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A standardized approach to multi-criteria assessment of CCS chains

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Abstract

For a commercial Carbon Capture and Storage (CCS) chain to be successful, it must satisfy a whole range of requirements: technical, economic, environmental, safety, and societal. A comprehensive, understandable and reproducible assessment of CCS projects is a complex task due to several reasons: wide range of actors and factors involved, substantial differences in the type and nature of both actors and factors, and numerous associated uncertainties. In this paper, a standardised methodology is described and illustrated on a few examples of relatively simple case studies. The proposed methodology provides means and tools for evaluation of several economic, environmental, and in the future also risk associated criteria and thereby enables selection of the most promising options for CCS. The methodology will also help to reduce the uncertainty by improving understanding of the most important dependencies and trends for the investigated key performance indicators as enlightened by the case studies examples. It could also help to design efficient incentives and measures to stimulate realization of CCS by identifying and evaluating the most important non-technical factors affecting the CCS chain viability.

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Keywords: CCS, carbon capture and storage; CCS chain assessment; techno-economic analysis, scenario development.

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1. Introduction

Since Carbon Capture and Storage (CCS) has been recognized as one of the most important measures to reduce the greenhouse gas emissions, extensive research within the field of CCS has focused on gaining fundamental knowledge and developing technology related to the particular chain components [1],[2]. Numerous studies providing the cost estimates and life-cycle analysis of CCS chain elements have been published [3]-[11]. However, in order to bring CCS closer to commercial realization, the viability of CCS projects must be explored by analyzing the chain as an integrated system considering both complex infrastructure including multiple chain components and the economic and political environment of the chain [12]. Furthermore, for a commercial CCS chain to be successful, it must satisfy a whole range of requirements: technical, economic, environmental, safety, and societal. A methodology that assures

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critical evaluation of the viability of CCS projects considering several relevant criteria and indicators and evaluating them in a consistent and transparent way is needed.

In this paper, we will present and discuss a methodology for multi-criteria analysis of CCS chains. The objective for the methodology is to enable fair comparison of various CCS projects based on integrated assessment of economics, environmental impacts, and associated risks taking into account also the economic, societal, and political environment of the CCS chain. One of the main requirements on the methodology is to ensure consistency, transparency, and reproducibility all the way along the analysis [13]. The proposed methodology is not meant to be a tool providing specific detailed information for investment decisions to be done by the industrial actors. However, the value of such a methodology is mainly in the support it provides to policy makers as it will help them to understand the governing trends and dependencies within a CCS chain and between the CCS chain and its environment. For the same reason, it will also be a helpful tool for communication with researchers working on development of CCS

2. Methodology

A comprehensive, understandable and reproducible assessment of CCS projects is a complex task due to several reasons: wide range of actors and factors involved, substantial differences in the type and nature of both actors and factors, and numerous associated uncertainties. The proposed methodology is designed to deal with all of the various aspects in an appropriate manner by applying relevant methods and tools. While the quantitative variables and parameters are treated by use of mathematical models, the non-quantifiable variables such as political incentives and regulations are investigated with help of methodologies aimed at soft-data handling. The toolbox of the methodology consists of three main building blocks, see Fig. 1: scenarios, case studies, and simulation tool for quantification of Key Performance Indicators (KPIs) for the CCS chain. Typical KPIs are for example: CAPEX, OPEX, consumption of electricity, steel, water, and climate impact.

