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Comprehensive Assessment of CCS Chains – Consistent and Transparent Methodology

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Abstract

Through combining insights from engineering, natural sciences, economics, and political science, one consistent, transparent, and comprehensive analytical framework for assessing and evaluating various CCS chains is developed. The presented methodology aims at improving knowledge on the design of efficient CCS chains by developing methods for assessing and comparing different CCS chains, their sensitivity with regard to internal factors and to external conditions, and what the most efficient policy tools and measures are for promoting CCS development.

Keywords: CCS Chain; Techno-economic; Environmental; Technical Risk; Policy, Incentives; Common Framework

1. Introduction

Large scale CO_2 Capture and Storage (CCS) is considered to be one of the most promising alternatives for reducing man-made greenhouse gas emissions. To bring CCS closer to commercial realization, the viability of CCS chains must be explored. For a commercial CCS chain to be successful, it must satisfy a range of requirements, economic, technical, environmental, and social. A consistent and transparent methodology that assures critical evaluation of the feasibility of any CCS project is therefore needed. The value of such a methodology is in the support it provides to the decision makers. Investors will be better equipped to select optimal CCS chains, while policy makers can explore how policy instruments affect the future of CCS. The purpose of this paper is to present such a methodology for feasibility assessment of CCS chains.

Previous work on CCS research focused primarily on developing knowledge and technology related to CO_2 capture from power production and industry, long-term CO_2 storage, and CO_2 for enhanced oil recovery (EOR). Only recently has research activity focused on analyzing the CCS chains as a whole. In 2008, a methodology for CCS chain analysis was published to illustrate a method for identifying feasible solutions and assisting the selection of the most cost-effective options for CCS [1]. The methodology uses a techno-economic analysis to assist in

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designing the CCS chain from parameter specification of the individual components (CO_2 source, CO_2 transport, CO_2 sink), incorporating relevant global parameters (oil price, CO_2 price, etc.) and evaluating economic outcomes of the chain, typically in net present values (NPV). The ECCO (European Value Chain for CO_2) project aims at facilitating robust strategic decision making regarding early and future deployment of CO_2 value chains. In ECCO [2], CCS case studies define value chains with techno-economic input data and global parameters, but ECCO does not directly analyze the environmental performance or risks related to the chains. The European research project COCATE, solely look at infrastructure for transportation of CO_2 from many relatively small point sources, with focus on economic and technical risk perspectives. From the environmental side a summary of life cycle assessments of CCS can be found in [3]. While these LCAs have provided some insight into the environmental effects of CCS, the studies differ in types of technologies assessed, the level of detail in the models, and place different levels of importance on the environmental impacts studied. In addition, many of the studies focus on primarily one part of the chain without giving as much attention to the entire chain. In addition, a traditional LCA study does not take into account economic factors such as market features and secondary effects of technological developments, or address social aspects or risk. Thus, by designing a CCS chain assessment methodology described herein to combine economic, environmental, political, and technical risk assessment, we can obtain a more inclusive and overall grasp on the viability of CCS chains and reduce uncertainty in the performance of a CCS chain.

2. Common Framework

The factors affecting the realization potential of a commercial CCS projects are numerous and cover a broad range of topics. The primary categories that these topics can be classified in are:

- CCS technology maturity level
- Business economy of actors within CCS
- Environmental impacts associated with CCS
- Risks associated with CCS
- The global environment (public acceptance, regulation, incentives and markets)

A comprehensive and consistent evaluation of the feasibility of CCS projects with respect to all these topics will require a well-designed methodology that compiles different existing methodologies for evaluation of the particular factors, applies rather broad range of modeling approaches, and consider several evaluation criteria. The methodology proposed and discussed in this paper was developed within BIGCCS, an International Research Centre for Environmentally Friendly Energy, and based on three main keystones: common framework, state-of-art models, and relevant case studies. One of the main requirements on the methodology was to ensure consistency, transparency, and reproducibility all the way along the analysis. In order to enable selection of the most promising CCS chains, the framework for the analysis is formed to include and assess primary categories, see Figure 1.

