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The environmental impact and risk assessment of CO_2 capture, transport and storage -an evaluation of the knowledge base using the DPSIR framework

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Abstract

In this paper we identify and characterize known and new environmental consequences associated with CO_2 capture from power plants, transport by pipeline and storage in geological formations (CCS). The DPSIR framework, describing environmental *Driver*s, *Pressures, States, Impacts* and *Responses,* is used to systematically review environmental impact assessment procedures and scientific literature on CCS. Also, it is investigated whether crucial knowledge on environmental impacts is lacking that may postpone the implementation of CCS projects. The findings of this study are that the capture of CO_2 from power plants results in a change in the environmental profile of the power plant. This change encompasses trade-offs and synergies in the reduction of key atmospheric emissions, being: NO_x, SO_2, NH_3, particulate matter, Hg, HF and HCl. The largest trade-offs are found for the emission of NO_x and NH_3 when equipping power plants with post-combustion capture. Synergy is expected for SO_2 emissions, which are low for all power plants with CO_2 capture. An increase in water consumption ranging between 32% and 93% and an increase in waste and by-product creation with tens of kilotonnes annually is expected for a large-scale power plant (1 GW_e), but exact flows and composition are uncertain. The cross-media effects of CO_2 capture are found to be uncertain and not quantified. For the assessment of the safety of CO_2 transport by pipeline at high pressure an important knowledge gap is the absence of validated release and dispersion models for CO_2 releases due to pipeline failures. There is also uncertainty in estimating the failure rates for CO_2 pipelines. Furthermore, uniform CO_2 exposure thresholds, detailed dose-response models and specific CO_2 pipeline regulation are absent. Most gaps in environmental information regarding the CCS chain are identified and characterized for the risk assessment of the underground, non-engineered, part of the storage activity. This uncertainty is considered to be larger for aquifers than for hydrocarbon reservoirs. Failure rates are found to be heavily based on expert opinions and the dose-response models for ecosystems or target species are not yet developed. Integration and validation of various sub-models describing fate and transport of CO_2 in various compartments of the geosphere is at an infant stage. Concluding, it is not possible to execute a quantitative risk assessment for the non-engineered part of the storage activity with high confidence. Finally, several recommendations have been formulated to deal with the knowledge gaps identified in this study.

"Keywords: Carbon Capture and Storage; Environmental impacts: risk assessment; DPSIR."

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1. Introduction

To realize capture, transport and storage of CO_2 (CCS) projects in practice several permits are required. Following the EU CCS Directive [1], commercial CO_2 capture, transport and storage activities are highly likely to be obligated to be subjected to an Environmental Impact Assessment (EIA) to acquire these permits. The EIA is a procedural tool with the main goal to assess the environmental impacts of a proposed project. It is used to include environmental criteria into the decision making process for that project. A complementary tool is the Strategic Environmental Assessment (SEA). This tool is used to facilitate policy decisions on a strategic level [2].

According to Finnveden et al. [3], both environmental assessments can be characterized by three elements: institutional arrangements, the procedure and applied methods. A fourth element would be the environmental impacts assessed in the procedure, i.e. the content of the environmental report or Environmental Impact Statement (EIS). In recent literature increasingly attention has been given to the role of EIA and SEA procedures in the implementation of CCS activities. It was foreseen that there would be several challenges when executing EIAs and SEAs [4, 5]. Parts of this challenge for administrative bodies and project initiators regarding the institutional arrangements and procedural elements of both assessments has been addressed already by Koornneef et al. [2]. There, the focus was aimed towards the identification of the scope of both procedures, yielding insight in the operational, technical, location and strategic alternatives that should be investigated in the assessments. No detailed attention was paid to the environmental impacts to be investigated in the assessments.

