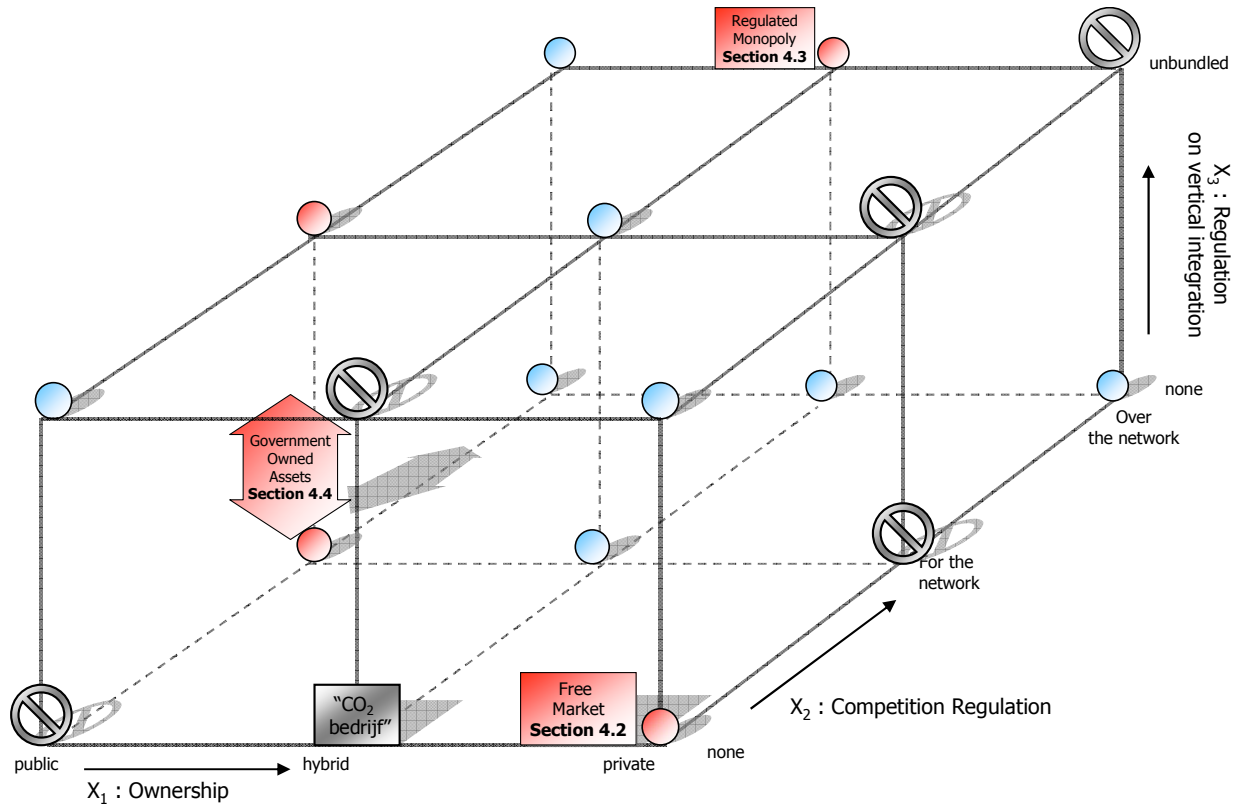
As discussed in the introduction of this chapter, the DCMR, the municipality of Rotterdam and the Port Authority (HbR) are interested in creating a new network company together with private companies. At the moment the plans are unclear, the plans have been evolving during this research. A common heard idea is that the CO<sub>2</sub>-network company should resemble the heat-network company (Warmtebedrijf Rotterdam, WbR) (Hanegraaf, Santen, & Knippels, 2007).

The WbR is owned by both public and private investors. Important to note here is that the private investors are energy companies (ROM Rijnmond, 2007). The WbR is both horizontally and vertically integrated. According to some angry consumers this causes problems with excessive pricing and low quality of service. (Actie Gigajoule, 2007). These concerns resonate at the political level, where politicians consider creating consumer protection measures in a new Warmtewet (Köper, 2007). Looking at the case of the Warmtebedrijf with the perspective of the analysis performed in this research it appears that the vertical integration of the energy companies distorts the market.

What the CO<sub>2</sub>-bedrijf will look like depends on the experiences with the WbR (Hanegraaf, 2007). The DCMR acknowledges differences between the technical, institutional and stakeholder differences between CO<sub>2</sub> and heat networks.

## 4.6 CONCEPTUAL DESIGN LESSONS

The conceptual design exercise has provided us with insights in how regulation on structure and conduct level shape the incentive structure wherein governance arrangements between companies can emerge. The dependence between the regulatory framework and the governance structures has become clear. Also the influence of the governance arrangements on the regulatory framework has come forward. In the free-market design it is shown that vertical integration leads to monopoly prices. CO<sub>2</sub> sources connected to the monopolistic market can take the initiative themselves to go to a regular court to explain their case. Whatever the outcome of the judicial process, legislation will follow, at least in the form of jurisprudence.



**Figure 28: Design Space of practical and discussed design options**

As discussed earlier, in theory, there are more conceptual designs possible than those discussed above. Now that we have more insight in the practical application of the design options discussed above, it becomes easier to understand the contents of the remaining feasible design options, the blue spheres in Figure 28.

**Table 8: Design options (nodes in design space)**

x1: Ownership	x2: Competition regulation	x3: Restrictions on vert. in	Description
Public	None	None	Not feasible, see chapter introduction
Hybrid	None	None	The CO <sub>2</sub> bedrijf, see section 4.5
Private	None	None	Conceptual design 1, see 4.2
Public	For the network	None	Conceptual Design 3, see 4.4
Hybrid	For the network	None	Very similar to CD3, but with a private party sharing the costs. This could be an investment bank or pension fund. In case of vert int, some monopoly power and stronger regulator is required.
Private	For the network	None	Not feasible, see chapter introduction
Public	Over the network	None	Very similar to CD2, but without private participation. A completely stated owned enterprise is operating the network.

**Table 8 Continued**

x1: Ownership	x2: Competition regulation	x3: Restriction s on vert. in	Description
Hybrid	Over the network	None	Very similar to CD2, but with vertical integration allowed, it requires stronger regulatory control to mitigate the risk of market power
Private	Over the network	None	Here a privately owned network is forced to open for third parties under regulated prices. This is feasible when a formerly private one-on-one connection becomes integrated in the network.
Public	None	Regulated	This is a vertically unbundled state owned enterprise. Similar to the option with competition for the network and complete public ownership.
Hybrid	None	Regulated	Not feasible, see chapter introduction
Private	None	Regulated	Similar to CD1, but with vertically unbundled network operator. Leads to an unregulated private monopoly.
Public	For the network	Regulated	Conceptual design 3, see 4.4
Hybrid	For the network	Regulated	Very similar to CD3, but with a private party sharing the costs. This could be an investment bank or pension fund. Since no capture or storage can take part in the investment, the regulator does not need to consider related market power issues.
Private	For the network	Regulated	Not feasible, see chapter introduction
Public	Over the network	Regulated	Similar to CD2, but with complete state ownership. Therefore more bureaucratic.
Hybrid	Over the network	Regulated	Conceptual design 2, see 4.3
Private	Over the network	Regulated	Not feasible, see chapter introduction

The exclusion of the eliminated designs was discussed at the beginning of this chapter. Now that we know the content of the red spheres, the content of the blue spheres can be reasoned by extending the properties from the conceptual design descriptions. The rightmost column gives small explanations for each blue sphere. This is shown in Table 8.

The value of making the conceptual design is not primarily in the outcomes presented above. Making the designs has provided many insights useful for the analysis. Making the analysis with the objective of making the design results in a sharper focus than a broad analysis would have provided.

However, when making design decisions one must beware not to create lock-ins and leave other feasible options open. Therefore we want to stress that the presented designs are not exhaustive.

The designs have posed more questions than can be answered by analysis alone. Some of the questions are dilemmas requiring a choice between two undesired outcomes. So to come to a

solution answers based on values and ideology are needed. And that is an exercise suited for politicians, resulting in a debate between government representatives, companies and non-governmental organizations.

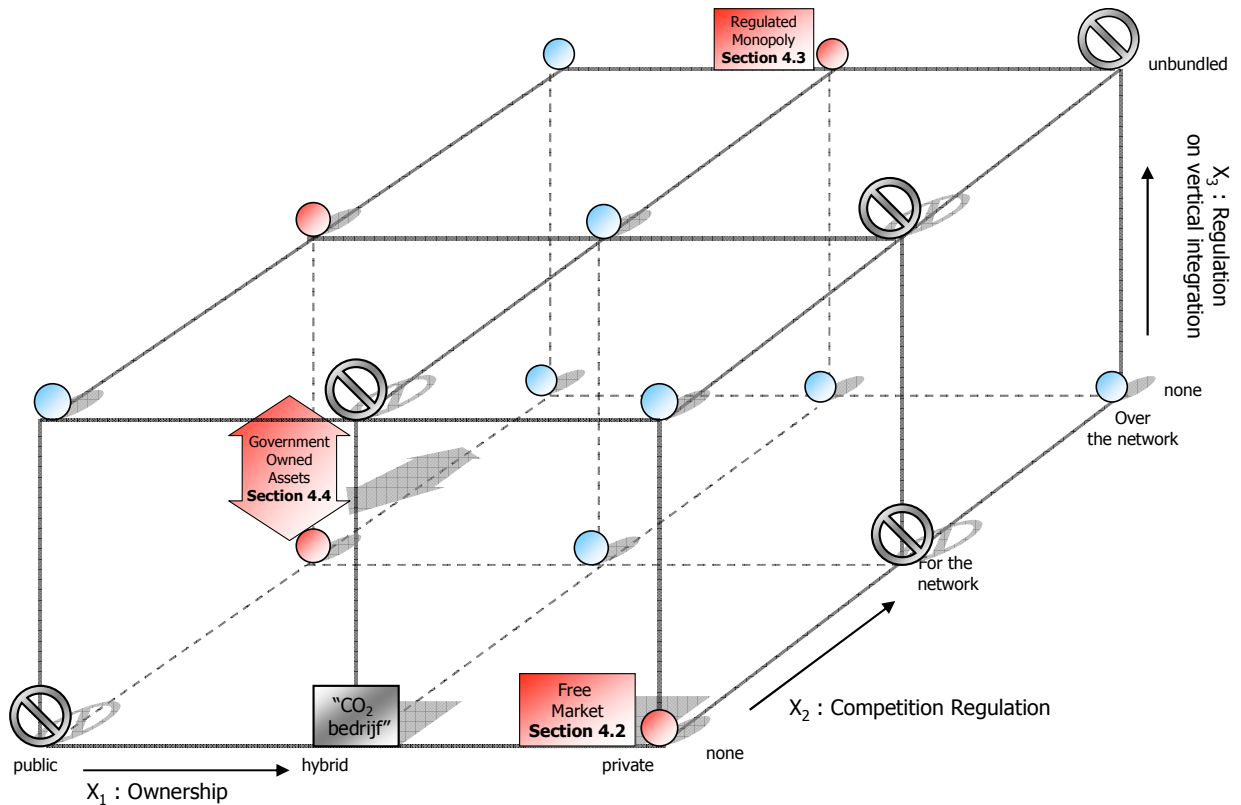
The questions and dilemmas are:

- Is the harm done by monopoly rents bigger than the costs for setting up a regulatory framework, including the enforcement?
- Is the involved public interest so significant that public spending of several 100 million euros can be justified?
- Obligating capture will push the market, but that does not fit the style of market pull regulation that has been in fashion since the 1990s. What do policy makers want?
- What will be the role of the ETS in the future? The companies want cuts on their allowances. Is it possible to stop grandfathering rights to CO<sub>2</sub> sources?, and what will be the consequence of CCS on the ETS? will that influence prices?

Apart from lessons, the conceptual design exercise has provided a clear recommendation. When CCS is included in the ETS, the right to trade the certified emission reductions should fall to the storage party. If this is realized product flow and monetary flow are in reverse directions. In other words, the business in storing CO<sub>2</sub> and keeping it underground has a much clearer economic motivation. And, when product and monetary flow are parallel, incentives are unclear. This will be further and more extensively discussed in phase III, where the main conclusions are collected and presented.

## 5 TEST & SELECT

To see which of the design options is most suitable, we propose to test them using a multi criteria decision analysis. In the following figure the position of the discussed designs is shown. As was discussed in the previous chapter the three axes represent the design variables.  $X_1$  and  $x_2$  make up the axes for ownership and competition regulation and they each have three values. The axis for regulation on vertical integration,  $x_3$  has only two settings.



**Figure 29: Design Options (II)**

The spheres with the red color were discussed in chapter 4. Where we should note that the third design of *Government owned assets* was discussed for the case both with and without regulation on vertical integration. The designs that were not extensively discussed will be considered for the evaluation. Table 8 has presented the contents of all practically feasible designs. With the knowledge of the three conceptual designs it becomes possible to conceptualize the characteristics of the other designs.

### 5.1 DEVELOP TEST

To test which of the combinations of design options best fits the criteria from the system analysis, a test needs to be developed. This section argues that a multi criteria decision analysis (MCDA) is an adequate test for the evaluation.

Dogson et al. describe the procedure for a MCDA test (Dodgson, Spackman, Pearman, & Phillips, 2000). The performance of the designs is scored on each criterion independently. Here, one can ask the stakeholders to evaluate the perceived performance of the designs. For the current research we have opted to fill in the performance score for each criterion. The views on the importance of the one criterion vis-à-vis another, is dependent on stakeholder interests and perspective.

The MCDA evaluates the criteria using scores. We have developed the following scores using an internal comparative assessment:

- 2 = definitely less performance compared to the other design options
- 1 = probably less performance compared to the other design options
- 0 = about the same performance compared to the other design options
- 1 = probably better performance compared to the other design options
- 2 = definitely better performance compared to the other design options

The criteria are taken from the conclusion of the system analysis (see crossref 2.4). For clarity they are repeated here in Table 9.