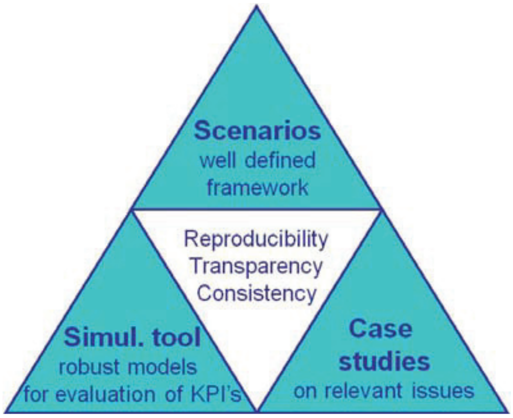


Fig. 1. Three main building blocks of the proposed methodology

2.1. Scenario development

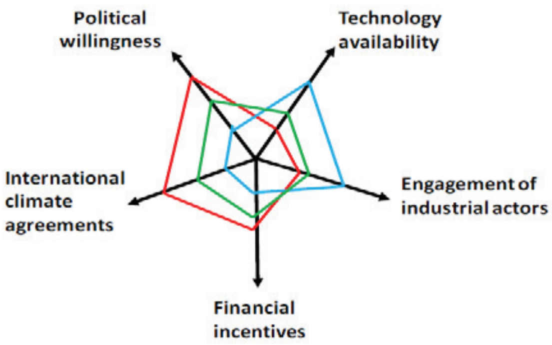
A scenario is a story line that describes one possible alternative future in terms of political situation, public opinion, regulatory framework, technology and infrastructure development, as well as global economic situation. Scenarios combine known facts about the future, such as demographics, geography, industry potential, and mineral reserves, with plausible political, social, technical, and economic alternatives [14]-[18].

The scenario development approach proposed here is a strategic scenario approach, or an intervention scenario approach. Such a scenario development process involves developing both mini-scenarios and more global and holistic scenarios and consists of the following steps:

1. Identifying major driving forces: The main actors and factors that would be shaping the future for CCS chains. Actors are defined as all existing and future stakeholders that take an interest in CO_2 value chains and stakeholders who will be affected by this issue. Factors are described as the major trends that affect the development of CCS. See examples in Fig. 2.
2. Formulating mini-scenarios: developing short stories focused primarily around one actor or factor.
3. Defining scenarios around governing axes: Identification of five main drivers or major uncertainties which will significantly affect the CO_2 value chain. These five axes are used to define the main features of each scenario. See examples in Fig. 3.
4. Drafting scenarios: describing both the situation at the end of considered time period – situational scenario, and the so called "how did we get there" story - corresponding development scenario.
5. Analysing scenarios and identifying new issues arising: cross-checking scenarios for consistency by use of a consistency matrix, in order to identify any inconsistencies in the stories and to suggest any additional scenarios that may be needed to encompass a wider range of possibilities.

ACTORS	***FACTORS***
1. POLITICS	
National politicians and governments International politicians and governments	Standards Regulations Financial incentives
2. PUBLIC	
Public & media Interest groups & non political organisations	Public acceptance
3. TECHNOLOGY	
Research & education institutions Technology developers Technology providers	Technology availability Technology efficiency Technology costs Environmental impacts
4. INDUSTRY	
Energy companies Oil& gas companies Steel producers Aluminum producers	Business strategies Business economic models
5. GLOBAL ECONOMICS	
Actors in other countries and world regions	Economic growth Energy demand Fossil fuel availability Availability of renewables Oil, gas, electricity, steel price
6. OTHER	
	Timing Logistics Ownerships Associated risks

Fig. 2. Examples of actors and factors



Scenario	Red	Green	Blue
Political willingness	high	medium	low
International climate agreements	high	medium	low
Financial incentives	high	medium	low
Engagement of industrial actors	low	medium	high
Technology availability	low	medium	high

Fig. 3. Illustrative example of five possible governing axes and three different scenarios defined around them

The scenario stories developed around the main five drivers or uncertainties as illustrated in Fig. 3 will define the environment in which the CCS project is to be realized. They will describe the actor's actions and the factors such as they would be expected under given assumptions about the main drivers.

2.2. Simulation tool

A modular, robust, and consistent tool is under continuous development for evaluation of techno-economic criteria, environmental impacts, and later also associated risks of a CCS chain. The core of the tool is coded in the object-oriented programming language C# whereas the user interface is developed in Microsoft Office Excel environment [19-20]. The tool is designed as a bank of components that the user can apply freely to build the particular chain of interest, see Fig. 4. The tool allows for evaluation of KPIs on several levels: chain component, actor or owner of components, and the overall chain. The tool is especially suitable for parameter sensitivity studies. New modules and assessment criteria can be easily added within this modular framework.