I. **Scenario:** Description of the governing factors affecting the CCS environment e.g. population growth & energy demand, energy/environmental/economic policy, public regulations and measures.

II. **Quantification of Global Parameters:** For scenarios to be used in quantitative models, some of the scenario features will need to be quantified, typically external parameters (for example oil/gas/electricity/steel prices) and their time profiles that reflect the global regulatory and economic conditions for CCS chains.

III. **CCS Chain Design:** CCS chains are designed from basic modules that imply connecting CO_2 sources and sinks with suitable transport options and matching them in capacity and time. Chain design also involves determination of systems boundaries. In some cases it might be relevant to include processes being affected by CCS implementation, such as power generation, and not only the CCS components.

IV. **CCS Chain Component Specification:** Each component in the CCS chain is specified, which means choice of technology and specification of governing parameters, such as efficiency, capacity etc. The level of detail at which the components are modeled should reflect required input for subsequent CCS chain assessments.

V. **Multi-perspective CCS Chain Assessment**

a. *Modeling on component level*: Techno-economic, environmental and technical risk factors are analyzed for the CCS chain components based on specifications in steps I – IV.

b. *Analysis of the whole chain*: Techno-economic, environmental and technical risk factors are analyzed for the whole CCS chain, based on a consistent interface between chain components and specifications in steps I – IV.

VI. **Representation of Results:** The results from the multi-perspective assessment can be presented in a spider web showing the CCS chain performance on different scales, illustrated in Figure 1. This enables assessment of how changes in specification (steps I-IV) affect the performance of a given CCS chain. E.g. a change towards stricter regulations of onshore CO_2 transport might alter choice of technology from onshore pipeline transport to ship transport of CO_2. This change in regulations might be motivated by the need to reduced technical risk, but could potentially also affect the economic and environmental performance of the CCS chain. Selected performance indicators could potentially be weighted against each other based on preferences of decision maker.