**Table 9: Performance Criteria**

<b>Code</b>	<b>Criteria</b>	<b>Contents</b>	<b>Factors</b>
C1	Effectiveness	The total volume of CO2 captured and stored before 2025 should be at least 20 Mton	<i>The time to build a network, waiting for hold up, investments match future growth of network</i>
C2	System efficiency	The regulatory framework should support an efficient operation of the total system	<i>The ability to generate an efficient balance between source and sinks.</i>
C3	Adaptability	The regulatory framework should be able to adapt against changes in policy and technology in a predictable, (stability enhancing) manner.	<i>The cost and time needed to adapt to new rules and regulations. Also the predictability of the changes. The expansion speed of the network plays a role.</i>
C4	Static efficiency	For efficient markets, prices need to be close to marginal costs. This gives investment signals and secures fair pricing.	<i>The likeliness that the pricing mechanism will lead to prices close to LRMC. Note that both <math>p &gt; mc</math> and <math>p &lt; mc</math> are undesired.</i>
C5	Allocative efficiency	All those in the market willing to pay the market price must be served	<i>Sufficiency of the network to include new connections, or abolish old ones.</i>
C6	<i>Dynamic</i>	<i>The regulatory framework</i>	<i>The incentives for cost</i>

	<i>efficiency</i>	<i>should stimulate cost reductions through time</i>	<i>reduction and the ability to introduce innovative arrangements.</i>
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Based on this table the first test is executed using the scores based on the factors as shown in the above table. The relation between the scores and the analysis is discussed in more depth in a dedicated appendix, Appendix E Test & Select.

## 5.2 RESULTS

Table 10 below shows the results for the three designs evaluated in sections 4.2-4.4. Note that for the design with the government owned assets two options were evaluated: one with regulation for vertical integration and one without this restriction.

**Table 10: Conceptual designs evaluated**

In the following section we will explain the scores. This will provide the basis for the evaluation

<b>Conceptual Design</b>	<b>Effectiveness</b>	<b>System efficiency</b>	<b>Adaptability</b>	<b>Static efficiency</b>	<b>Allocative efficiency</b>	<b>Dynamic efficiency</b>	
	<i>c1</i>	<i>c2</i>	<i>c3</i>	<i>c4</i>	<i>c5</i>	<i>c6</i>	<b>total score (sum)</b>
Free market	-1	1	2	-2	-2	2	<b>0</b>
Regulated Monopoly	2	1	0	1	1	1	<b>6</b>
Government owned assets <u>without</u> reg. on vert-integration	2	2	2	1	1	1	<b>8</b>
Government owned assets <u>with</u> reg. on vertical integration	2	2	2	1	2	1	<b>10</b>

of the other design options.

### 5.2.1 Free market

The free market design allows for vertical integration. As the analysis of the free market design (section 4.2) has shown, vertical integration leads to inefficiencies. The owner of the network has the opportunity to raise costs of entry, blocking access to the network to his competitors. This leads to prices above marginal costs, thus a low score for static efficiency. Furthermore, the network is not expanded beyond the owner's capture or storage plant. So therefore the effectiveness is less than in other designs. The efficiency of the system however can be expected

to be reasonably good. The owner has all controls needed to design the network such that it meets his own requirements. This leads to a cost reduction for the total system.

Looking at the adaptability to external changes, the free market can deal with changes since there is no regulatory body that needs to adapt. The market players themselves can choose whether or not they want to continue to use the network. Since the participants have taken this risk into account before they join the network, it can be expected that their strategies match the future development, or are able to adapt to them. In the case of obligatory capture the position of the vertically integrated monopolist is strengthened further. Such a development would lead to a further distance between price and marginal cost.

The high score for the dynamic efficiency of the free market is logical. Since markets are more innovative than government dominated economic activities. There is a greater incentive to reduce cost, as the company results and the related managers pay-check are linked to cost reduction.

Concluding, a free market is not to be considered for the detailed design. The private operation of infrastructure requires too costly regulation, monitoring market power and other types of opportunistic undesired behavior. Still in the case of ETS incomes going to storage, the incentives are aligned much better, and CO<sub>2</sub> is traded as an economic product. This improves both effectiveness and efficiency.

### **5.2.2 Regulated Monopoly**

In the Regulated Monopoly design, the transport is unbundled from capture and storage, and is owned by a hybrid arrangement between public and private participants.

This option is considered very effective, as the public stakeholders can direct funds to secure that the network has sufficient volume and sufficient connections to make sure that the goal of storing 20 Mton in 2025 is reached. The private stakeholders will argue for efficiency and cost effectiveness. Therefore, a balance can be reached in making decisions on efficiency and effectiveness. This argument can be extended to system efficiency.

The downside of this arrangement is in the adaptability. The transport organization is made up of stakeholders with different interests. When it needs to adapt quickly, this mismatch can result in a slow reaction. Therefore, the Regulated monopoly scores low on adaptability.

Dynamic efficiency can be achieved, the private participation enables this. Since all parties have something to gain in a cost reduction, it can be expected that each will try to innovate and bring down costs. Again, the incentive for dynamic efficiency is strongest when the storage plant gets the right to trade on the ETS.

When capture becomes mandatory, the CO<sub>2</sub> sources are better protected against the market power of the monopolist, as it is in the hands of a public authority, who serves the common good, translated in a price that is close to marginal costs.

### **5.2.3 Government owned assets**

The conceptual design discussed the public ownership with competition *for* the market in both the cases with and without regulation on vertical unbundling. When a public authority owns the



infrastructure he can hold a tender for handing out a concession for operation of the infrastructure.

Since a public authority owns the network, he can make the important investment decision on the adequate size of the network. This leads to a high score on effectiveness, similar to the regulated monopoly design. This is the same for both cases.

Once the basic network is constructed, the tender is issued to attract CO<sub>2</sub> handling and transporting companies. The tender can specify the specific requirements needed at that specific time. Therefore, the designs containing competition for the network score high on adaptability. Again, this is the same for both with and without restrictions on vertical integration.

The difference in performance is in the trade-off between system efficiency, monopoly costs and regulatory costs. To open the tender for companies active in either capture or storage allows companies in other parts of the value chain to join. Integration will lead to advantages through coordination of the value chain, settings for pressure, temperature, integration of intermediate storage can be adapted to the needs of the capture and storage activities. However, this will probably match the conditions only to the advantage of the incumbent<sup>3</sup> or companies with similar conditions. Therefore extra regulation is required to control that the incumbent will not put up barriers for competition, by introducing higher costs to his competitors. Since such regulation requires extensive monitoring and detailed knowledge from the regulator, it is very costly. That is the main reason why the option with unbundled competition scores higher. Besides, there are other companies with experience in transporting and handling CO<sub>2</sub>, who can also generate the system efficiency.

### 5.3 SELECTION

Table 11 and Figure 30 show the scores of all feasible design options.

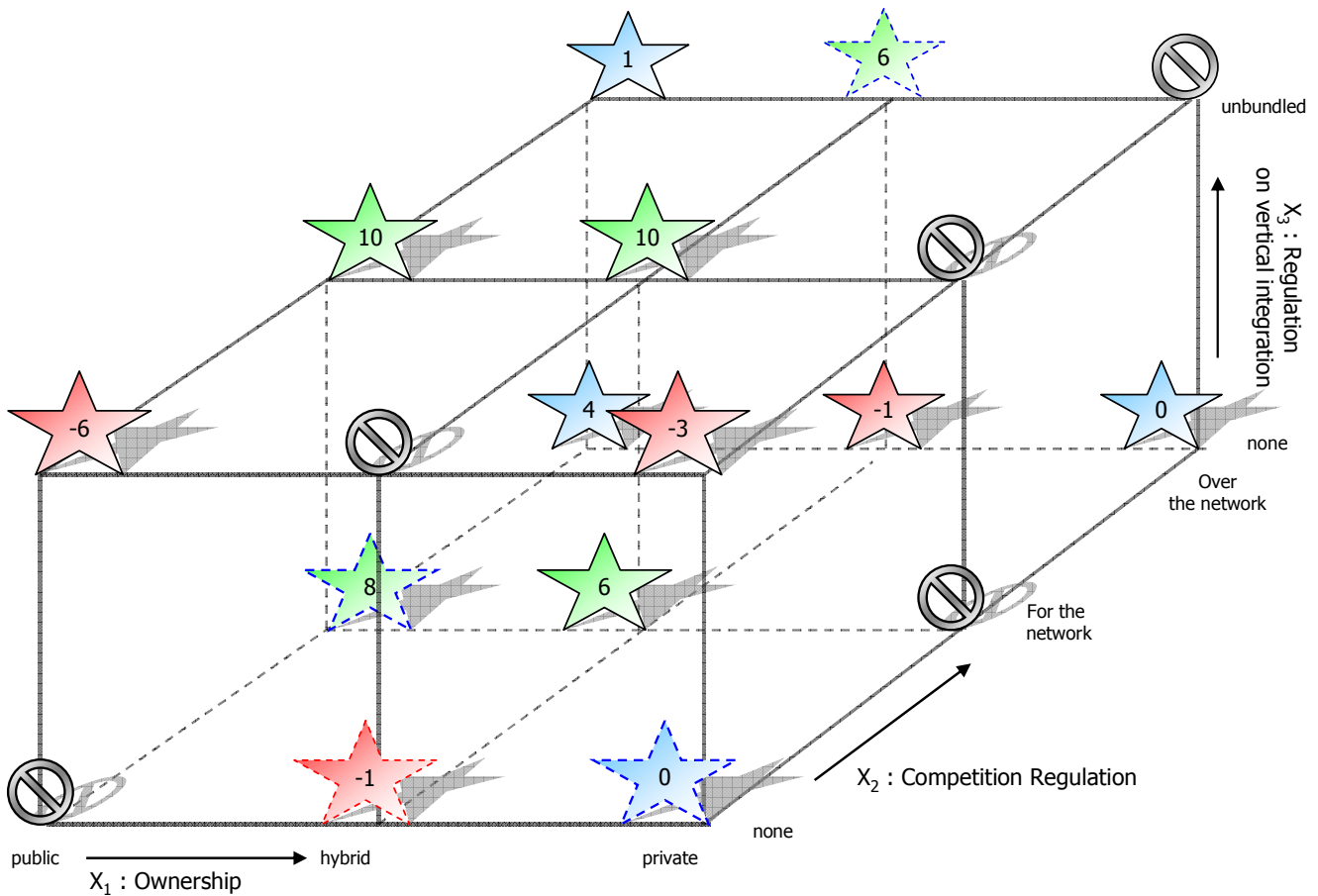
**Table 11: MCDA scores**

<i>Design option</i>			Effective	System efficiency	Adaptability	Static efficiency	Allocative efficiency	Dynamic efficiency	
x1	x2	x3	c1	c2	c3	c4	c5	c6	<b>score</b>
0	-1	0	-1	1	0	-1	-1	1	<b>-1</b>
1	-1	0	-1	1	-2	-2	-2	2	<b>-4</b>
-1	0	0	2	2	1	1	2	1	<b>9</b>
0	0	0	2	1	1	0	1	1	<b>6</b>
-1	1	0	2	1	1	-1	2	0	<b>5</b>
0	1	0	1	-2	1	0	0	0	<b>0</b>
1	1	0	0	-2	0	1	1	1	<b>1</b>

<sup>3</sup> The company that holds the concession

-1	-1	1	0	-1	1	-2	-1	-2	<b>-5</b>
1	-1	1	-2	-1	0	0	0	0	<b>-3</b>
-1	0	1	2	2	2	1	2	1	<b>10</b>
0	0	1	1	2	2	1	2	2	<b>10</b>
-1	1	1	1	1	-1	0	0	0	<b>1</b>
0	1	1	2	1	0	1	1	1	<b>6</b>

To visualize the scores of for each design, the scores for each design option are positioned in the design space as shown in Figure 30.



**Figure 30: Scores in design visualization**

The scores with red color are below zero, they are clearly not preferred. The blue stars represent the scores of those designs with moderate results (0-5). The green stars indicate the positions of the designs that justify some further attention and more detail.

From Figure 30 we can draw some interesting conclusions:

- The designs with complete private investment are not preferred in any of the constellations. This could already be expected based on the analysis; the expectation is confirmed by the test.
- The designs without competition regulation do not give any good results.
- The best results are scored by the designs in the plane spanned by  $x_2=0$ , with competition *for* the network.
- When alternative designs are compared between with identical setting of  $x_1$  and  $x_2$  and changing  $x_3$ , it does not always lead to a clear improvement. So moving upwards over the  $x_3$  axis does not lead to a clear improvement. This ambiguity probably arises from the complex trade-off between the damage done by monopoly on effectiveness and the gains in efficiency and private investment when monopoly is allowed.
- The CO<sub>2</sub> bedrijf as proposed by the DCMR and the HbR does not seem a successful candidate for further research. However, keep in mind that the exact details of the planned network company are unsure.

What also catches the eye in Figure 30 is the high score for the design option with hybrid ownership, competition for the network and restrictions on vertical integration. This design has the efficiency benefits of private investment in the infrastructure, the effectiveness related to public ownership and the adaptability of competition for the network. If such a design is considered considerable effort should be directed to attracting private investment. But, as discussed in the next chapter, start up of the network requires different conditions compared to when it is in operation for a few years.

## 6 DETAILED DESIGN

The next step in the research is to select design variables which go into more detail based on the previous analyses. From the design space analysis the position and design of a regulatory authority proved to be a design variable outside the structure-conduct-performance framework.

Furthermore, the conceptual design exercise has shown that the option to introduce competition for the network deserves some further attention. Especially the timing and sequence of regulation periods that this form of competition regulation makes possible will be discussed.

Finally, the expansion of the network to areas beyond the port of Rotterdam is considered as a business opportunity for the port authority and CO<sub>2</sub> transportation and handling companies (see section 2.2). They often speak of Rotterdam as a CO<sub>2</sub> hub for North West Europe, connecting the industrial areas of Antwerp, IJmuiden and the Ruhr-gebiet to the North Sea.

The following sections present first the issue of sequencing regulation, then go into the design of a regulator and end with the issue of expansion of the network.