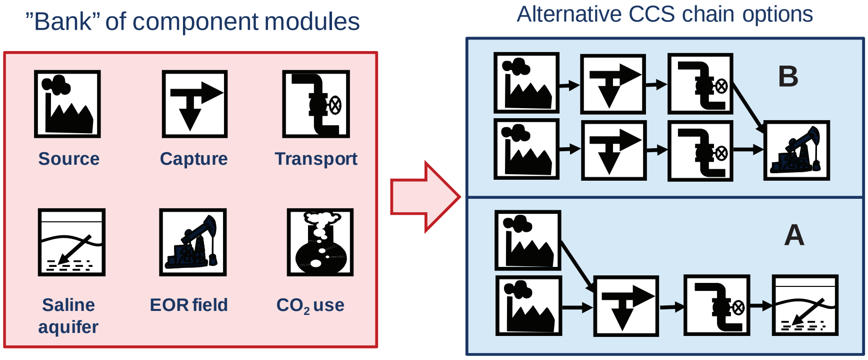


Fig. 4. Illustration of the modular structure of the tool

The quantitative analysis of CCS chain KPIs with the tool follows the six steps illustrated in Fig. 5: I. CCS chain design; II. Specification of global parameters; III. Specification of component specific parameters; IV. Modeling of chain components, which means evaluation of KPIs on component level; V. Performing the overall analysis by evaluating key performance indicators for the whole chain; and VI.

Representing the results as spider diagrams including all KPIs and/or aggregating KPIs into overall reporting measures (NPV, CO_2 captured, CO_2 avoided). The component models applied in step IV are parameterized mathematical expressions for evaluation of time distributions of KPIs as functions of input variables and parameters. The functions are derived from results obtained by more detailed technical modeling of the CCS chain components. Choice of appropriate parameters and the level of detail of the modeling work are of most importance.

As CCS is an emerging technology, there are several uncertainties that must be taken into account during the analysis. Transparent documentation of assumptions made with respect to all the issues that may potentially cause differences and bias in the obtained results is crucial. For example: chosen perspective (investors, policy makers, public), applied methodologies for KPIs evaluation (bottom-up vs top-down, aggregated vs disaggregated), definitions used for reporting measures (CO_2 captured, CO_2 avoided), assumptions made for underlying parameters (technology maturity, location, 1_{st}- or N_{th}-of-akind project), chosen boundary conditions and the time scale must all be well documented.

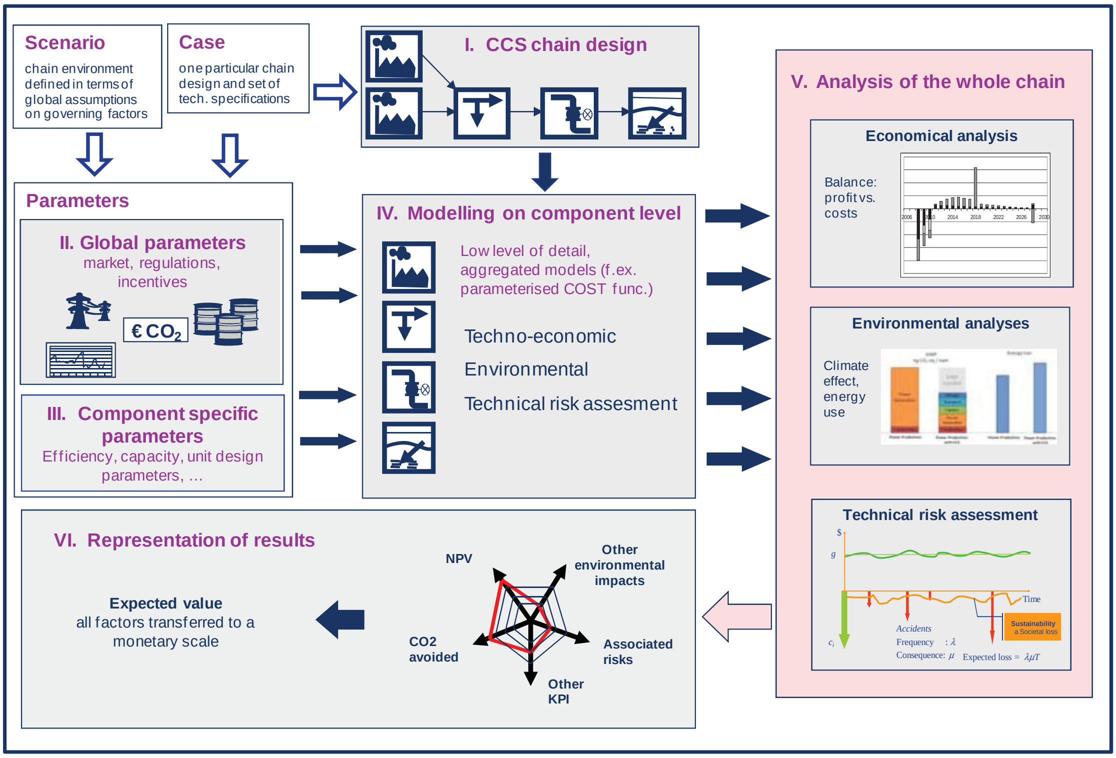


Fig. 5. Principal sketch of the process of the quantitative assessment of CCS case with the tool