The challenge remains to take the existing assessment frameworks for EIA and SEA and apply them on CCS activities. This includes the possibility to use existing tools to investigate the environmental consequences of CCS activities. Recently, this issue has also been addressed in a IEA GHG[2] programme study which was, next to reviewing international procedural EIA frameworks, oriented towards the identification of information requirements and possible knowledge gaps on environmental consequences when these frameworks are applied to CCS activities [6]. The results of that study indicate the presence of gaps in environmental guidelines, standards and knowledge required for the execution of environmental assessments. The study concludes that additional knowledge is required on:

- The environmental performance of large-scale CO_2 capture systems;
- The modelling of the dispersion of supercritical CO_2 releases;
- The probability, size and environmental consequence of CO_2 leakages resulting from CO_2 storage.

Especially the latter turns out to be a primary concern in the public debate about an onshore CO_2 storage project in a small depleted gas field in the Netherlands, the Barendrecht project [7]. In this case, the results of the EIA turned out to be of very high importance for the governmental bodies involved in the decision making process for that project. The environmental consequences and the way they are assessed and presented in an EIA procedure may be a pivot in the further deployment of CCS (demonstration) projects, especially when storage takes place onshore.

In this study, knowledge gaps identified above are systematically explored further. Therefore, specific attention is paid to indicators that are or may be used to report on the environmental consequences of CCS activities. Such indicators can be used to report on complex phenomena in a simple form that in turn can be used in decision making [8]. The causality chain of indicators is specifically addressed here making it possible to investigate where in the cause-effect chain environmental information or indicators are lacking. This causality is captured by the indicator framework DPSIR (Driver, Pressure, State, Impact and Response) that is used in this study to systematically assess the environmental information.

The goal of this study is to identify and characterize known and new environmental interventions associated with CCS activities that are typically addressed in EIA procedures. Also, it will be investigated whether crucial environmental information is lacking that may postpone the implementation of CCS (demonstration) projects.

Specific emphasis is put on knowledge that should be available if CCS is to be implemented on a large-scale in the short-term. This focuses this study towards technologies that are available at present or in the near future. We focus here on identifying and characterizing quantified environmental information.

[2] IEA GHG = Greenhouse Gas R&D Programme of the International Energy Agency.

2. Approach and research method

In order to fulfil the goal of this study we carried out a review of documents related to analogous EIA procedures and EIA procedures for CCS activities as well as scientific literature on CO_2 capture, transport and storage. Analogous EIA procedures were reviewed for three distinctive process steps of a CCS project: the power plant with capture, the transport and finally the underground storage of CO_2. The selected analogues include the construction of new power plants, transport of natural gas by pipelines, underground natural gas storage (UGS), natural gas production and enhanced oil recovery (EOR) projects. For a comprehensive list of the reviewed EIA procedures see Koornneef [9]. In addition, EIA procedures for CO_2 storage projects were reviewed.

The review was performed using a tool based on the DPSIR framework shown in Figure 1. This framework has been developed and used by the European Environmental Agency as a conceptual model to describe the relationships between the environment and society in a simplified manner [10]. It helps to select and structure environmental indicators and provides insight in cause-effect relationships between them. In this way environmental information can more easily be used in the decision making process. This framework is also used in the Netherlands to classify environmental indicators in the environmental cause-effect chain [11].

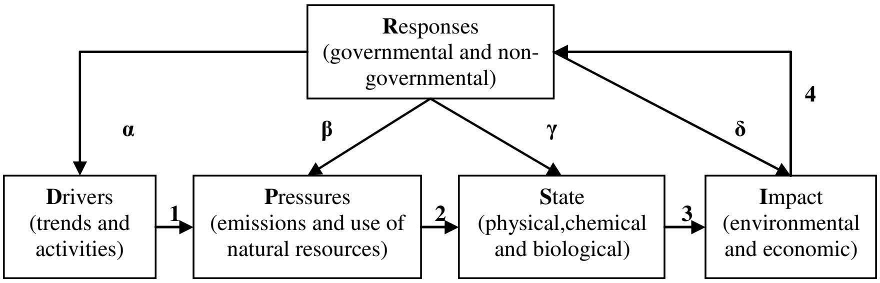

Figure 1 DPSIR framework for reporting environmental information, adapted from [10].