### 6.1 DYNAMICS OF REGULATIONS

The option of competition *for* the network gives the option to introduce dynamics in the regulation by changing the terms of the concession after each regulatory period.

The owner of the infrastructure (either government or hybrid) can decide on the terms of the concession. Before tendering out the concession, it is imperative that the owners do a solid job on determining the goals and objectives they want to achieve with the network in the upcoming period. These need to be translated to requirements on which the tender applicants can be evaluated.

A clear procedure with short and long lists and strategic decisions needs to be developed. The site selection procedure as described by Dijkema et al. serves this purpose well. See Dijkema et al. (Dijkema, van Zanten, & Grievink, 2005).

The dynamics of regulations can be once the needs and requirements for the upcoming regulatory period are known. At the start up phase of the network the public authority first designs, plans and constructs the back bone infrastructure. Once this is ready, he can start the tender. The design of the pipeline should leave plenty options open to connect to it. Also, it should be able to handle a sufficiently large volume, at the least the required yearly volume of 20 Mton from the reduction goals. However, the most important capacity constraint the design should be able to meet is not the average load, but a peak load. Research needs to point out how high this peak load can become.

**Additional design requirements:**

- connection possibilities
- peak load

### **6.1.1 Timing of regulations**

In the first regulatory period, the network needs to connect multiple source and sinks. The volume of the CO<sub>2</sub> transported needs to grow. The design of the conduct regulation should provide incentives for network expansion.

As a pricing mechanism, rate-of-return regulation is then preferred over price-caps. A ROR regulation allows the concession holder to increase his return proportional to the investments he has made. As this may lead to over investment the regulator needs to monitor if the investments were 'used and useful' (see section 3.2.1 Price & Return).

Other conduct regulations can focus explicitly on expansion of the network. By giving a reward for each connection, the public authority can further encourage the concession holder to increase the connections. The public authority also has the option to use the stick instead of the carrot, by taking up a minimal expansion of the amount of connections (or increase in volume) as a term in the concession agreement. The regulator can control if this demand has been achieved.

The requirement that no capture or storage company can apply for the concession allows the regulator to shift his attention away from market power and competition issues and focus on the CO<sub>2</sub> specific elements.

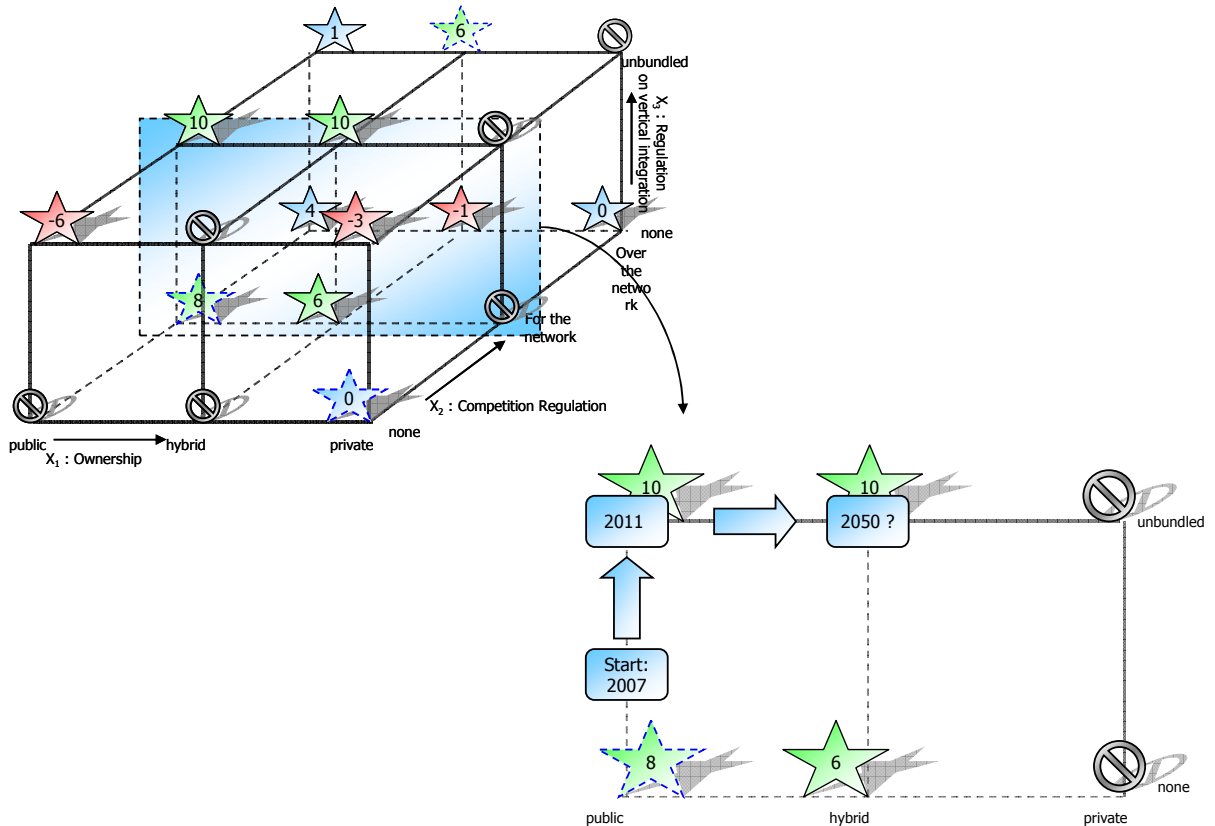
Once the network is in operation and has connected multiple sources and sinks, a shift from effectiveness to efficiency can become desired. The investments have been made and the network is deployed. To stimulate efficiency, cost reduction and innovation a form of conduct regulation more fitting to these criteria can be chosen. Price cap regulation allows higher profits when costs are reduced. Therefore it is a clear encouragement for cost reduction and thus efficiency.

In the early effectiveness focused phases profits can be made by expanding the network. This will attract companies with experience in this type of operation. They can use their position on the learning curve to bid competitively on the tender offer. The companies can then use their skills and expertise to build and expand the network, encouraged by performance incentives. Again, if capture becomes mandated, the network needs to expand to match the increased demand. The concession agreement should contain provisions for this situation.

In an efficiency focused phase companies with experience in network balancing can enter the tender. The tender competition can now be extended to include network companies from other utility sectors. Clear unbundling of these network companies is required if they formerly were part of a electricity producing company. The company able to bring down costs farthest without losing the effectiveness will win the tender.

A major complexity arises between regulatory periods. To make a smooth switch between network operators requires some clear coordination. Stakeholder commitment to this process is crucial. The opportunities for opportunistic behavior are numerous. To create commitment of the incumbent to leave his network in good order for the next concession holder and not sweat out the assets or perform other forms of opportunistic behavior a separate set of carrots and sticks aimed at a smooth transition is needed.

Another future development could be to include private ownership of the network. Interested parties can be banks or pension funds, but also industries. Before such private parties decide to invest in network ownership a set of historical data on the performance of the network is required. If it is a profitable venture with a risk-return structure that matches the private investors' portfolio, a move from a publicly owned entity to a hybrid or even a completely private entity can be made. To involve private investment in a *for-the-network* constellation at the start, or even before, the operational phase is difficult, if not impossible. Historical data on the network performance is required to base the investment decision.



**Figure 31: possible transition**

The terms of the concession will then change accordingly to the desires of the board of owners. Whether or not to involve private involvement remains a decision of the public authority. This decision can be made in the light of developments at that point in time when this decision becomes a concern. A possible transition path is shown in Figure 31.

### 6.1.2 The “CO<sub>2</sub>-bedrijf”

In the port of Rotterdam, a joint venture is in setting being set up by the port authority, the DCMR and CO<sub>2</sub> transport and handling company Lindegas benelux. The information on this venture is scarce. The involved parties do not disclose much information on their plans. From the report of the DCMR ‘CO<sub>2</sub> opslag in de Rijnmond’ it can be distilled that the CO<sub>2</sub>-bedrijf can be

positioned at the front face of the box, at the higher center position, or in other words, without regulation on competition, but with a hybrid ownership structure and independence from capture and storage companies. We would advise the involved public authorities to start considering implementing competition regulation, to enhance the performance of the entire value chain.

Our critique on the CO<sub>2</sub>-bedrijf is centered on the starting conditions. To include private party in ownership at the start is a lock in and will result in conflicting interests when it is in the public interest to change regulations and conditions. If it turns out that the network is an inefficient monopolist and economic regulations needs to be introduced. By making the investment of public money dependent on the returns made on the network (a profitable infrastructure) creates conflicting interests for the public authority to deal with. On the one hand, they need to regain their investments, and therefore can be convinced to charge prices above marginal costs. On the other hand, they need to secure the public interests connected to the CO<sub>2</sub> network. The double role in an unregulated network will create complex conflicts of interests. It can easily be avoided by introducing competition: either for the network by splitting ownership and operation or by regulated monopoly regulation. Where, as concluded from chapters 4 and 5, competition *for* the network is preferred.

Public authorities should be very careful signing contracts with private operators. On the other hand, if interests are aligned, go ahead, but do not forget the economic part and the issue of natural monopoly and the lock-ins such a decision creates.

## 6.2 THE DESIGN OF A CO<sub>2</sub> REGULATOR

As promised in chapter 3, the design of a regulator is discussed here. The role of a regulatory authority is important as it determines the robustness, flexibility and predictability of the regulatory framework. The previous section has shown that regulation is a dynamic business, with constant changes. The performance of the regulator is evaluated on its ability to adapt its practice to the changing conditions of external conditions. Where the manner in which the regulator adapts needs to be predictable to the involved stakeholders, as they need to adapt as well. The regulator constantly balances on the tightrope between robustness and adaptation.

The results of the system analysis are the basic inputs for the design of a regulatory institution. As with the framework, the constraints posed by the technology, the requirements posed by stakeholder interests, and the need to fit the existing institutions provide the inputs for the design.

A list of requirements and constraints are listed below. These are followed by a set of performance criteria. Finally, a similar figure to those used to visualize the design space is presented. Here, we must keep in mind that the regulatory institution is based on a choice for competition *for* the network, restrictions on vertical integration, and part or complete government ownership of the assets.

Requirements for a CO<sub>2</sub> network regulatory institution, with the source of the requirement in bold:

### **From competition *for* the network**

- The regulator should control the terms of the concession
- The regulator should resolve conflicts between public authority and concession holder
- The regulator should advise on the terms in the tender and in the concession contract.
- The regulator should ensure that the competition works
  - o investments in the network do not provide barriers for competition
  - o The tariffs charged should be in agreement with the regulation of that period
  - o Monitor all transactions in the value chain
- The regulator should ensure that the investments in the network are 'used and useful'
- The regulator should facilitate the transition between network operators

### **From technological / institutional analysis**

- The regulator should monitor the flows of CO<sub>2</sub>
- The regulator should monitor and enforce the application of approved protocols for monitoring the CO<sub>2</sub> once in the storage site
- The regulator should facilitate the design of protocols for monitoring the CO<sub>2</sub> in the storage site
- The regulator should approve individual monitoring protocols
- The regulator should mediate in conflicts on the CO<sub>2</sub> standard (pressure, temperature)

### **From stakeholder interests**

- The regulator should provide monitoring and control mechanisms such that they minimally influence the company related processes
- The regulator should provide a robust and predictable execution of regulation

The role of the regulator can be a mediating one between the concession-holder on the one hand and public authority on the other. If unreasonable demands are made by the public authority, the regulator can also take the side of the concession holder. This element of conflict regulation can provide a balance between public and private interest.

The performance criteria are:

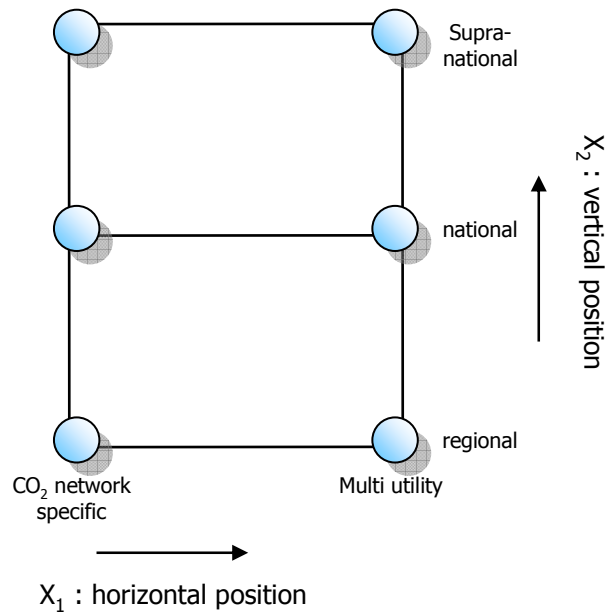
- o regulatory cost
- o robustness
- o adaptability
- o Predictability
- o Independence
- o Accountability
- o Transparency

(Berg, 2001; Estache & Martimort, 1999; Kessides, 2003)

The design options are taken from the design space analysis of chapter 3. This analysis has provided two major dimensions of regulatory design: the vertical position, related to the geographical and institutional level of the regulator; the horizontal position, related to the scope



of the regulator. Figure 32 presents the design variables in a similar fashion as the design space of the regulatory framework has been presented, Table 12 supports the figure.



**Figure 32: Design Space of a Regulatory Authority**

**Table 12: Design variables and range of a Regulatory Authority**

Design variable	Range		
	-1	0	1
$x_1$ : horizontal position		CO <sub>2</sub> specific	Multi-utility
$x_2$ : vertical position	Regional	National	supranational

The requirements contain less conflicting requirements compared to the design of a regulatory framework. Therefore, it is much less complex to design. Below we will discuss the design options for the different settings of the design variables.

### 6.2.1 Horizontal position

As can be deduced from the list of requirements presented above the regulator needs considerable knowledge of CO<sub>2</sub> and its characteristics. Setting up monitoring protocols is a procedure that requires cooperation with stakeholders. To be able to control and facilitate that process understanding of CO<sub>2</sub> and the associated chemical and physical processes is required. This argues for a CO<sub>2</sub> network specific regulator.