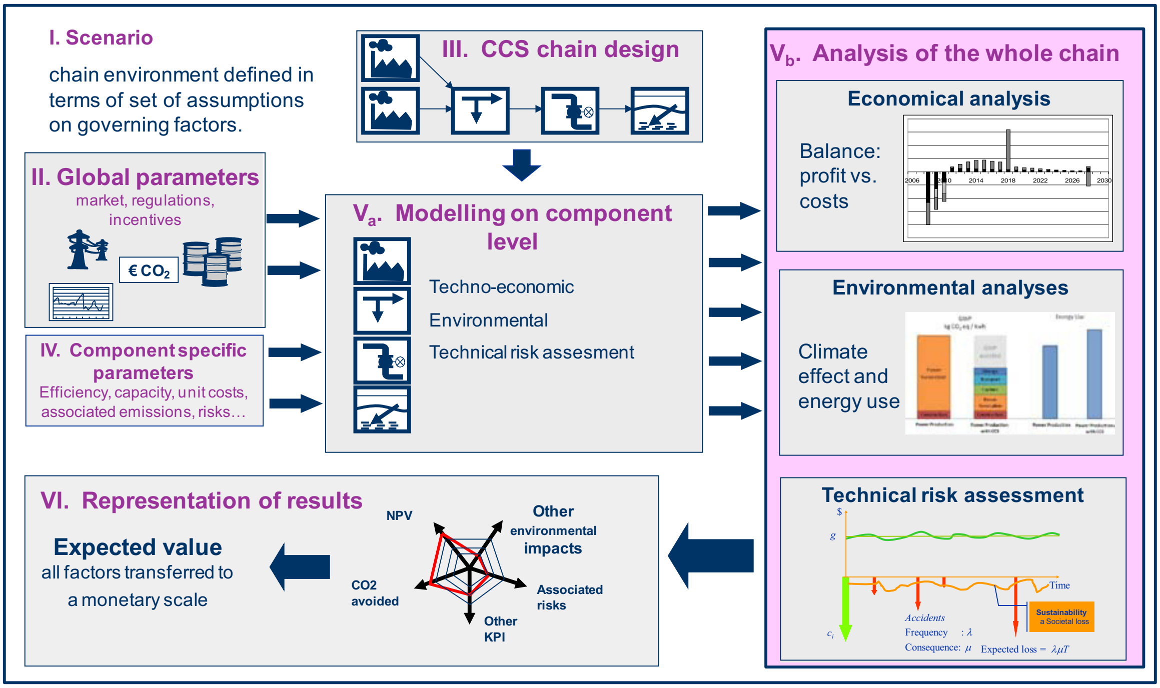

Figure 1: Common Framework

2.1. Scenario

Since political decisions, particularly regarding climate policy and energy system development, is an essential part of the overall operation conditions for CCS, explicit assumptions must be made about these factors and included in the overall framework of analysis [4],[5]. For this purpose we develop global scenarios including important assumptions related to technology and infrastructure development, economic development, development of energy systems, climate policies and public opinion [6]. The scenario development process has been explained in detail previously in both the Enabling Production of Remote Gas research project [7] and the ECCO project [2]. In Step I of the framework described herein, scenarios are used to define the chain environment in terms of a set of assumptions on governing factors. These scenarios can then be used as input to the global parameters (Step II), and aid in defining conceivable CCS chains (Step III) to be analyzed in a specified global environment.

The economic and policy conditions that CCS operates under can be defined at two different levels. The first level consists of general climate policy conditions represented by the international climate regime and national climate policies, which foremost determine the CO_2 price. Since CCS is only motivated by an interest in reducing CO_2 emissions and since today there is a substantial gap between a high cost per ton of CO_2 handled and the value of CO_2, e.g. the price of emission allowances in the European emissions trading system, the development of CCS technologies and the future potential of CCS depend heavily on these future climate policies.

In addition a wider global scenario under which CCS will operate is determined by drivers for CO_2 emissions such as GDP growth, energy efficiency and demand development, energy system development – including development of various renewable energy sources and biomass technologies, and structural changes in global and national economies. The next level consists of specific policies to stimulate CCS invention, innovation and deployment. Whereas invention (R&D) to a large extent is funded by government money, and deployment is foremost dependent on a sufficiently strict climate policy that leads to a sufficiently high CO_2 pricing, stimulation of innovation is more challenging.

2.2. Quantification of Global Parameters

The qualitative scenarios are used to generate quantitative global parameter time profiles, for CO_2 prices, energy prices, CCS subsidies, relevant policy instruments, incentive mechanisms, etc. These global parameters are required to analyze CCS chains with respect to techno-economic, environmental, and technical risk. Global parameters are partly determined by policy instruments and incentive mechanisms. Since there are a number of uncertainties involved in what level of CCS development that can be met at some future point of time, the robustness of different instruments and possible combinations of instruments is of importance. With the help of the framework, we explore how policy instruments impact global parameters and CCS chains from techno-economic, environmental, and technical risk perspectives. This can provide valuable insight on how policies can affect CCS chains, aiming to find the most efficient measures to stimulate CCS development.

2.3. CCS Chain Design

The design of a CCS chain, defines the specific case being analyzed in an environment set by step I-II. A CCS chain would typically consist of single or multiple CO_2 sources with capture, transportation infrastructure and storage location(s). Step I and II could put restrictions on the CCS chain design process, e.g. in case of capture technology standards or regulations against onshore CO_2 transport. Constructed CCS chains do not necessarily need to be realistic, but could simply be constructed to give new insights to features of CCS chains.