In Figure 1, *Drivers*[3] reflect trends in societal and/or economical development on the macro scale; though can also refer to a single activity that leads to interventions in the environment. Examples are: land use, extraction of materials and the emission of substances into geo-, hydro- and atmosphere. These interventions are the *Pressures*[3,4] put on the environment. The *Pressures* may alter the *State*[3,5] of the environment. This altered *State* of the environment has consequences or *Impacts*[3,6] on the ecological, societal and economical functions of the environment. With *Responses*[3] the society can intervene to reduce the *Drivers*, *Pressures*, *State* and *Impacts* or to adapt to the consequences posed by alterations in the *State* of the environment [10]. The society at large can, amongst others, respond to environmental *Impacts* through the formulation of environmental policy, legislation and regulation. Through legislation and regulation, norms are for instance set for the activities to comply with. Solely these formal *Responses*, indicated by α, β, γ and δ in Figure 1, are considered in this study.

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[3] Throughout this paper '*Driver, Pressure, State, Impact, Response'* a will be denoted in italics and start with a capital letter when referring to the DPSIR framework. Note that use of non italic 'pressure' refers to force per unit area (N m^{-2} or Pa).

[4] *Pressure* is defined as: The development in the release of substances (emissions), physical and biological agents, the extraction of resources and the use of land. [10, 12]

[5] *State* is defined as: the description of the quantity and quality of biotic and abiotic (physical and chemical) occurrences in a certain area. [10]

[6] *Impact* is defined as: effects on human health, nature and man-made capital resulting from changes in the *State* of the environment. [11, 13]

The linkages 1, 2, 3 and 4 in Figure 1 represent the (quantitative) relationship between DPSIR indicators. Analytical tools can be used to model the relationships between the elements, for example: scenario studies, life cycle assessment, (noise) dispersion models, dose-response models and integrative evaluation tools (multi-criteria assessment). Other tools can be used to directly estimate, calculate and monitor the DPSIR indicators.

In this study, the DPSIR framework was used to characterize the environmental information assessed in the reviewed literature. This characterization was done by attributing a *P(ressure)*, *S(tate)* or *I(mpact)* to the environmental indicators reported in the assessments. With this information the following research steps were carried out:

1. Identify and characterize quantitative environmental indicators reported in EIA documents for CCS and analogous activities;
2. Discuss new environmental information, possible indicators and assessment tools for CCS activities;
3. DPSIR characterization of environmental information on: power plants equipped with CO_2 capture, CO_2 transport by pipeline and geological storage of CO_2.

3. Results and conclusions

In this paper only a selection of the results of the full study are presented. A more detailed discussion can be found in [9]. In Table 1 the key issues regarding the assessment of environmental interventions of the considered CCS activities are summarized. The results show that for all steps in the CCS chain additional research and regulatory efforts would help to improve the environmental information to be used in decision making procedures. For the first step in the CCS chain, CO_2 capture from power plants, we found that depending on the applied CO_2 capture technology, trade-offs and synergies can be expected for key atmospheric emissions, being: NO_x, SO_2, NH_3, particulate matter, Hg, HF and HCl. An increase in water consumption ranging between 32% and 93% and an increase in waste and by-product creation with tens of kilotonnes is expected for a 1 GW_e power plant, but exact flows and composition are uncertain. Further, we found that there is considerable uncertainty on how the environmental fate of emissions may shift when equipping power plants with CO_2 capture. Information on cross-media effects when capturing CO_2 is underexposed at present and not quantified. We recommend that environmental monitoring programmes for demonstration plants should help to fill this knowledge gap.

We regard the availability of tools that are used to assess *State* (e.g. concentration) and (sparsely) *Impact* (e.g. damage or health effects) indicators to be appropriate, although adjustments may be required to cope with 'new' emissions from predominantly post-combustion CO_2 capture technologies.

We recommend that formal *Responses* (i.e. regulation) should be aimed at developing norms for environmental *Pressures* stemming from power plants equipped with CO_2 capture. An example is the inclusion of CO_2 capture in BREF documents as Best Available Technology for large combustion plants. The above mentioned issues (i.e. trade-offs and co-benefits) should then be addressed properly.