However, a regulatory authority for industry emissions exists in the Netherlands. The 'Nederlandse Emissie Autoriteit' (NEA) monitors and enforces emission protocols. The NEA already has knowledge on CO<sub>2</sub> and its properties. It is therefore worth researching if the two can be integrated.

Besides knowledge on the particular properties of CO<sub>2</sub>, the CO<sub>2</sub> regulator also requires expertise in the field of network regulation, especially in the context of competition *for* the network regulation.

The human resources who have knowledge of both types are scarce. This argues for a multi-utility regulator, where the issues of regulations between sectors are similar.

The companies involved in a CO<sub>2</sub> network are active in other sectors, some of them in regulated ones. To minimize their administrative burden of complying with different regulators the regulator of a CO<sub>2</sub> network could cover more than CO<sub>2</sub> alone.

A choice for single or multi-utility regulation also has geographical arguments. A multi-sector regulator typically has a wider area of interests, spanning a larger geographical region. For instance electricity markets are regulated nationally. If CO<sub>2</sub> and electricity regulation were to be performed by the national regulator, it makes no sense to create a regional CO<sub>2</sub> regulator within the nationally oriented electricity regulatory authority. Before concluding the decision on the horizontal position of the regulator we first need to look into the issues of the vertical position.

### **6.2.2 Vertical position**

The vertical position of the regulator is related to the geographical scope. The decisive factor is the scope of the market under regulation (see section 3.1.3 and Kessides, 2003). The industries participating in a CO<sub>2</sub> network are the electricity generation sector and the oil and gas sector. The geographical scale of the former is under debate, it is either European, or national. The oil and gas sector operates on a world scale, but can be considered European, as the CO<sub>2</sub> related regulation plays a role in the site selection decisions at a European level. This argues for a European regulator.

On the other hand, arguments for a more decentralized regional approach are strong. The importance of knowledge of the local conditions, for technical, economical and social reasons is plain for CO<sub>2</sub> networks. Technical because local conditions determine the selection of a storage location and the related appropriate monitoring protocols. Economical, as commitment from stakeholders is required to start up the value chain. Social, since efficient regulation is supported by a central position in the social network of relations between stakeholders in the region.

The consideration of a supra national institution is not uncommon. A European level regulatory framework covering the regulations on CO<sub>2</sub> storage is considered (ZEPP, 2006a). My arguments favor a more decentralized approach with a regional focus for enforcing regulation. However, when an European scale network is considered, connecting for example the Ruhr industrial area with the port of Rotterdam, coordination of distribution networks at a European level is required. This will be treated in section 6.3 *Interconnection with other areas*.

### **6.2.3 Perspective on a CO<sub>2</sub> regulator**

Looking at the analysis of the design of the regulatory framework as presented in the report, we can present the design of a regulatory institution as follows:

Starting off, the regulator should be at the national level, but with a regional focus, and develop regulations and practice based on local relations and conditions. For the involved companies this

type of regulation is also new, and therefore, they need to be supported in implementing the regulation. To avoid conflicts of interests, the regulator needs to be independent of the public authorities owning the network. To realize both independence and a sufficient knowledge base, the regulator can be brought under the Dte or NMa. At least, it should be independent of the port of Rotterdam and the DCMR or whichever public authority will own the CO<sub>2</sub> network.

Communication is at least part of the solution for maintaining the balance between predictability and adaptability. To decrease regulatory uncertainty the regulator can publicize documents (whit papers) concerning the 'policies and procedures that will guide their decisions in the future' (Kessides, 2003, p. 54). Another approach is to 'set up a consultative industry forum where interested operators, service providers, and potential investors could openly discuss issues affecting competition and other policy matters' (Kessides, 2003, p. 55). This latter options is practiced by the NEA (Alessie, 2007).

### 6.3 INTERCONNECTION WITH OTHER AREAS

Recently (may-june 2007) public statements regarding the creation of the port of Rotterdam as a European hub for CO<sub>2</sub> have been released by spokesmen of the port of Rotterdam, the municipality of Rotterdam, the DCMR and Lindegas Benelux (het Financiële Dagblad, 2007a). The cover of the Lindegas corporate magazine *Flow* offers a view into the company's aspirations. In the future it is considered to connect Corus near IJmuiden, DSM near Geleen, the port of Antwerp, and the coal fired power plants of the German Ruhr area. Figure 33 shows the cover of *Flow* magazine, with an impression of the future network.



Figure 33: the cover of *Flow* magazine (Lindegas, 2007b)

It will be a complex engineering project to connect the industrial zones with a CO<sub>2</sub> network. Again, the economic regulation of these interconnectors needs to be considered. Although outside the scope of this research, expansion of the network to other industrial areas should be considered in the design of a regulatory framework. The framework should avoid building lock-in preventing or blocking interconnection. The objective of storing as much CO<sub>2</sub> as possible is in line with the collection of CO<sub>2</sub> from other regions. Also the involved private companies in storage and transport benefit from the connection of other industrial areas as the volumes traded increase enormously. The Neurath kraftwerk at Frimmersdorf produces a yearly CO<sub>2</sub> emission of 19.3 Mton, placing it 5<sup>th</sup> in Europe's dirtiest power plants (WWF, 2007), equaling the total objective of CO<sub>2</sub> to be stored in 2025 for the port of Rotterdam in total.



**Figure 34: 'Kraftwerk Frimmersdorf' a 2,143 MW power plant south of Cologne, Germany. The yearly emission is 19,3 Mton CO<sub>2</sub> (image from Bühne, 2007; WWF, 2007).**

The creation of a European electricity market is currently an issue for European energy regulators and policy makers. The issue of interconnection and coordination of markets poses many difficulties, both from engineering and institutional perspective. For CO<sub>2</sub> networks to evolve and extend to nearby industrial areas, the incentives are more aligned. An increase in CO<sub>2</sub> stored would mean higher revenues for both transporters and storage companies.

To coordinate the massive streams of CO<sub>2</sub> and match them to storage sites is a complex operation of enormous scale. Imagine six of the Frimmersdorf scale power plants being connected to the port of Rotterdam and the CO<sub>2</sub> transported to the North Sea. This would mean a six fold capacity increase compared to the current plans. When CO<sub>2</sub> capture becomes mandated, the CO<sub>2</sub> needs to go somewhere, and it might be the port of Rotterdam. (Although storage of CO<sub>2</sub> in nearby aquifers might be possible, this is still being researched).

For the interconnection of different regions experience with economic regulation from the electricity sector is available. There are many possibilities for organizing capacity auctions and related market based capacity allocation mechanisms, how these can be applied to interconnecting CO<sub>2</sub> networks is an interesting topic for some other research.

## PHASE III: EVALUATION

Phase III contains two chapters. Each is related to one of the design objectives as defined in chapter 1. For clarity they are repeated here:

### **Objectives:**

- design a regulatory framework for CO<sub>2</sub> pipeline network
- develop a design methodology for institutional design

### **The research provides:**

- conclusions on the performance criteria and design options for a regulatory framework
- recommendations for policy makers concerned with designing a regulatory framework
- recommendations for further research to find answers to remaining questions, necessary for designing a regulatory framework in reality
- a contribution to the discussion on institutional design

Chapter 7 *Reflection* discusses the use of the application of the selected design approach to the design of a regulatory framework. Here the contribution to the discussion on institutional design is presented. Chapter 8 is the final chapter of the report and presents the important conclusions. The conclusions with respect to the design of a regulatory framework are, translated to recommendations. Also, recommendations for further research are made. These recommendations are useful for researchers at private enterprises such as Ecofys and for knowledge institutes.

## 7 REFLECTION

The report has described the design process of the institutional design of a regulatory framework. Applied to the design of a regulatory framework for a CO<sub>2</sub> network, the design process has provided many insights in the nature of institutional design. The greenfield nature of the infrastructure and the novelty of both product and of the technology provide a unique starting point for the design exercise. The co-evolution of technology and institutions is undoubtedly present in CO<sub>2</sub> infrastructure. The difference with other infrastructure related institutions is that the design can explicitly focus on both issues simultaneously and is not restrained to either technology or institutions.

This chapter contains a review of the design process in two parts. The first part provides a collection of insights on the use of the design approach formulated in five requirements. The second part provides a critical evaluation of the method that is applied in this research.

## 7.1 CONTRIBUTION TO THE DESIGN OF INSTITUTIONS

During the design exercise presented in the report five propositions on the design have been made. These are formulated as requirements on the design process. With the complex and case sensitive nature of institutional design it is impossible to come to a generalist approach (Klijn & Koppenjan, 2006). It is however possible to formulate requirements on the design process. In this section five requirements on the design process are treated. The requirements are substantiated with examples arising from the experience of this research. To indicate possible universality of the requirements, each is accompanied by arguments supporting the universality. To come however to a full proof of the universality of the requirements more research is needed.

### **7.1.1 Requirement 1: Independence of the designer**

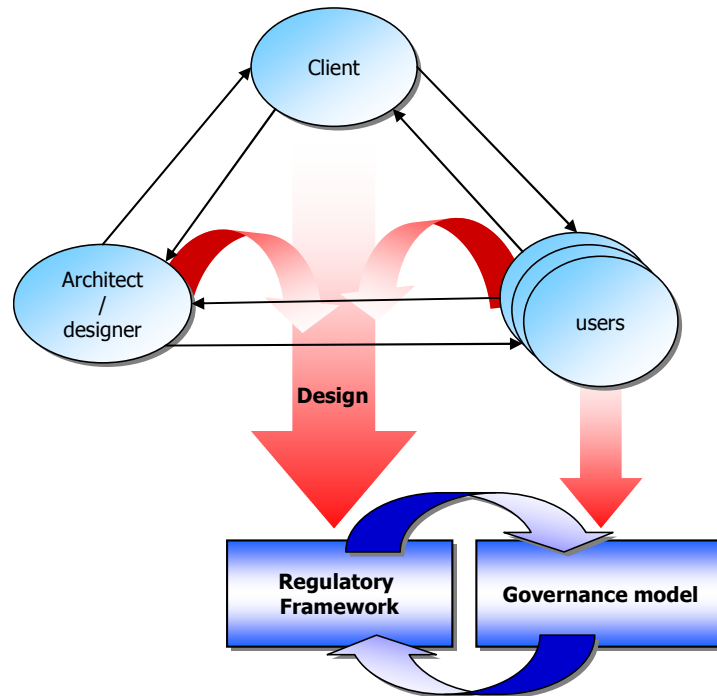
In regulatory design a top-down approach of coerce-and-control is not possible for four reasons (De Bruin & ten Heuvelhof, 1999):

First there is a network of stakeholders, with multiple interests and levels of power, all influencing the outcome. Concretely this means that the actors in the policy network of a CCS system are dependent on each other, without the others, they cannot achieve their goals. Secondly, stakeholders do not share all their information, they use their information strategically. Thirdly, the participants of a CCS system have origins in different industries, have different world views and problem definitions. Finally, the environment where the stakeholders are settled in is dynamic. Changes in the basic conditions are not uncommon, fuel prices change, policy changes etcetera.

These four conditions make it so that hierarchical top-down approach of regulation is not possible. To come to a design, the interests of all stakeholders need to be examined and taken into account, because of the criticality of participation by all parties in the value chain. To achieve this we have formulated the first proposition as follows:

#### **1. The designer should be independent of both client and user**

The requirement argues for a clear separation between client and user. When the designer is forced to look beyond the interests of the client (the principal) and take into account the interests of the user (the agent) he can create a design that contains benefits for both parties. Maier and Rehtin (2000) discuss this requirement based on their evaluation of design methods for socio-technical systems. Figure 35 represents their views, with the addition of the interaction of governance model and regulatory framework. The client gives an assignment to the designer for a regulatory framework to control the behavior of the 'user'. The user in turn tries to influence the regulatory framework through the formation of governance arrangements. This is the interaction at the basis of the arguments of the authors who deny the possibility of institutional design. We argue that by anticipating this interaction more successful regulatory frameworks can be created.



**Figure 35: Design Triangle**

The design approach as applied in our research has taken the perspective of the client (public authority) as a starting position and included the interests of the users as an input. The design of the regulatory framework is based on an analysis of what the stakeholders would do in a certain situation. The coordination of activities that is required for operation of a CCS value chain is facilitated by the regulatory framework. Ergo, institutional design is possible, as long as the designer is sufficiently separated from the client.

The universality of this requirement is linked to the arguments of Maier & Rehtin. The client and the user have conflicting interests, as indicated by De Bruin and Ten Heuvelhof. To solve this principal agent problem a distant designer needs to study the relationship between client and user and incorporate it in the design. The only way to achieve this is when the designer is not linked with either client or user.

### **7.1.2 Requirement 2: Analysis of dynamics in Technology, Stakeholders and Institutions**

Another issue is created by the dynamics in institutions. The interaction between regulatory framework as indicated by the feedback between 'regulatory framework' and 'governance model' in Figure 35 is never finished (Correljé, de Jong, van der Linde, Snijders, & Thönjes, 2003). Once the regulatory framework is in place, the game is not finished, and participants will constantly try to change the rules if that is in their interest. This argues again for a thorough analysis of stakeholder interests, also including the stakeholders that are only indirectly involved with the design. arguments reason for the inclusion of all stakeholder interests in the design phase.



A similar argument holds for technology. New technologies create new possibilities for behavior. The reasoning behind the idea of the co-evolution of technologies and institutions of Finger, Groenewegen and Künneke (2005) is correspondent to the inclusion of technology in the analysis. Apart from the dynamics, the design of the regulatory framework should explicitly consider the technological system subject to the regulations. The constraints put forward by the laws of nature constitute the basic starting conditions of the system. Therefore, a designer cannot do without knowledge on the basic elements of the technology. As this seems trivial it is not, as it requires the designer of a regulatory framework to be multi-disciplinary.

The notion of embeddedness of institutions (North, 1990; Williamson, 1998) dictates the need for a research of the institutional framework within which the design is to be placed. Existing laws pose constraints on the solutions possible. But not only formalized rules constrain the solution space. Also informal rules embedded in the culture or social system in which the institutional design is to be placed create a need for an analysis of the institutional environment of the design.