2.3. Case study

Case studies, if properly designed, might provide insight on the key issues related to CCS chain realization. Case study is an in-depth investigation that explores causation and governing underlying principles of the problem at hand. Case study as a research method is successful only if it is carefully planned and crafted to study a particular situation, issue or problem. The most important steps in the design of a case study are:

I. Determining and defining the research question
II. Selecting cases and case variations that will allow to study the question
III. Collecting data
IV. Evaluating and analyzing the data
V. Interpreting the results and drawing conclusions on the targeted research question
VI. Formulation of newly arising research questions

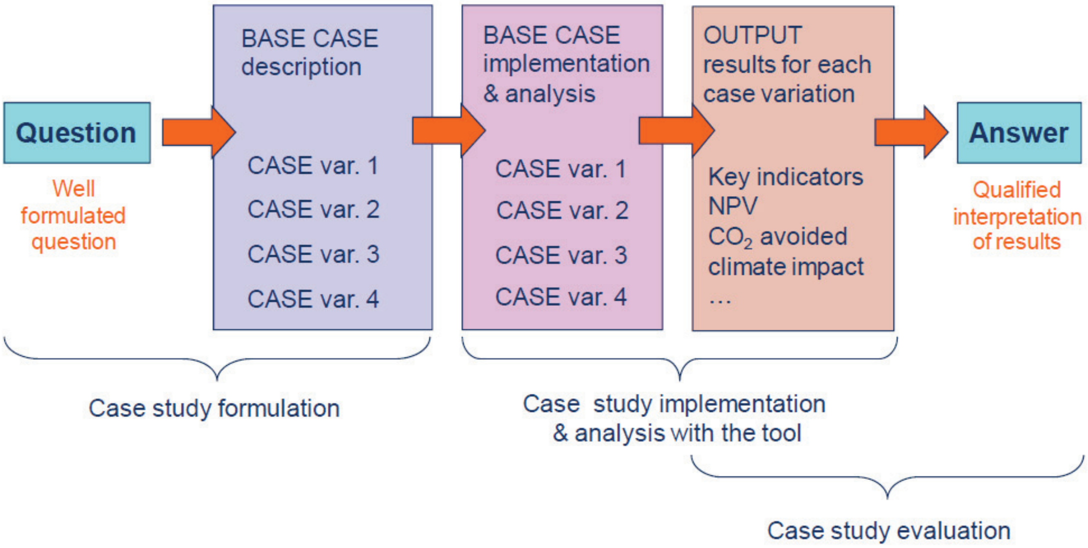


Fig. 6: Illustration of the process of case study design, analysis, and evaluation

The issues suitable for CCS chain case studies can be categorised according to the topic and particular involved actor/factor as listed in Fig. 2 or as studies focusing on either the CCS chain environment studying the effects of global scenarios on the CCS project performance or CCS infrastructure studying the effects of the CCS chain internal design and organization. Some of the case studies will be leading to analysis of different chain designs and some only to parameter sensitivity analysis of one chain. Examples of a few specific case studies performed with the use of the methodology and the simulation tool described in this paper are briefly presented in the following section. Full description of the cases and more detailed discussion of the results are to be found in the papers specifically devoted to each case study.

3. Case study examples

3.1. Comparison of transport by onshore pipeline and shipping between harbours [24]

In this case study, onshore pipeline and CO_2 shipping between two onshore harbours are compared for different distances and capacities in a North-West European context, and not only for a fixed capacity as in the IPCC report [21]. Using the simulation tool for the assessment, the overall costs of transport, including the environmental costs of the two transport options are compared for capacities from 2 to 20 $MtCO_2$/y and transport distance from 200 to 2,000 km.