2.4. Chain Component Specification

To what extent the different CCS components are specified in detail, will depend on the aim of the CCS chain assessment. All desired component specifications are not necessarily required for every assessment perspective in Step V_a. For example, if we design a CCS chain with a single 150 km onshore pipeline, to obtain the costs of steel and the environment impact (GHG emissions) of producing the steel for the pipeline, we would be mainly interested only in the type and amount of steel required as a component-specific parameter. From these perspectives, the pipeline diameter and wall thickness are not explicitly needed, but will be required for the technical risk assessment to determine, for example, the risk of fracture in the pipe. Therefore, the total amount of steel alone is not an appropriate component specification to ensure consistency in the models. Hence, the level of detail required in multi-perspective CCS chain assessments will put requirements on component specifications and needs to be consistent in each analysis.

2.5. Multi-Perspective CCS Chain Assessment

To perform multi-perspective CCS chain assessment we use of state-of-the art models to analyze the performance of specified CCS chains. Three main perspectives are selected, namely techno-economic, environmental and technical risk, all important for the feasibility of future CCS chains. The purpose of the developed CCS chain assessment methodology is not only to calculate the performance of components or a static CCS chain by summing the cost or environmental impacts of different components. In an environment with high level of uncertainty, especially with regards to future technology development, policy & regulations, it is also important to understand the dynamics of CCS chains. How does the CCS chain performance and optimal chain design change with altering conditions, e.g change in commodity prices, emissions regulations or safety requirements.

2.5.1. Techno-Economic Assessment

Techno-economic assessment of investments in CCS chains are typically based on income and cost estimates over the project lifetime. These are essential inputs to calculate the NPV, where expected future cash flows are discounted at the opportunity cost of capital reflecting the project risk. Using standard NPV criteria, a project should be undertaken if the sum of discounted cash flows is positive. Referring to the common framework, estimation of future cash flows will be based on general inputs from step I and II, such as expected future energy prices and regulations, and chain specific inputs from step III and IV, such as technology specific cost, capacity and contracts among chain actors. This approach is used in the European ECCO project where SINTEF Energy Research takes part. Techno-economic assessment of CCS chains can also be performed using more advanced methodologies and decision criteria's than the static NPV approach. The matrix in Figure 2 illustrates different valuation models, with regards to their treatment of uncertainty and decision structure.

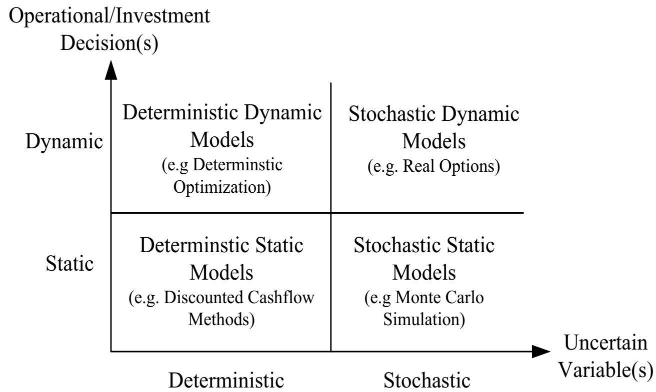

Figure 2: Economic Assessment Matrix

Sensitivity analysis and scenario analysis are two commonly used methods to include uncertainty in static decision models, treating input variables as discrete variables. Sensitivity analysis presents changes in output measures, e.g. NPV, with respect to variations in a single input assumption at a time. Scenario analysis typically includes more than one input variable changing across the cases considered. The scenario approach might be relevant when e.g. two future policy scenarios are possible, one resulting in both high CO_2 and energy prices, while the other result in low CO_2 and energy prices (see section 2.1). By assigning probabilities to the discrete changes in both sensitivity and scenarios analysis, it is possible to calculate expected outcome and variance of the economic output measure, typically NPV. Sensitivity analysis can also be used in deterministic models without assigning probabilities, e.g. to see effect of discrete changes in controllable variables such as level of subsidies for CCS.