This leads to the second proposition:

- 2. The design should include an analysis on the involved Technology, Stakeholders and Institutions with a focus on the dynamics.**

### **7.1.3 Requirement 3 & 4: include an explicit design exercise**

The third and fourth requirements deal with the inclusion of explicit design considerations during the design phase. To include the design activity in an early phase of the analysis leads to a feedback with the analysis.

The third requirement is formulated as follows:

- 3. The design should include an analysis of the design space resulting in a hierarchy of design decisions.**

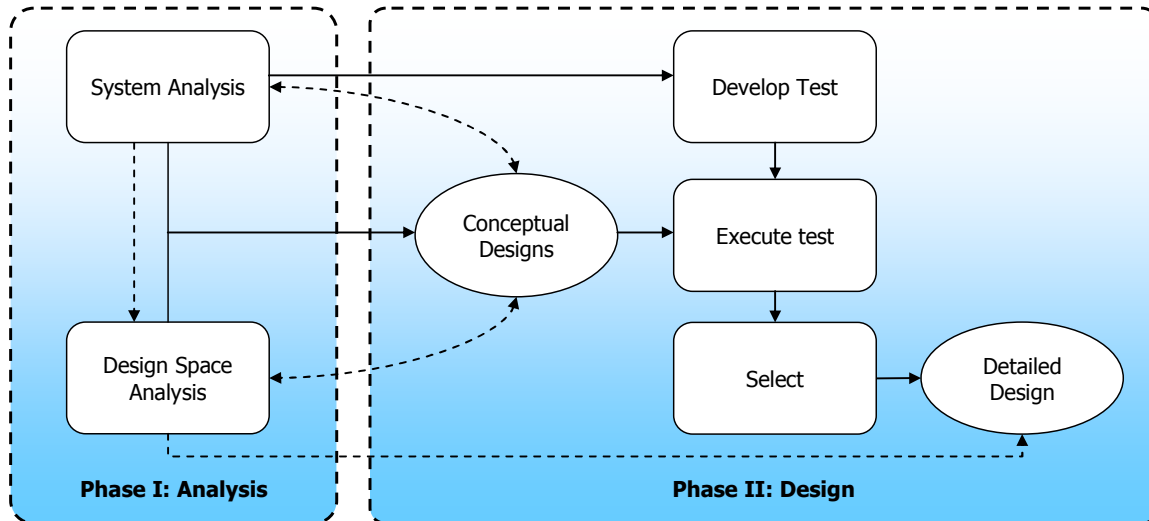
The idea of a hierarchy in design decision gives structure to a complex design exercise. The multitude of issues in regulatory design is large, resulting in complex design issues. Choices for one option result in exclusions of other possibilities. By making an analysis of the different design variables a hierarchy of design decision can be made. The Structure-Conduct-Performance framework by Sanvord Berg is especially useful for making a distinction between primary and secondary design decisions.

The fourth design requirement:

- 4. The design should include a phase where alternative designs at the conceptual level are made.**

The included conceptual designs provide a feedback with the analysis. By conceptualizing ideas for the institution under design, the designer can apply a sharper focus to his analysis. The

repeated interaction between actually designing and analyzing supports the general design process. The conceptual designs should be made in an early phase of the design process. In that way, the design exercise uncovers gaps in the analysis. And, on oppositely, the renewed analysis generates new insights for the design. The design poses questions, the analysis answers. The analysis is supportive of the design, and the design supports the analysis.



**Figure 36: Design approach repeated**

From experience with the case of the design in this research it can be noted that the limited detail of the conceptual design directed the design space analysis towards bringing a hierarchy of design variables. This resulted in a separation of issues which can be optimized independently following the primary structural design decisions. These issues can be transferred to the detailed design, as indicated by the dotted connection between the *design space analysis* and *detailed design* in Figure 36. The conceptual design exercise also causes problems, these are discussed in the section 7.2.

#### **7.1.4 Requirement 5: Test against “Business as Usual” not against an optimum**

To test the design before it is implemented is a truly difficult problem. If we want to design a test with participation of representatives of the actual stakeholders it will be impossible to create the correct conditions to match reality. It is hard if not impossible to create a test with cooperation of stakeholders where they will show the same behavior as in real life. The test will become part of the game of interaction as explained in Figure 36. Experimental isolation is not possible. Or in the wording of the famous example: There can be no experiment to find out if a falling tree makes a sound in the forest when there is no one around to hear it.

This lead to the fifth and final requirement:

## **5. The alternative designs should not be tested against an unobtainable optimum, but against a business as usual scenario.**

Testing against optimum is not realistic since an optimal situation does not exist in infrastructure (Shirley & Walsh, 2000). An optimum is a subjective state based on perception. According to Shirley and Walsh a test should aim to evaluate the performance of a regulatory framework against a counterfactual, also referred to as a business as usual scenario, a situation where without the implementation of regulations (Shirley & Walsh, 2000).

The evaluation of alternative designs is the most debated element of the institutional design as it is dominated by subjective judgment and stakeholder interests. To incorporate the subjective interests the designer can opt for a test procedure that includes them. The analytic hierarchy process developed by Saaty offers this possibility. The AHP evaluates the relative importance of performance criteria (Saaty, 1980). With the AHP as an input a multi criteria analysis can prove a suitable procedure. More research is needed to find an adequate test procedure when there is more than one design competing for implementation.

Comparing developments between different regions and sectors is prone to many errors. Even the slightest condition change can make results incomparable. So how can a regulatory framework be evaluated?

In a guest lecture by Jacques de Jong<sup>4</sup>, he told students that regulating is an art. Extending his argument designing the regulations requires an artist. And how does one evaluate the performance of an artist?

## **7.2 CRITICAL EVALUATION**

The second part of the Reflection chapter provides a critical evaluation of the performed design method. This section is again divided in two parts; first the addition of conceptual designs will be discussed. Second the more general critique on the model is treated.

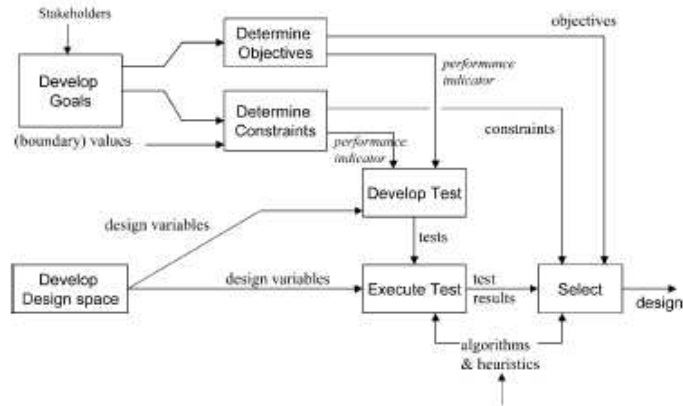
### **7.2.1 The introduction of conceptual designs**

The block with the conceptual designs form the addition to the standard meta-model design process as described by Herder & Stikkelman (2004). In the standard model, here is no explicit design step between the design space analysis and the tests. The design options are directly tested against the performance criteria taken from the basis of design. The conceptual designs were added to solve two problems of the meta-model.

The first is the lack of a form of communication between the analysis and the design. In the original, there is no feedback between the analysis and the design (see Figure 37).

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<sup>4</sup> Jacques de Jong is the former head of Dte and now a member of the Clingendael Interantional Energy Program. He gives an annual guest lecture at the faculty of Technology, Policy and Management



**Figure 37: The original meta-model (Herder & Stikkelman, 2004)**

This is regarded as a flaw in the meta-model (Koppenjan & Groenewegen, 2005). By explicitly introducing a feedback this is partly solved. The conceptual designs serve as an application of the design space. In practice this resulted in iterations between design and analysis. From the analysis ideas for the design originate. When these are then put together in a conceptual design, flaws and deficiencies in the analysis emerge. The flaws can then be mended in the analysis.

The second is that it is impossible to test a design variable individually. It is the combination of design options that constitute the performance of a design. Individually, the variable of ownership tells us nothing of the final performance of a regulatory system. When combined with competition regulation or other forms of regulation the testing begins to make sense.

### ***Critical issues of conceptual design***

The conceptual designs have not only solved problems, they have also created difficulties. One major issue is the depth of the conceptual design. In the field of institutional design there is common and well-know heuristic: The devil is in the detail. And detail is by its basic characteristic limited in conceptual designs. Therefore, it can be argued that the conceptual designs do not offer a sound basis for making a decision on critical issues. Errors in an early phase can have large consequences in later phases.

Another issue arises in which design to choose. The design space offers many possibilities, and the time of the researcher is constrained. It is not possible to work out all. To solve this problem we have taken distinct designs based on the visualization of the design space (see for example figure 23) based on insights from experimental design. However, when more than three design variables are present, such visualizations become impossible to construct. The field of statistical process design offers a large body of knowledge on the design of experiments. In this research we have taken inspiration from this field. However, the variables used in Design of Experiments are rational variables. The design variables used in the present research are certainly not rational, rather dichotomous (no regulation, regulation) or categorical (public, hybrid, private ownership). This raises questions of the validity of using design of experiments as a justification for choosing conceptual designs. For this reason, we have used it only as inspiration, not as justification.

### 7.2.2 General critical evaluation

This section provides a critical evaluation of both the institutional design in general and specific to this research.

In all aspects of institutional design actors behave strategically. This clouds the analysis and creates difficulties for the designer. In this research this occurred with respect to CO<sub>2</sub> shipping companies. The companies that were approached refused to cooperate and give information on their position. With the pipeline companies as a central player in a pipeline network it has become hard to assess their willingness to participate in an investment. For this research, we had to rely on second hand information. Some company statements were released but still, the actual position of pipeline companies on the network investments remains unclear.

The construction of the hierarchy of the design decisions in chapter three remains disputable. Although the hierarchy is based on the structure-conduct-performance framework alternative views can be equally valid. The starting point can be different, without compromising the validity of the steps. The decision for ownership, vertical integration and competition regulation as starting position is based on preference. Another view is to begin with regulations aimed at starting up the value chain. A regulatory framework then starts at performance regulations, for example with feed-in tariffs for electricity produced in a zero emission power plant. This perspective is held by the European Commission, who consider this type of performance regulations and as alternative have communicated it considers obligatory capture for coal fired power plants (European Commission, 2007).

The choices made in this research for the three most dominant design variables are made during the analysis of chapter 2. In that light, the choices are justified. The point is that different perspectives yield very different designs.

The meta-model is originally made for designs in a static environment. As the research has clearly shown, the field of CO<sub>2</sub> capture and storage is anything but static. The dynamic of the developments have been attempted to capture in this research by focusing on the dynamic relations in technology, stakeholders and institutions. The basic method however is not designed to handle dynamic relations. The field of Game Theory may prove an interesting insight to treat the interactions between stakeholders in different institutional settings.

The analysis of everything involved in institutional design can never be so fully complete to be able to make a rational design. Nonetheless, if stakeholders want to be successful players in the strategic game of institutional design they need to have a clear conception of the regulatory framework that serves their interests best. In that light, the institutional design exercise appears to serve another purpose. Instead of actually designing the regulatory framework, institutional design builds a perspective of possibilities. The final result will be an institutional mechanism which creates arrangements between actors that facilitate coordination and bring down costs. The probability that it will exactly resemble the views of the designer remains small. Of course this is not a problem. Seen in the light of Maier & Rechlin's book *The Art of Systems Architecting*, is it not so that true art is created when one loses control and a system becomes a life of its own?

## 8 CONCLUSIONS

The conclusions related to the design of a regulatory framework are translated to recommendations for policy makers here. Before turning to the recommendations, we will repeat the conclusions of the first phase of the research project here.

### 8.1 CONCLUSIONS OF THE ANALYSIS

The first conclusion is the confirmation of the natural monopoly of the CO<sub>2</sub> pipeline network. Based on the analysis of both phase I and II it has been confirmed that the monopoly leads to inefficiencies. The motivation for the research into the design of a regulatory framework focusing on the economic aspects is justified.

The research of scientific publications from the field of transaction cost economics has led to three conclusions. First, there is the observation that vertical integration in the value chain including a natural monopoly subsystem leads to economic inefficiencies. This holds for a CCS system where the transportation of the CO<sub>2</sub> is a natural monopoly. The opposing side of this argument is related to the technical system. Here, there are some benefits related to the vertical integration of transportation and storage systems.

Secondly, the analysis has shown that the both public and private investments have their merits. Public investment leads to greater leverage of public values, and a more effective CCS system. On the other hand, private investment leads to a more efficient distribution of risks. A hybrid ownership system can combine best of both worlds. The design of such a hybrid structure is a governance issue and care must be taken not to combine the worst of both worlds.

Thirdly, the literature on market based instruments was researched in chapter 3. The most important conclusions here are on the application of a competition schemes to create a market based governance of the CO<sub>2</sub> infrastructure. Both competition *for* and competition *over* the network have their value. Competition for the network creates the flexibility for the owner of the infrastructure to redefine the terms of the concession after each period. The owner, be it public, or a hybrid, can adapt the terms of the concession to the current needs of the network. In times of required expansion firms with experience of constructing CO<sub>2</sub> equipment can be attracted. In times of required efficiency increase the terms of the concession can be made such that network operation companies are attracted to the tender. A disadvantage is the resulting complexity in the handover of the network between concession holders.

Competition *over* the network also has advantages. The creation of a regulatory authority provides control of prices and limits monopolistic behavior by the network operator. Although the mechanism works it is less flexible. This is not completely a downside, as it inherently means that the system is more robust, also an important requirement for a regulatory system. Section 8.2 translates the conclusions in clear policy recommendations.

## 8.2 RECOMMENDATIONS FOR POLICY MAKERS

These recommendations are principally aimed at policy makers, but the insights will also be interesting for strategic managers of companies.