The results obtained for the “switching” distance between the two transport options in a North-West European context are pictured in Fig. 7. As expected, for a fixed annual capacity, the onshore pipeline transport is used for "short" distances while shipping between two onshore harbours is used for longer distances. Regarding the "switching" distance between the two technologies, it shows that higher annual capacity and volume benefit the onshore pipeline transport as the line shifts to the right. For the annual capacity panel considered, i.e. from 2 to 20 $MtCO_2/y$, the switching distance between the two technologies growths from around 275 to around 875 km. Fig. 7 also enables to draw conclusion on the particular case in a North-West European context and under the hypothesis of the assessment. Indeed, based on the chart, one can conclude that a coal power plant with CCS capturing 4[*] $MtCO_2/y$ will use an onshore pipeline to transport its emissions if the transport distance is shorter than 400 km. However, if the coal power plant pools the transport of its emission together with others industries to reach 8 or 12 $MtCO_2/y$, the switching distance between onshore pipeline and CO_2 shipping between two onshore harbours shifts to around 575 and 675 km respectively.

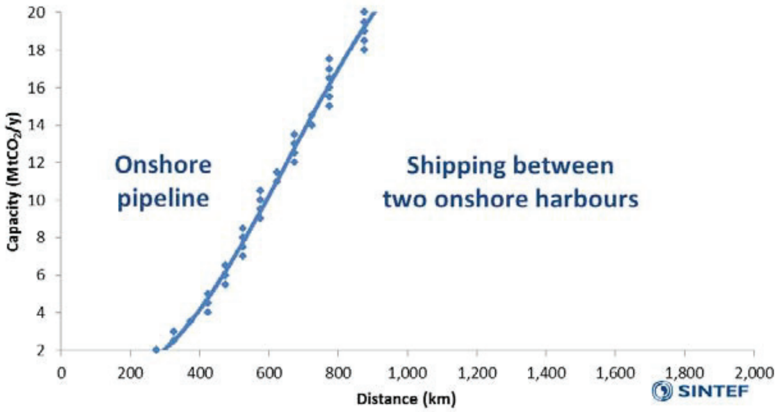


Fig. 7. “Switching” distance between onshore pipeline and shipping between two onshore harbours in a North-West European context

In addition, a sensitivity analysis was performed to address and quantify the impact of different parameters on the choice of the optimal transport option. The study has shown that the four most influential parameters are: the geographical context, the regional effect of pipeline costs, the First-Of A-Kind effect, and the ownership effect.

3.2. Multi-criteria analysis of onshore pipeline and shipping between harbors [22]

In this case study, onshore pipeline and CO_2 shipping between two onshore harbours are compared including not only the economic aspects but also the GHG emissions, the energies and the cooling water consumptions. The case study is based on a scenario described by The Zero Emission Platform [6] in which 10 $MtCO_2/y$ from an industrial cluster are transported over a distance of 500 km. The CO_2 emission profile from the cluster is assumed to lead to a 10 $MtCO_2/y$ infrastructure used at 100% over 30 years. For the considered flow and under the technical and costs evaluation assumptions considered, the two transport technologies have very similar costs. With a Net Present Value (NPV) of costs of 1.7 B€, the onshore pipeline is only 9% less expensive than the shipping option (1.8 B€). Therefore the optimal technology for the case cannot be selected only considering the overall project costs but shall be tempered with a multi-criteria assessment.

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[*] Corresponding to the annual emission of a coal power plant producing 1GWe.

The results of the different criteria assessments are presented in Fig. 8 for the two cost-optimized transport technologies. The multi-criteria analysis shows that the pipeline technology exhibits the best KPIs except regarding the initial investment. However there are different discrepancies between the different technologies among the different KPIs. Indeed, even if the are only small differences between the costs of the two cost-optimized options, the pipeline transport consumes much less utilities (fuel, electricity and water) and is less climate intensive than the shipping transport. In addition, even if, the two options have similar overall costs, their costs breakdowns are different. Indeed, the onshore pipeline chain requires more than twice the upfront investment of the shipping option while the shipping chain leads to higher operating costs. The shipping transport required lower upfront investments for almost the same overall project costs. A consequence of this might be that even if the pipeline transport has most of the best criteria, shipping might be used to kick-off the CCS chains deployment. It is likely that when large scale CCS will start to be implemented, large transport infrastructures would be deployed step by step. In these cases, CO_2 shipping could be used in a first time period while pipeline networks would be deployed later on in order to limit initial investments and financial risks.