For the second step in the CCS chain, high-pressure CO_2 transport by pipelines, we found several important knowledge gaps to be present in the assessment of risks of CO_2 pipelines. The foremost gap is the absence of validated release and dispersion models for high-pressure CO_2 pipeline failures. Models that accurately assess the consequence of a pipeline failure scenario on the *State* of the environment are thus considered a challenge.

Another challenge is the assessment of the effects of impurities on operation, failure rates and HSE impacts. Defining failure rates for CO_2 pipelines may not be as straightforward as formerly suggested in literature.

In addition, the absence of uniform norms or HSE (Health, Safety & Environmental) thresholds for the *State* indicators (CO_2 concentration) and the absence of a formally accepted dose-response model for CO_2 that provides the possibility to assess an *Impact* indicator are both challenges that are recommended to be resolved in the short-term.

We found that guidelines for (quantitative) risk assessment for CO_2 pipelines are currently absent. Therefore, we recommend that *Responses* are required which set guidelines for assessing the risk of (high-pressure) CO_2 pipelines. These should include a definition of the type of failures that should be assessed, the methodological choices to be made, uniform exposure thresholds and dose-response model, and safety distances for CO_2 pipelines.

For the final step in the CCS chain, CO_2 storage in geological formations, we found that the above ground part of the CO_2 storage activity and the assessment of environmental interventions can be considered current practice. The safe and long-term storage of CO_2 is however a critical issue compared to environmental assessments for current proficient activities in the geosphere. Depending on local conditions, environmental consequences of CO_2 storage could be ground movement and displacement of fluids in the geosphere. In addition, leakage of CO_2 into environmental compartments as result of a failure may result in environmental consequences that should be considered in environmental assessments.

This study has identified several challenges with respect to the assessment of these interventions. One of these challenges is a detailed characterization of storage formations and overburden, and a translation of this information into static and dynamic models that take into account dominant processes in the underground and multiple environmental compartments. Subsequently, the validation of these models is needed to make assessment of performance indicators possible. Uniform performance indicators are currently absent and we recommend therefore the development of formal *Responses* in the form of norms for to-be-developed performance indicators (*Pressure*, *State* and *Impact*) for various environmental media (geosphere, hydrosphere and atmosphere) and their (sub)compartments. These *Responses* should also be linked to actions concerning monitoring, mitigation and remediation plans. In addition, it is recommended that in future environmental assessments it is specified at which specific indicator (*Pressure, State and Impact*) the mitigating or remedial actions is aimed at.

To assess the possible consequences of leakage scenarios, fluxes of CO_2 between environmental compartments can be modelled or estimated, being it with significant uncertainty. However, using these fluxes to assess effects and impacts on the various organisms and ecosystems present in the various environmental compartments is currently a missing link. We recommend therefore that dose-response models for ecosystems or target species are developed and applied, taking into account site specificity. Another challenge is that time horizons for fluxes and consequences resulting from storage failures are not clearly demarcated.

Typical failure scenarios for CO_2 storage activities are: leakage along a well and wellhead failure, caprock failure or permeability, leakage along a spill point and leakage through existing or induced faults and fractures. The assessment of failure rates for most of these scenarios lacks an empirical base and is heavily dependent on expert judgement. There is also no methodological standard on whether and how these scenarios should be modelled to estimate the risk using quantitative indicators.

Summarizing, it is currently not possible to execute a quantitative risk assessment (QRA) for the non-engineered part of the storage activity with high confidence. Uncertainty is however expected to be reduced when learning-by-injecting increases.

We recommend the development of guidelines for risk assessment. In absence of a methodological standard, the focus of the guidelines should be on the development of uniform reporting standards, especially, concerning parts of the RA that heavily rely on expert judgement.