### **8.2.1 Go for the structural choices first**

When designing the regulatory framework we would recommend creating a hierarchy in design decisions. The fundamental issues on especially ownership need to be resolved before the other issues can be answered. Currently, the regulations under design aim at the entire CCS value chain. In our view, the economic regulation of the infrastructure does not receive enough attention. The fact that the European commission does not consider economic regulation of the CO<sub>2</sub> infrastructure can not be a reason to omit in the Dutch regulatory framework. The situation of a CO<sub>2</sub> network linking multiple sources and sinks of CO<sub>2</sub> in a specified region may well be a rare case.

### **8.2.2 Start up of the CCS value chain**

Policy makers in the Netherlands want to get the value chain started to reach the ambitious emission reduction goals. We will give a set of recommendations arising from the research project.

- **Invest in infrastructure**

The investments in necessary for the creation of a network are too large to be borne by private investors. This creates a hold-up problem. Since a CCS system is connected to public values this hold-up problem needs to be solved by including public investment. Furthermore, by including public funds the design of the pipeline can be aimed at maximizing public values. The diameter can be increased to accommodate future network growth. And, the government can support the spatial planning issues arising in the design of a network route. The participation of government signals its commitment towards the long term support of CCS as a CO<sub>2</sub> emission reduction technology. Finally, it fits the current line of policy, where in liberalized markets the natural monopoly is separated from competitive elements. For these reasons, the considerable investment needed to build the infrastructure is justified.

- **Facilitate demand and supply guarantees of CO<sub>2</sub>**

Policy makers should show that there is both a supply and a demand for CO<sub>2</sub>. Performance incentives should not focus on supply and demand separately, but on an agreement of supply and demand together.

- **Avoid feed-in tariffs**

Feed-in tariffs are a mechanism that results in below cost prices. According to the analysis this causes unwanted effects. Feed-in tariffs are temporary, and therefore cannot be maintained indefinitely. The involved companies will need to bear the costs at some point themselves, and it is inefficient if they are stuck with costly assets because of feed-in tariffs.

- **Apply a standard for CO<sub>2</sub> in the network**

After doing some research, apply a standard for pressure and temperature for CO<sub>2</sub> in the network. This creates clarity at the interfaces between elements in the value chain. It solves design issues.

- **Realize that you are in a strategic game**

Making regulation and maintaining it is a strategic game between public authorities and private companies. The government can design the rules of the game, but the governance structures that emerge are out of the scope of influence. The awareness of this interaction should be the basis of the actual regulatory design.

But first, more research is needed. With respect to the technical system particularly Storage would benefit. The other steps of the value chain have performed an economic function in other technical systems. There is limited experience with storage of CO<sub>2</sub> just for the sake of storing it. This research should be done with considerable haste, as there may be a window of opportunity soon. This recommendation is not explicitly included in the list, as this research into storage systems is being carried out, by the NAM, TNO and TU Delft (CitG). Broadly echoed through the sector, and recognized by the government, is the need for demonstration projects. The consensus on the demonstration projects has already led to two tenders for storage projects.

### **8.2.3 The inclusion of storage in the ETS**

This is a recommendation to be implemented on a European level. From the analysis of the performance of the conceptual designs, it has come forward that the economic incentive to store CO<sub>2</sub> emerges naturally when storage companies are included as trading participants at the ETS. To make storage parties traders, they need to be included in the ETS regime. Even in non-regulated vertically integrated market designs, the incentives work well and result in a start up of the value chain.

The issue is related to the status of CO<sub>2</sub> as a waste or product. A economic definition of a waste-substance is that the monetary flows are in the same direction as the product flows. Including storage in the ETS generates a demand for CO<sub>2</sub> as product. The value chain starts to get the characteristics of a commodity, where the commodity is 'CO<sub>2</sub> stored'.

To achieve this market pull, a well functioning ETS is critical. Currently the European Commission is in the process of allocating emission reductions to the member states. By increasing the scarcity, the EC tries to increase the price of a Certified Emission Reduction. Their success in this venture is crucial for the success of CCS, and CO<sub>2</sub> emission reduction in general.

Therefore, my recommendation is to include storage companies as a party in the ETS.

### **8.2.4 Mandated capture**

Mandating capture is a blunt instrument to get the value chain started. Based on the analysis of the market designs, it worsens the bargaining position of a CO<sub>2</sub> source. It becomes dependent on the transport and storage company. A capture obligation leads to more rigidity in the value chain. Prices will increase, as the CO<sub>2</sub> sources are vulnerable to monopolistic behavior by storage and



transport companies. The problem can be reduced when storage gets the ability to trade at the ETS. Then the demand for CO<sub>2</sub> increases as the ETS generates a market pull for stored CO<sub>2</sub>.

Mandating capture might be a quick way to solve the problem. But overruling the market and dictating such a technology choice will cause a lot of antagonism with the involved industry. Nonetheless, the threat of such a harsh regulation has the side effect of speeding up the process.

The influence of mandating capture and the ETS is an interesting interaction. If capture is mandated, the reduction of CO<sub>2</sub> emissions will be substantial. See 8.3 *Recommendations for Further research*.

### **8.2.5 Reality: the DCMR plans – “CO<sub>2</sub> bedrijf”**

The route the DCMR and the HbR have chosen looks promising. They have adopted a cooperative stance and are looking to create a joint venture agreement with a private company (Lindegas) to start constructing and operating the infrastructure. As of yet, there are no indications that they have considered the need for monopoly regulation. Apparently, in their opinion, the monopoly can only attract CO<sub>2</sub> from capture plants if it serves on a cost-only basis. But, once storage and capture are aligned, and a network is formed, monopoly rents will cause inefficiencies. Therefore my recommendation is for the DCMR and the port authority to consider the economic implications of operating a network infrastructure. For an effective CCS system, efficient operation of the network is crucial.

## **8.3 RECOMMENDATIONS FOR FURTHER RESEARCH**

This can be for both researchers at a university and also provide opportunities for work for Ecofys.

### **8.3.1 CCS and the ETS**

What is the effect of CCS on the ETS? The ETS is designed to be at the level of the marginal cost of a CO<sub>2</sub> reduction. If the ETS is used to compensate expenses made for CCS systems this might have effects. Especially if CCS starts to store significant volumes of CO<sub>2</sub>, the ETS might become flooded with credits of companies participating in CCS. A large part of the European CO<sub>2</sub> emissions can be stored with CCS.

### **8.3.2 Storage capacity is not availability**

The capacity of storage sites says nothing over their availability. More research needs to be done on actual field behavior in the storage phase of the field life span. This can be of influence on the economical system. If a storage site becomes temporarily unavailable, the CO<sub>2</sub> needs to be directed somewhere else. Insight in the mechanisms of a balancing market can provide a solution. The advantages of a network are clear here. It provides some flexibility to direct the CO<sub>2</sub> flow away from the temporary unavailable site, and crank up injection capacity at another storage location.

Linked to the next recommendation is the direction of research in characteristics of storing in aquifers. The capacity of aquifers is enormous, both off and onshore. If this capacity appears

accessible, it might prove a very good opportunity to store the CO<sub>2</sub> close to the site where it is produced.

### **8.3.3 Growth of the network**

There are many planned CCS demonstration projects, starting up in around 2010. This leads to one-on-one connections between sources and sinks. When the step is made from several small scale demonstration projects to large scale operation of the CCS system the network infrastructure will need to evolve accordingly. This could be an interesting case to analyze or design a growth model for the network.

### **8.3.4 Expansion of the network to other regions**

The German areas with large scale CO<sub>2</sub> sources can be connected. But onshore storage is possible. Recently, a demonstration field for storage at Ketzin near Potsdam has been opened. The field generates results for the possibility of storage onshore. Therefore, do not see the enormous numbers as business opportunities right away.

Becoming the CO<sub>2</sub> hub of Europe is easier said than done. The volume of CO<sub>2</sub> related to one of the German Lignite power plants is comparable to the total reduction goals of the climate initiative.

As explained in the previous section, it might be more efficient to store the CO<sub>2</sub> near the source site, in aquifers. A European scale network is then no longer necessary, we can only consider a network when there is a close concentration of point sources.

### **8.3.5 Game theory in Institutional Design**

This recommendation is related to the institutional design exercise. The outcome of the interactions between the regulatory framework and the governance structures adopted by the organizations where the framework exerts its influence can perhaps be analyzed with game theory. If there had been time, I would recommend a game theory approach to regulation.



# Appendix A RESEARCH QUESTIONS

## **Research Objective**

To design a regulatory framework for a CO<sub>2</sub> infrastructure network for the port of Rotterdam

To propose a design method for the design for a regulatory framework

## **Research Question**

What regulatory design leads to an effective and efficient regulatory framework for a CO<sub>2</sub> pipeline network?

## A.1 SUPPORTING RESEARCH QUESTIONS

What are the characteristics of a Carbon Capture and Storage (CCS) system which cause the need for the design of regulatory framework?

### **Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with the concerned companies.

### **Result:**

List of requirements posed by technology

Direction for research of solution space

**Sections: 1.2, 2.1, 2.3**

What are the requirements on the design of regulatory framework for a CO<sub>2</sub> pipeline network from the perspective of:

- Technology;
- Stakeholders, and;
- Institutions?

### **Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

### **Result:**

List of requirements from technology, stakeholders and institutions.

**Sections: 2.1, 2.2, 2.3**

What are performance criteria for an effective and efficient Carbon Capture and Storage system from the perspective of:

- Technology;

- Stakeholders, and;
- Institutions?

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

**Result:**

Set of Performance criteria concerning effectiveness and efficiency

**Sections: 2.1, 2.2, 2.3**

What are the design variables for a regulatory framework?

**Method:**

Literature research of industry documents, scientific publications, conference proceedings and interviews with representatives of the concerned companies.

**Result:**

A set of design variables spanning a design space with a range

**Sections: 2.1, 2.2, 2.3**

What are the primary and secondary design decisions for a regulatory framework?

**Method:**

Literature research, use of the Structure-Conduct-Performance paradigm

**Result:**

A set of primary and secondary design variables

**Sections: chapter 3**

How can the primary design variables be combined to produce concrete design options for a regulatory framework?

**Method:**

Analysis of the primary design variables

**Result:**

Insight in the possible conceptual designs, and three detailed descriptions of the conceptual designs

**Sections: chapter 4**

Which of the conceptual designs generates the most promising results and is selected for detailed analysis?

**Method:**

Multi Criteria Analysis

**Result:**

Insight in the performance of the conceptual designs and, an input for the detailed design exercise

What can be solutions to the issues of the detailed design?

**Method:**

Usage of the insights from phase I and the conceptual designs to propose solutions for detailed design issues

**Result:**

Recommendations for solving the issues of the detailed design

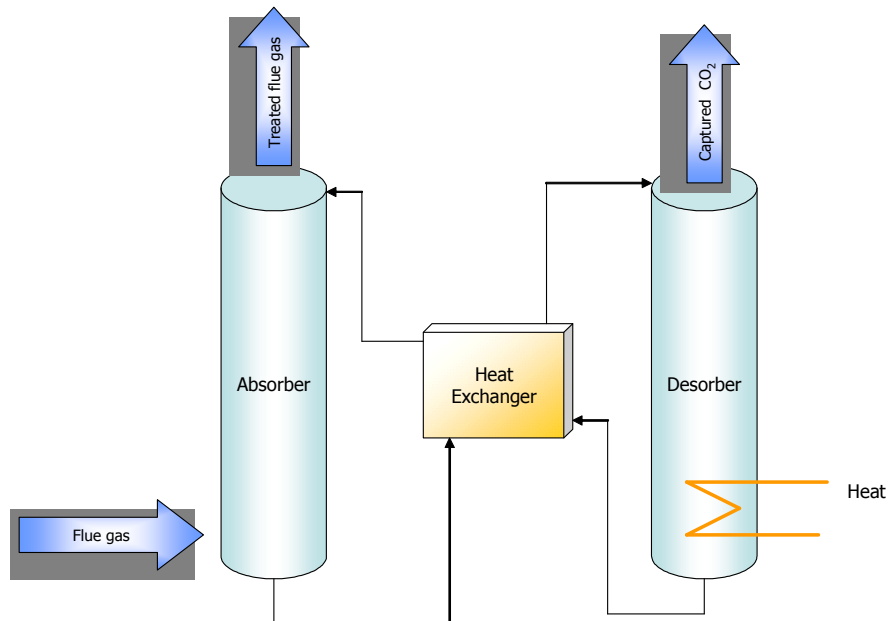
The research is constrained to the Netherlands because of scope and time issues concerning the master thesis research. It is however conceivable that the designed governance model can be extended beyond the Netherlands and provide the basis for a European wide governance system.

## Appendix B CAPTURE TECHNOLOGY

### B.1 POST-COMBUSTION CAPTURE

A Post-combustion system captures the CO<sub>2</sub> at the very end of the plant, just before the flue gas enters the exhaust. Before the flue gas is emitted, a capture plant is added in the process line. This makes the technique suitable for retrofitting combustion processes.

Many post-capture processes can be distinguished, I will discuss two, one of which is the current standard of technology (separation with sorbents) and one which is actively considered for a new power plant in the Rotterdam harbour. Figure 38 shows the process of solvent separation.