It is worth noting that the criteria included here should serve mainly as an illustration of the multi-criteria approach. Other criteria could be relevant when comparing the two transport technologies under a specific context. For example, pipelines have the advantage of being insensitive to weather, of being a continuous process with automation possibilities, etc. The choice of criteria will always depend on the case characteristics: location, context, perspective.

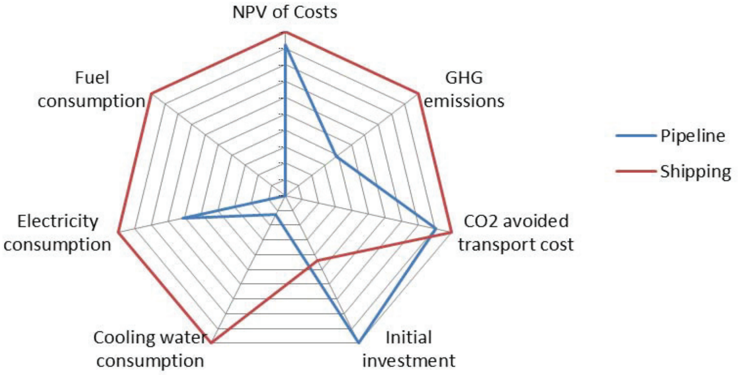

Fig. 8. Results of the multi-criteria analysis of the pipeline and shipping transport

3.3. Optimization of pipeline network - effects of ownership and political incentives [23]

In this work, a set of case studies was investigated that was relating the non technical aspects of the chain to technology deployment using the CCS chain valuation framework described by Jakobsen et al. [12].
The case studies focused especially on three aspects:

The economy of scale in a simplified pipeline network: how the economy of scale changes for different pipeline lengths investigated by comparing the NPV of costs for different pipeline lengths, both with 1 large-diameter pipeline and three smaller-diameter pipelines when the transport distance ranges from 100 – 700 km. It was found that benefits from economy of scale increase significantly with distance, raising the benefits of cooperation from sharing a larger pipeline. The difference in the NPV of costs between three small pipelines and a large one is 980 MNOK at a pipeline distance of 100 km and 6,200 MNOK at a distance of 700 km, with the large pipeline always being more economic.

Effects of pipeline network ownership and profit distributions: investigation of different ways of dividing ownership and profit among the different parts in the chain. The results of this case study have shown that regarding infrastructure ownership, if transport and sink sectors are independent from the source, different profit strategies need to be applied depending on the CO_2 price. This creates need for complicated and dynamic contracting and raises transaction costs, resulting in potential benefits to vertical integration.

Effects of government investment on pipeline infrastructure: considering the NPV of costs for the chain if the government shares the investment on building a large pipeline infrastructure. The results of this case study have shown that government investment in pipeline infrastructure to build an oversized pipeline is indeed a possible way to increase economic efficiency and overcome transaction costs by lowering the discount rate as well as lowering slightly the project breakeven costs.

The work described in detail in [23] illustrated again on relatively simple case studies how the proposed methodology and tool could be used in order to enlighten some critical issues related to CCS realization. From the economic analysis of the selected CCS value chains focusing on pipeline infrastructure, one could conclude that CO_2 price is the major driving force for the realization of CCS projects and though the most efficient political incentive for CCS. The governmental co-founding of the transport infrastructure will not affect the overall NPV to a large extend, but it might sent an important signal indicating how serious are the political intentions to realize CCS and lead to the selection of the most cost-efficient system by lowering the risks. The large-capacity pipeline would always be the most profitable option if the same form of ownership is considered for both alternatives. However, the small-capacity pipelines can become competitive with different ownership and profit distribution strategies. The small-capacity pipelines might also shown to be better alternative if other issues than only the investment costs shall be taken into consideration, such as risk and uncertainties related to the need for agreements and an independent operator of the common infrastructure. It will of course also be dependent on the geographical locations and the distances between sources and sinks.

4. Conclusions

A methodology for a standardized approach to the assessment of CCS projects was described and illustrated on a few simple case studies. The proposed methodology for multi-criteria analysis of CCS value chains enables selection of the most promising options for CCS by evaluating and ranking several economic, environmental, and in the future also risk associated criteria. The methodology will help to reduce the uncertainty by improving understanding of the most important dependencies and trends for the investigated key performance indicators as enlightened by the case studies examples. It could also help to design efficient incentives and measures to stimulate realization of CCS by identifying the most important non-technical factors affecting the CCS chain viability.

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