Simulation methods, like Monte Carlo Simulation, generate NPV probability distributions, based on continuous probability distribution(s) of the uncertainty variable(s). This enables not only estimation of the expected NPV based on certain discrete input values, but also financial risk measures such as standard deviation of the NPV distribution, value at risk etc. This requires adequate information about the studied uncertainty.

Dynamic decision models, in contrast to static models, include operational or investment decisions (behavior) that, at one time, depend on decisions at another time. For a CCS chain where, for example, the timing of the investment is flexible, the investor faces an optimization problem of timing the decision to invest so that the sum of future cash flows (expected cash flows if inputs variables are uncertain) is maximized. Hence dynamic models can be appropriate when decision making is dynamic, e.g. if you invest today you can not invest tomorrow and vice versa. So even though the static NPV of a CCS chain is positive, an investor can be reluctant to invest today and would rather wait. This illustrates that different techno-economic valuation approaches, used on the same CCS chain, can result in different investment decisions. Performing such an analysis would require additional input on flexibility, such as for how many years you can postpone an investment and possibly also associated cost of obtaining construction permits. Decision tree analysis and real options analysis are commonly used method to analyze stochastic dynamic problems, see [8], whereas deterministic optimization models typically is used when underlying variables are (or at least treated as) deterministic.

The appropriate techno-economic model to support decision making in CCS investments will depend on scope of work and the degree of embedded uncertainty and/or managerial flexibility. Whereas static deterministic NPV is a natural starting point for techno-economic assessment, BIGCCS seeks to include more advanced methods when suitable[13] , having in mind the tradeoff between modeling accuracy, complexity, and transparency.

2.5.2. Environmental Assessment

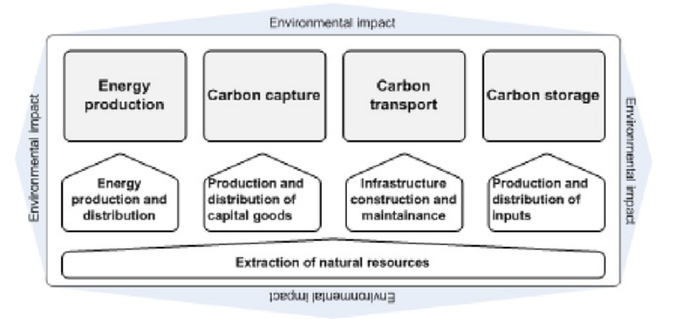

Figure 3: LCA System Boundaries

To be able to evaluate the overall environmental performance of CCS chains, their environmental impacts must be assessed based on a holistic approach. Example of such one approach is the Life Cycle Assessment (LCA) method, which investigates environmental impacts of products or production systems throughout their life cycle. The main strength of LCA is that it includes the whole product system that is induced to provide a product, e.g. 1 kWh of electricity from a power plant with CCS. Also processes that underpin the production system with materials and energy inputs (e.g. the extraction and storage of a defined amount CO_2) are included in a LCA. Therefore, for the environmental assessment, the CCS chain system boundaries are expanded to include all processes from extraction of natural resources and energy production to production and distribution of inputs and capital goods [9]. LCA is an "engineering-like" tool in the sense that technical systems with potential changes in them are studied, but at the same time it is a multi-disciplinary approach to model the impacts on the natural environment. International standard for LCA lists the following applications: identification of improvement possibilities, decision making, choice of environmental performance indicators, and market claims [9].

A major challenge in LCA is in the inventory stage where material- and energy balances is established for each unit processes in the production system. As stated LCA has a holistic approach, if one were to truly map all processes that are induced in the whole techno-sphere and in terms of all kind of environmental impacts the data requirements would be infinite. Simplifications have to be done and the level of detail in the modeling of the production system must be according to the goal for the LCA.