**Figure 38: Schematic solvent based post combustion installation (adapted from: E.On, 2007)**

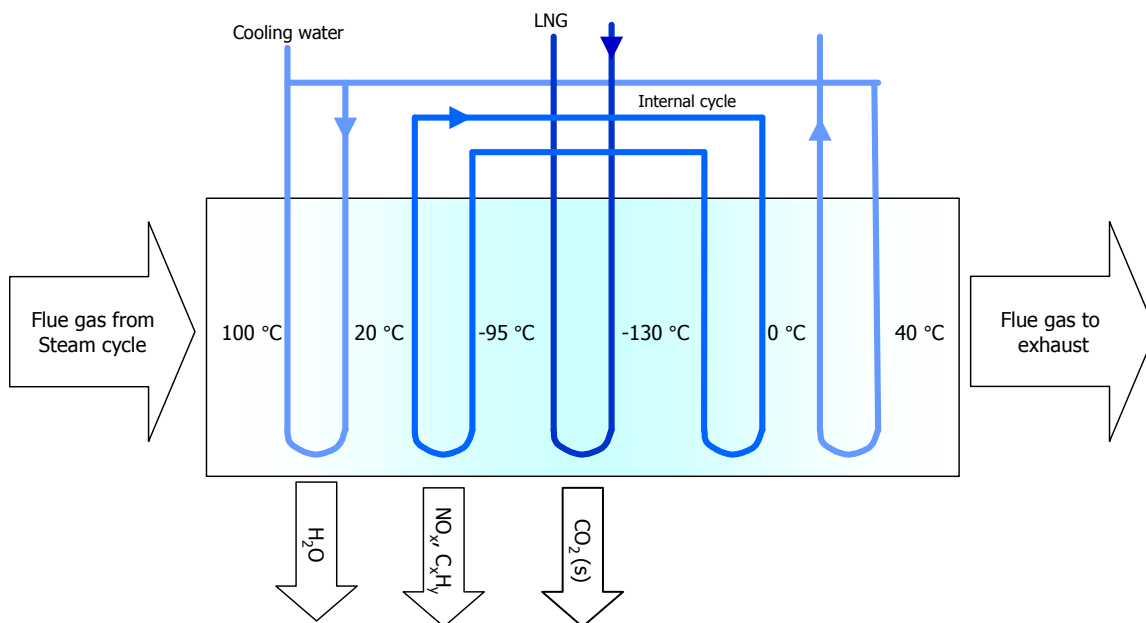
Separation with a sorbent (Figure 38) uses the typical chemical or physical characteristic of the sorbent material to capture the CO<sub>2</sub>. The sorbent containing the CO<sub>2</sub> is transferred to a regeneration vessel where the CO<sub>2</sub> is separated from the sorbent, where the pressure and temperature are such that the CO<sub>2</sub> is removed from the sorbent.

The problem with such a structure is twofold. First, the post-combustion equipment is placed after expansion has taken place in the process. Therefore it needs to match the high volumes with a low partial pressure of CO<sub>2</sub> in the flue gas stream, leading to high equipment costs. Secondly, the treatment of the flue gas and sorbent requires extra energy. For the sorbent to be able to absorb the CO<sub>2</sub>, the temperature typically needs to be low, for example with MEA (mono-ethanol-amine) the absorption temperature is 40°C and for regeneration the solvent needs to be reheated to 100-140 °C to remove the CO<sub>2</sub> from the sorbent. These operations require energy

and lead to an efficiency reduction, for example in coal fired power plants around 8-12% with current technology (IPCC, 2005).

In the port of Rotterdam, this technique can be applied in coal fired power plants. E.On is preparing its Maasvlakte pulverized coal plant to be fitted with a demonstration installation of a solvent based post combustion capture system. The installation will capture 70-250 kg CO<sub>2</sub> each hour, which is estimated to be 0,02% of the yearly plant emissions (E.On, 2007). The main purpose of the system is to evaluate the influence of the capture system on the performance of the power plant (Huizeling & Groeneveld, 2007).

Another technique that can be applied is cryogenic separation of the CO<sub>2</sub>. By cooling of the flue gas to -130 °C the CO<sub>2</sub> transfers to the solid phase and can be removed from the flue gas stream. The Dutch company Eneco is studying a co-siting procedure with the cold from a nearby LNG regasification plant and a capture installation for their natural gas power plant. Although promising from an energy efficiency standpoint, the technology still needs to go through further research stages and laboratory experiments before it can be applied (Jacobsen & van de Woudenburg, 2007). Figure 39 gives an overview of the product flows and temperature.



**Figure 39: overview of the Enecogen cryogenic separation (adapted from Enecogen, 2007)**

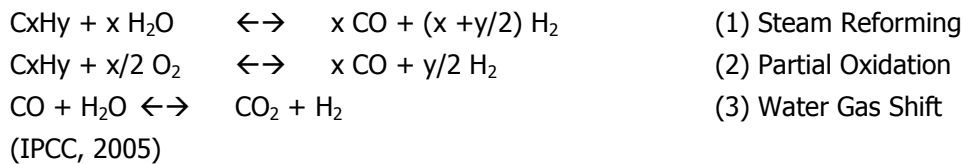
An advantage of the cryogenic CO<sub>2</sub> is the liquid phase of the CO<sub>2</sub> exiting the process. It does not require compression before it can be fed into a pressurized transportation system (see 2.1.2 Transport) whereas the CO<sub>2</sub> from other post combustion processes is gaseous, requiring extra energy for compression.



## B.2 PRE-COMBUSTION CAPTURE

Pre-combustion capture systems are an extension of fossil fuel reforming processes which create synthesis gas (a mixture of H<sub>2</sub> and CO) from natural gas, coal, oil residues or any other hydrocarbon material. In practice, processes known are steam reforming and partial oxidation of a natural gas or other light hydrocarbons. Gasification is used for heavier hydrocarbons (i.e. longer carbon chains, less hydrogen) such as coal, oil residues or biomass. The synthesis gas, syngas for short, has many applications in the chemical process industry and is an important base chemical (Moulijn, 2005). One of these is to use the syngas for the production of electrical power in a combustion cycle.

To separate the CO and H<sub>2</sub> from each other, a second reaction needs to be added, fortunately, this reaction adds another hydrogen molecule so it is relatively energy efficient. This reaction is commonly known as the water gas shift reaction, or shift reaction. Under the shift reaction the CO reacts with water to form an extra hydrogen molecule and CO<sub>2</sub>.



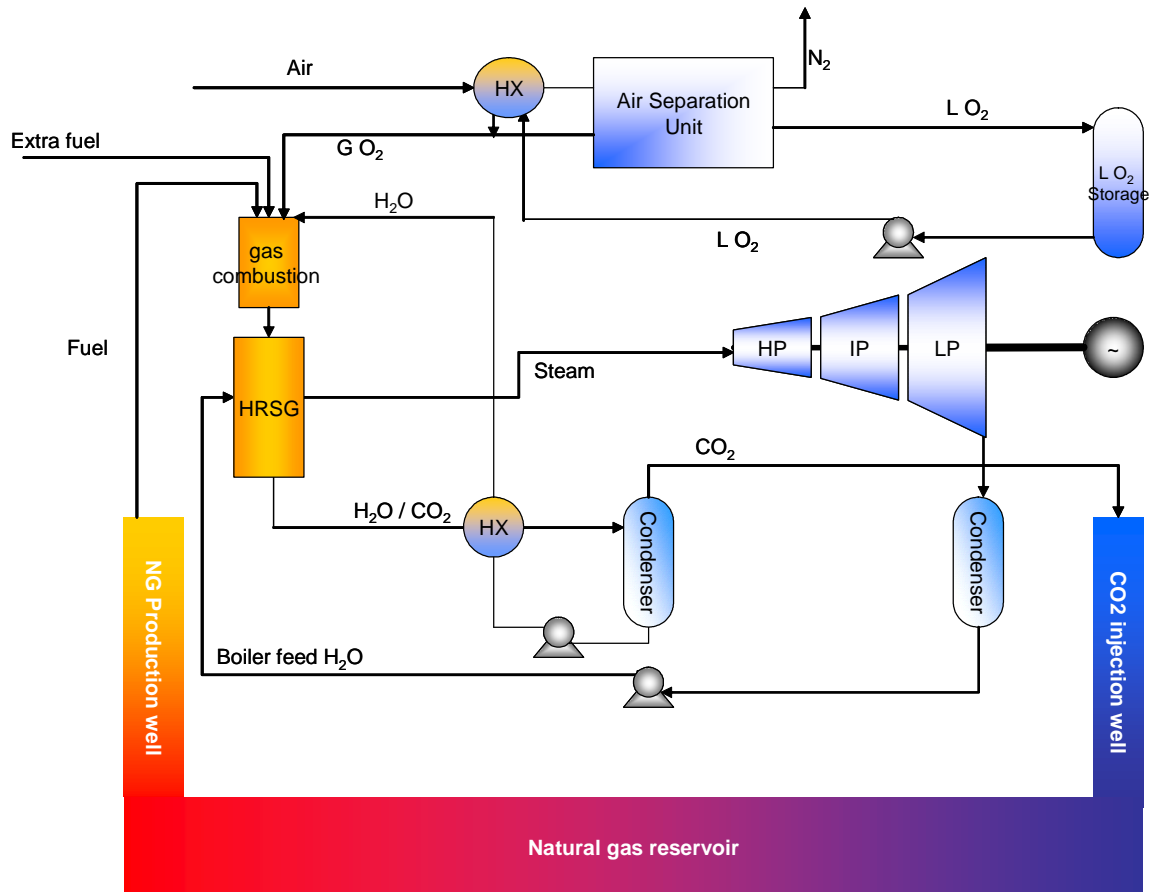
After these reactions the CO<sub>2</sub> can be separated from the stream by a physical or chemical stripping. The physical process is preferred in pre-combustion systems because of its lower energy demand. The driving force for absorptions is pressure difference. This is in contrast with post-combustion capture where chemical adsorption processes based on temperature differences are preferred. The advantage of this technique lies in the smaller volume and the higher partial pressure of the CO<sub>2</sub> making the separation less energy intensive (IPCC, 2005).

## B.3 OXYFUEL TECHNOLOGY

Oxyfuel systems use an air separation unit to create pure oxygen to combust the fuel with. The exhaust stream consists of a mixture of CO<sub>2</sub>, water vapor, left over oxygen and various contaminants such as SO<sub>2</sub> and NO<sub>x</sub>. The concentration of CO<sub>2</sub> is much higher compared to normal combustion, and the CO<sub>2</sub> is easier to separate from the water vapor. Because of the removed nitrogen, the mass of the flow is much lower and the combustion temperature is much higher. In principle the technology can be applied to combined cycle plants as well as conventional power plants. Coal fired power plants with a integrated gasification are also suitable for oxyfuel technology. The design of the compressor, combustor and turbine needs to be adapted to the new mixture since the properties of the working fluid have changed. Most notably, the molecular weight of the O<sub>2</sub> / CO<sub>2</sub> mixture has a molecular weight of 40-43 whereas an air mixture has a molecular weight of 28.8 An oxyfuel gasturbine in a combined cycle has a higher optimal compression ratio of 30 to 35, compared 10 15-18 for a air based combined cycle. The exhaust temperature of about 600 °C is optimal for a steam cycle (IPCC, 2005).

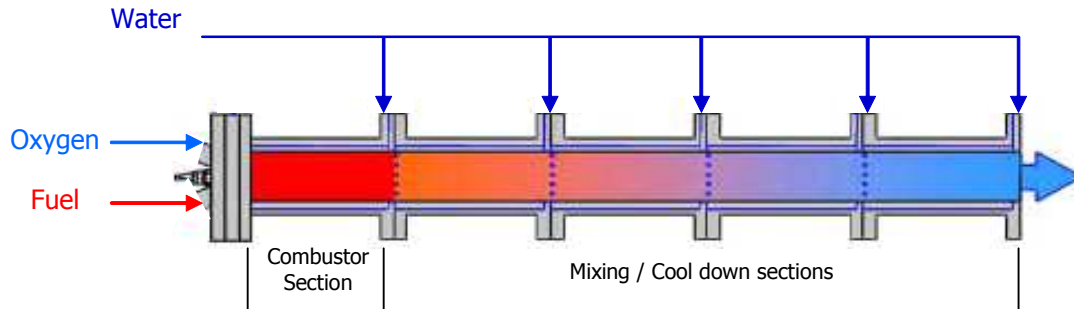
In the Netherlands an initiative to realize a Zero Emissions Powerplant (ZEP) is taken up by a group of energy entrepreneurs organized in SEQ. SEQ plans to build a zero emissions power plant with a combination of innovative technologies (SEQ, 2007).

Figure 40 from Anderson, Doyle and Pronske (2004) gives the flow scheme of the proposed plant.



**Figure 40: SEQ process flow diagram (adapted from Anderson, Doyle, & Pronske, 2004)**

The figure shows the combination of an air separation unit (Gasunie) with a special cooled combustion chamber with a multi stage steam turbine and the direct use of the CO<sub>2</sub> for enhanced gas recovery (see 2.1.3 Storage). The cooled combustion chamber is a technology adapted from space technology and reduces the temperature to efficient levels for the steam cycle.



**Figure 41: Clean energy systems Gas Generator (Cleanenergysystems.com, 2007)**

After condensation an oxyfuel power plant produces gaseous  $\text{CO}_2$  which needs to be compressed and possibly dried before it can be transported or injected.

## B.4 INDUSTRIAL POINT SOURCES

Apart from power production other industrial point sources of  $\text{CO}_2$  should also be considered as potential  $\text{CO}_2$  producers. Cement kilns, steel production, ammonia plants and refineries are all large producers of  $\text{CO}_2$ . For cement kilns with a concentration of  $\text{CO}_2$  in the flue gas of approximately 3-15%, post-combustion techniques are the most appropriate (IPCC, 2005).

The production of steel from iron ore can be achieved with two methods: through a blast furnace or through the direct reduction of iron ore using hydrogen. Capture of  $\text{CO}_2$  in the method using the blast furnace can be achieved through using oxyfuel technology. For the direct reduction process the production of hydrogen generates  $\text{CO}_2$ , which can be captured using pre-combustion technology (IPCC, 2005).

Most of types of ammonia plants and some refineries produce a pure product stream of  $\text{CO}_2$ . Part of the  $\text{CO}_2$  can be used as a feedstock for other processes or sold as food grade  $\text{CO}_2$ . An ammonia plant can be combined with a urea plant which uses  $\text{CO}_2$  as a feedstock. Other pure point sources such as refineries and can produce food grade  $\text{CO}_2$  (Hijfte, 2007) or  $\text{CO}_2$  which can be used in greenhouses (OCAP, 2007). The capture costs from such processes arises from purifications, drying and pressure and temperature control.

## Appendix C BASIS OF DESIGN

The basis of design consists of three elements: a list of requirements, a set of performance criteria and a set of design options.

### C.1 LIST OF REQUIREMENTS

#### 2.1

The regulatory framework should promote efficiency considering issues of scale and scope

The purity, temperature and pressure should match between steps in the value chain

The entire value chain should be monitored

The institutional arrangement should stimulate innovation

#### 2.2

The institutional arrangement between companies in the value chain should be efficient.

The returns should be correspondent with the risks taken.

The regulatory framework should allow for cost recovery

The regulatory framework should ensure that the system stores at least 18 Mton in 2025

The regulation and governance should encourage to connect as many sources and sinks as economically feasible

The regulations should be stable and predictable

The institutional arrangement should stimulate innovations

#### 2.3

The institutional arrangement between companies in the value chain should be efficient.

The institutional arrangement should fit the existing style of market based control

Institutional arrangements need to be stable and predictable

When a regulator is considered, it should operate independent of elected government representatives

The institutional arrangements need to be flexible and adaptive

The regulation of the value chain needs to fit the requirements of the inclusion in the EU-ETS

### C.2 CONSTRAINTS

State aid, article 87(1) of the European Union

Network balance

#### 2.1

Dependence of the control of capture process for electricity production

Technological constraints by capture, transport and storage technologies

Safety and permitting constraints,  
Privacy of company related figures

## 2.2

The regulatory framework should ensure that the system stores at least 18 Mton in 2025

## 2.3

No below cost service

The regulation of the value chain needs to fit the requirements of the inclusion in the EU-ETS

### C.3 PERFORMANCE CRITERIA

#### **Effectiveness:**

- The total volume of CO<sub>2</sub> captured and stored before 2025 should be at least 19 Mton

**Score:** The score for effectiveness is based on the likelihood of achieving the goal defined by the Rotterdam Climate initiative in the given setting. Factors include the time to build a network, waiting for hold up, likeliness of future investments match future growth of network.

Publicly owned options score higher, since the public values inherent in this criterion are calculated in investments. Inclusion of competition regulation also leads to higher scores, as this leads to more connections. Vertical integration will lead to lower effectiveness as the incumbent will block entry, leading to lower transported volumes.

#### **System efficiency:**

- The technical aspects of the system should be integrated in the regulatory framework in such a way, that the regulations support the technological system efficiency.

**Score:** The score is based on the ability to coordinate technological systems between participants.

Private operators with vertical integration score high, since coordination of subsystems contribute to system efficiency. Public operators score low, as they have no integration at all. Competition regulation *for* the network also scores well. Regulation *over* scores less, as it is harder to manage different connection types. Vertical integration scores high on this criterion.

#### **Adaptability**

- The regulatory framework should be able to adapt against changes in policy and technology in a predictable, (stability enhancing) manner.

**Score** The score is based on the adaptability of both the regulations and the physical network. Systems with public ownership or with some form of regulation already in place are easier to adapt to new policies. Existing regulations are easier to change compared to situations with no regulation in place at all.

The physical part of adaptability refers to adaptations needed on the network. Such as rapid extension when CCS becomes obligatory. Designs with public participation are expected to be able to better coordinate spatial planning

constraints. Competition *for* the network is also considered more adaptable, as new regulatory periods offer the possibility to include new terms in the concession.

#### **Static efficiency (price=LRMC)**

- For efficient markets, prices need to be close to long run marginal costs. This gives investment signals and secures fair pricing.

**Score** The score is based on the expectation of the functioning of the market in the CCS value chain. Competition regulation leads to a higher score. Restrictions to vertical integration also contribute. Ownership is relatively indifferent.

#### **Allocative efficiency**

- The network must connect all the parties who are willing to pay at least the market price. This leads to efficient network expansion. (allocative efficiency)

**Score:** The score is based on similar considerations as for static efficiency. Vertical integration leads to low allocative efficiency, as incumbents would want to block new entrants.

#### **Dynamic efficiency**

- The regulatory framework should contain incentives for reducing cost through innovations. This criteria is also known as dynamic efficiency.

**Score** Dynamic efficiency is expected to be higher when private investments are included in the investment. Private firms have a incentive to constrain costs. But, they are risk averse. It is expected that public private cooperatives are well equipped invest in new technologies with a high public value.

### **C.4 CCS SYSTEM CRITERIA**

1. Total volume of CO<sub>2</sub> captured and stored [Mton/yr]
2. Cost of system €/Mton stored [€/Mton]
3. time to system at least 10 Mton/yr [yr]
4. Market involvement [% private]
5. investment security, or robustness of regulation [discount rate %]
6. safety, leakage [kton/yr]

### **C.5 CRITERIA FOR A REGULATOR**

- o regulatory cost
- o regulatory robustness
- o regulatory adaptive
- o Predictability
- o Independence
- o Accountable

- Transparency
- Innovation stimulus
- Service flexibility
- Service quality

## C.6 TECHNOLOGY BASIS OF DESIGN

- Performance indicators / criteria
  - minimal energy requirement [% input / MWh]
  - maximum CO<sub>2</sub> reduction [% / kWh]
  - availability and reliability [%] and [MTBF]
- Requirements on the capture stream:
  - purity of the CO<sub>2</sub> at the exit [%mass of contaminants]
  - pressure and temperature of the CO<sub>2</sub> stream [bar], [K]
- Requirements by the capture plant
  - location [m<sup>2</sup> available], [km to storage site]
  - optimal temperature and pressure of flue gas [bar], [K]
  - solvent purity
- Constraints
  - all produced CO<sub>2</sub> should be transported to a storage site
  - life expectancy of the plant [yr]

### C.6.1 **Transport**

Summarizing the requirements, performance indicators and constraints of the transportation system are (IPCC, 2005; Svensson, Odenberger, Johnsson, & Strömberg, 2004; ZEPP, 2006b).:

#### Performance indicators

- cost [€/ton CO<sub>2</sub> / km]
- available capacity [ton CO<sub>2</sub>]
- safety [DALY]
- leakage [ton/yr]
- ecological footprint [m<sup>2</sup>]
- flexibility [# routes]
- lifetime [yr]

#### Requirements on transport

- cost should be minimal
- the capacity should match the demand
- the safety should be in accordance with regulation
- the leakage of CO<sub>2</sub> should be minimal
- the ecological footprint should be minimal

- the transport system should enable the economically desirable links of sink and source
- the lifetime of the infrastructure should be maximal

#### Requirements by transport

- the water content in the CO<sub>2</sub> cannot exceed solubility levels
- there should be intermediate storage facilities available (ship transport only)
- the CO<sub>2</sub> should be fed into the transport system at adequate levels of temperature and pressure (pipelines: 80-100 bar and <48°C; ships: 6 bar and -54°C or 18 bar and -40°C) (M. Barrio, 2006; IPCC, 2005)

#### Constraints

- Spatial planning constraints
- Available demand by CO<sub>2</sub> sources
- Available capacity of CO<sub>2</sub> sinks

### C.7 DESIGN OPTIONS

<i><b>Design Option</b></i>	<i><b>Range</b></i>
Ownership of the infrastructure	[public, ... , private]
The introduction of competition	[fully regulated, for, over, among]
Restrictions or freedom on vertical integration	[fully unbundled, ... , fully integrated]
The design of a regulatory authority	[none, single, multi-utility, local, national, supranational]
The design of a price & return mechanism	[none, pricecap, ROR, capacity auctioning]
The design of network expansion incentives	[none, per connection, per volume, auction, ...]
The design of regulation on entry barriers	[none, NTPA, RTPA]
The design of added performance incentives	[none, per volume, ...]



## Appendix D VALUES USED IN THE DESIGN

Numbers are based on the 2005 IPCC special report and the DCMR report of June 2007. Notice that for storage and income or positive flow of cash is generated based on the income from EOR. There is some insecurity about the revenues from EOR and EGR. For the evaluation of the business cases presented in the conceptual design we have assumed that some of the fields generate income, others generate costs. The mixed revenue is slightly positive, ranging from break-even to an income of €10.

The price level of the ETS is an estimate of around €30,-. What the actual level of the ETS will be is unsure, but the value of the carbon credits post 2008 is now around €20,- (ABN-AMRO carbon market update newsletter) but expected to rise to at least €30,- / Mton in the new regulatory period, according to Ecofys Consultants.

<b>Capture Cost</b>	<b>[€/Mton]</b>
For pure sources:	10
For post-combustion capture:	20
For Pre-c + Oxyfuel	16-19
<b>Transport Cost</b>	<b>[€/Mton]</b>
Pipeline transport	2
<b>Storage Return</b>	<b>[€/Mton]</b>
Average cost, with share for EOR	0-10
Horticulture	45
<b>Income from ETS</b>	<b>[€/Mton]</b>
ETS price level	30

## Appendix E TEST & SELECT

Design					Effect tive	system eff	Adapt ability	Price =cost	Alloc eff	Dyn eff	
	x1	x2	x3	<b>score</b>	c1	c2	c3	c4	c5	c6	
hyb, no comp, no reg vi	0	-1	0	<b>-3</b>	-1	1	-2	-1	-1	1	
priv, no comp, no reg vi	1	-1	0	<b>0</b>	-1	1	2	-2	-2	2	Section 4.2
pub, for N, no reg vi	-1	0	0	<b>9</b>	2	2	1	1	2	1	
hyb, for N, no reg vi	0	0	0	<b>6</b>	2	1	1	0	1	1	
pub, ov N, no reg vi	-1	1	0	<b>4</b>	2	1	0	-1	2	0	Section 4.4
hyb, ov N, no reg vi	0	1	0	<b>-1</b>	1	-2	0	0	0	0	
priv, ov N, no reg vi	1	1	0	<b>2</b>	0	-2	1	1	1	1	
pub, no comp, reg vi	-1	-1	1	<b>-6</b>	0	-1	0	-2	-1	-2	
priv, no comp, reg vi	1	-1	1	<b>-3</b>	-2	-1	0	0	0	0	
pub, for N, reg vi	-1	0	1	<b>10</b>	2	2	2	1	2	1	
hyb, for N, reg vi	0	0	1	<b>10</b>	1	2	2	1	2	2	
pub, ov N, reg vi	-1	1	1	<b>1</b>	1	1	-1	0	0	0	Section 4.3
hyb, ov N, reg vi	0	1	1	<b>6</b>	2	1	0	1	1	1	

The scores of the designs are based on the performance of a design on a specific criterion. The performance is drawn from the conceptual designs in chapter 4. For example, private ownership, no competition regulation and no regulation on vertical integration is the design discussed in section 4.2. It scores low on effectiveness, as the private investors will only consider private values and disregard the public values of CO<sub>2</sub> reduction and regional economic development. The System efficiency has a higher score because private investment and vertical integration make an efficient coordination of subsystems possible. The score for adaptability is interpreted as the ability to cope with new regulations. The private ownership of the network

## Appendix F RECORD OF CHANGES FROM GREEN LIGHT VERSION

This presents the changes after Green Light version. The changes in ***bold-italics*** were added with reference to the need to make the link between theory and analysis more clear.

### 2.1:

- to appendix capture
- more strong conclusions
- small notes by Chris on CCS technical aspects

### 2.2

- small notes by Chris
- bijschrift figuur 16
- extra figure from remark by Aad

### 2.3:

- small notes by Chris
- ***Structure changed. Now first sections on General infra, then CO<sub>2</sub> specific.***
- Added asset specificity types from Joskow & Williamson: site, physical assets, human assets, dedicated assets and intangible assets.
- Connect the asset specificity to types of risk: technical, economic, regulatory.
- ***Added new, and adapted old conclusions to fit storyline better***
- Added quote Energiened representative

### 3:

- Small adaptations
- Changed the introduction with special reference to ch 2.

### 4:

- Added piece on "CO<sub>2</sub>-bedrijf" in a special section 4.5

### 4.1

- ***Added as section clarifying the link between the largely theoretical analysis of chapters 2 and 3 and the practically oriented description of the conceptual designs.***

### 4.2

- Clarified: Transstor is a backwards integrated storage company.

- Emphasis added: natural monopoly of the CO<sub>2</sub> network.

#### 4.3

- Emphasized difference between previous conceptual design
  - Here there is a hybrid public-private ownership structure and competition regulation.
- Clarified Imbalance.
  - Balancing of the network is now a more pronounced responsibility. In the previous design the integrated company could control the network balance as he can coordinate two functions: capture and transport, or transport and storage.
  - Apart from safety issues associated with over or under pressure economic issues also play a role.
- Removed my statement that underpressure in a CO<sub>2</sub> pipeline can lead to hazardous situations. Indeed, with an operating pressure of 100 bar, under pressure will not be a problem for the materials.
- Explained that storage capacity held by the transport company to use in case of imbalance should be priced higher than the market price to secure that it is only used when there is no alternative in the market. As such it gives an investment signal.

4.5: new sub section on the CO<sub>2</sub> bedrijf.

4.5 → 4.6 Lessons learned

- Changed format of table

5:

- Included the score of the CO<sub>2</sub> bedrijf
- ***Added an appendix to make the connection between analysis of theory from chapter 2 to the scores.***

6:

- Minor changes.

7:

- Largely redid this chapter
- Included the five requirements from my scientific paper.
- Maybe this makes the paper less original. On the other hand, it gives the reflection the depth it deserves. It also provides a more clear fulfillment of my second research objective.
- Next to the requirements I have included a critical evaluation of the method.
  - To what extent is the design method general?
  - What are the flaws?
    - Limited detail in conceptual design,

- Choices in which conceptual designs to choose. Included reference to Statistical Process Control and Design of Experiments.
- To shallow stakeholder analysis. Especially the strategic interests of CO<sub>2</sub> shippers are missing.
- The hierarchy made in the design decisions can be clearer. By taking up the world bank view, I might miss some other options.

8:

- ***Redid the first section of the conclusions. A more clear connection between theory and practice, and not just a summary of findings.***
- Small adaptations to section 8.2

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List of literature references:

Books & Book chapters	28
Journal Articles	28
Conference proceedings	14
Reports	24
Laws & Government Doc's	5
Electronic Articles	9
Generic (brochures)	3
Magazine & Newspaper articles	12
Personal Communication	12
Unpublished work	3
Web pages	22
Total	160

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