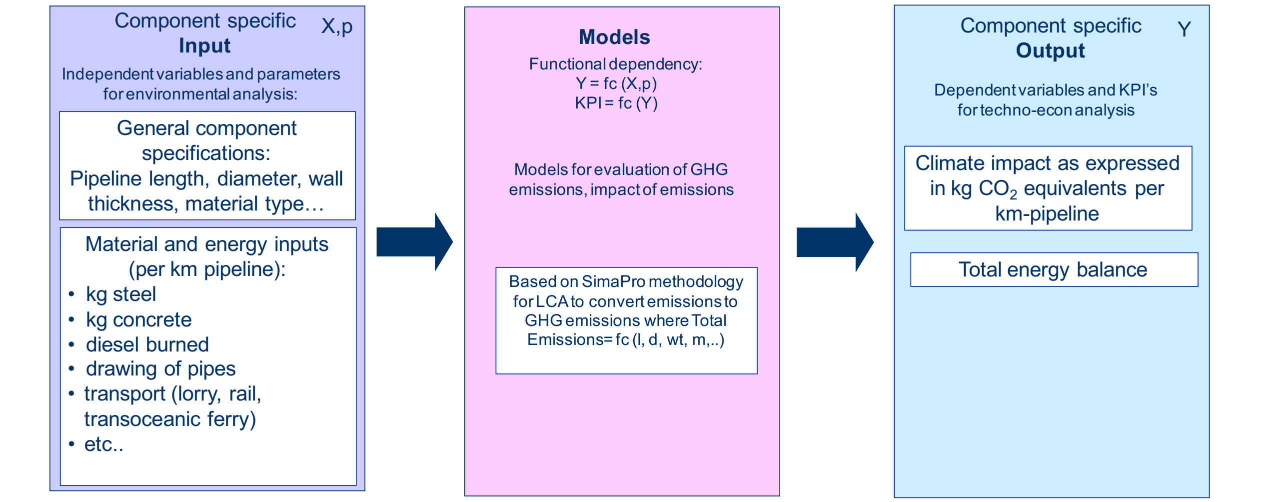

Figure 4: Example for a transport module for environmental assessment of pipeline for CCS.

The environmental assessment will start out with a screening LCA (SLCA) that only includes greenhouse gas emissions (GHG). The results from the SLCA will also be used to evaluate the effects of how the system model is designed, system boundaries, allocation strategies, and data requirements. The screening will form a basis to evaluate methodological alternatives. The framework (Figure 1) will also be applied to the environmental assessment, where the CCS chains (Step III) are modeled at the component level (Step V_a.) By establishing a pool of components, a variety of CCS chains can be analyzed in a transparent way (Step V_b.), where it is easy to change or perform sensitivity analyses of important environmental parameters. In Figure 4, an example of one component (or unit process), a transport via pipeline module, briefly illustrates the methodology in terms of inputs, models, and outputs.

2.5.3. Technical Risk Assessment

The objective of the risk analysis is to estimate the total expected loss resulting from the activity and to identify those elements or areas in the system that contributes the most to the total loss. Intuitively, a measure of risk should be some increasing function of both the probability of occurrence of the adverse event and the consequence of the adverse event represented on some numerical (monetary) scale. For events that occurs in time, the risk r is equal to the expected (monetary) loss defined as the product of the (annual) frequency, λ, of occurrence of the given adverse event and the (monetary) consequences, c, associated with the event

$$r(A) = \lambda c \tag{1}$$

The frequency λ refers to the expected number of occurrences of a specific unwanted event, e.g. a fire, in a specified time window, typically a year. The frequency may be identified by expert judgment, assessed by reference to observed data, calculated by careful probabilistic modeling, or by a combination of the aforementioned procedures. Frequency λ and consequences c are specified as component specific parameters in Step IV. Generally a risk analysis consists of the following 5 steps [10]:

I. What may go wrong?
II. How often will the critical event occur and what consequences will it imply?
III. How may we improve the conditions and reduce the risk?
IV. How large an investment must be made and how large are the benefits that will result from the improvement?
V. What actions should be activated?

For exemplification purpose, starting with capture, one hazard is leakage of amines. This amine leakage may lead to the formation of carcinogenic compounds, which in turn can lead to loss of life or loss in good life. For both transport and storage one hazard is CO_2 leakage which can lead to loss of life or environmental damages. These are of course only examples of hazards and their consequences. For each defined component, a coarse risk analysis is to be performed (Step V_a). This implies a qualitative assessment of the frequencies and consequences. The result from this coarse risk analysis will be in form of the expected monetary loss. When the risks on the monetary scale are identified, they will need to be assessed with regards to what is acceptable risk. In principle, the operator enters an activity only if there is a reasonable expectation of a tangible return on his investment. The objective of acceptance criteria setting is to assure that the operator do not cynically exploit societal interests, but operate these in a social responsible way. On the other hand, society may suffer both recoverable and non-recoverable harm from the activity not covered by the operator. Therefore, the society will similarly accept the activity only if it can anticipate a corresponding positive expectation to its benefit, although in this instance the benefit may take tangible (taxes) or intangible form. These two criteria can be combined into one single criterion that the rule maker can use to define acceptance limits that expectedly satisfies both operator and societal preferences. When the operator makes decision about the general arrangement of his plant, he will first calculate the difference between the expected income and the expected operational cost. Depending upon the market conditions, the operator will expect to arrive at a gross solution that meets the forecast market need. From this solution the operator may calculate a net gain (g) from which all the running costs are subtracted. From this net gain all calculated expected losses (i.e. the risk) that may be caused by the occurrence of unwanted and unplanned events. Omitting any interest rates (which may be included in a straightforward way) we can consider the operators decision criteria by the following equation [11],[12]:

$$g - \sum_{i=1}^{N} \lambda_i \, \mu_{oi} > 0 \tag{2}$$

in which N is the number of considered unwanted events; λ_i is the frequency of occurrence of unwanted event category i; $\mu_{o,i}$ is expected loss of the operator (index o for operator) following the occurrence of unwanted event category i. The $\lambda_i \mu_{o,i}$ term is the annual risk. The term under the summation is the risk. The operator can pay an insurance risk premium to cover parts of any potential losses. The operator must require that the expected annual net gain minus the expected annual losses is larger than zero otherwise it will lead to bankruptcy. Similarly, if parts of the losses are covered by insurance the premium paid must expectedly be larger than the expected (annual) loss since the insurance company otherwise will meet bankruptcy. The rationality problem of setting public acceptance criteria for the operation is essentially that there are two decision makers with partly conflicting settings of the preference ordering, the operator and the public. In a free society the operator has priority with respect to setting the preference ordering but the public specifies certain regulating rules to protect its interests, which besides the protection of human lives and welfare embraces the protection of public property, aesthetic values, culture, and environmental qualities of nature. Among the interests of the public is also that the public gets a benefit from the production activity of the operator through the creation of jobs and tax paying. Therefore the public should not impose too onerous restrictions through the acceptance criteria. Compliance to the proposed acceptance criteria the operator will assure that operating the CCS chain will comply with societal requirements to sustainability, human and environment. This compliance is also known as *corporate social responsibility.*

3. Conclusion

Through combining insights from engineering, natural sciences, economics, and political science the project's contribution to this research area is the development of one consistent, transparent and comprehensive analytical framework for assessing and evaluating various CCS chain designs. This analytical framework is a significant value added for the CCS research community, and also for public and private stakeholders that should be able to make use of the framework and related tools to improve CCS-related decision-making. At the end of the project we seek to have gained significantly improved knowledge on the design of efficient CCS chains, developed improved methods for assessing and comparing different CCS chain designs, their sensitivity with regard to internal factors and to external conditions, and what the most efficient policy tools and measures are for promoting CCS development.

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