In conclusion, most gaps in environmental information regarding the CCS chain were identified and characterized for the underground part of the storage activity. This holds especially for aquifers in comparison with hydrocarbon reservoirs. This should however not be confused with an assertion on the magnitude of environmental consequences. That is, most environmental interventions and impacts are expected to be induced in the operational phase of the power plants with CO_2 capture. Especially in the case of coal fired power plants.

Regarding the safety of CCS, it is found that the CO_2 release in case of a failure is reported to be the highest for the transport activity, see Figure 2. Although the failure of the underground CO_2 storage system appears to have limited consequences, suggesting a low risk, the uncertainty regarding the assessment of the risk has the potential to become a bottleneck for wide scale implementation of CCS if not properly addressed.

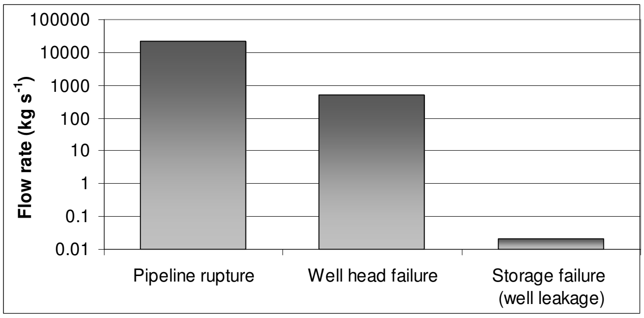

Figure 2 Maximum flow rates reported in risk assessments for CO_2 transport and storage activities reviewed in this study.

To deal with these uncertainties, we recommend a stepwise approach starting with an intensive (e.g. annual) evaluation cycle of CO_2 storage activities, including: planning, modelling, monitoring, verification and calibration, evaluation, planning etc. This cycle should focus on the operational phase and post-closure phase. With assuring monitoring results it then can be decided to gradually reduce the frequency of this cycle and reduce the intensity of monitoring depending on the outcomes of an evaluation using above recommended performance indicators.

Our final recommendation is that in future EIAs environmental interventions in the full life cycle of electricity generation with CCS, cross-media effects and effects of impurities in the CO_2 stream are specifically addressed.

Table 1 Key issues in the assessment of environmental impacts regarding CO_2 capture, transport and storage as indentified and characterized with the use of the DPSIR framework

	Indicator (DPSIR)a	Models/tools (1, 2, 3, 4) b	Regulations (α, β, γ, δ)c
Capture	P. Atmospheric emissions quantified but uncertain. Co-benefits (PM, SOx, HCl, HF) and trade-offs (NOx, NH3) probable due to application of CO_2 capture. Depends on applied capture technology. P. Emissions of solvents and degradation products (focus: post- combustion). P. Limited quantitative data available on emissions to water and solid waste streams. P. Water consumption increase due to capture.	1. No reliable emission factors for emissions to water and air. No model seems available that models waste generation for capture technologies (focus recommended: coal fired post-combustion and oxyfuel). 2. Possibly adaptation of immission models is required to cope with 'new' emissions due to capture. 1, 2, 3. See transport for issues of release and dispersion modelling of CO_2 from the engineered system.	a. No BREF and BAT. β. No PSR that takes into account efficiency penalty. γ. Emission and concentration norms for solvent emission and their degradation products should be formulated. γ. Uniform atmospheric concentration limits CO_2 to be used ir RA.
Transport	P. Characteristics of released content are, within boundaries, uncertain. Maximum reported release rate is 22 t s-1. S. Concentration of CO_2 and impurities in surrounding of a failed pipeline is assessed to be above concentration thresholds at up to 7.2 km. I. Impact ($1*10^{-6}$ risk contour) of CO_2 pipelines is assessed to be possible up to 3.3 km based on a concentration threshold. With a preliminary probit function this contour extends up to 124 m.	1. Probability of infrastructure failure requires scrutiny. 1. Release models should include impurities and thermophysical properties. 2. Release/dispersion model validation for high-pressure CO_2 release. 3. Dose-response models (e.g. probit function) for target species (or ecosystems) should be developed depending on environmental compartment. Currently, these models are not (yet) available.	α. Pipeline standards are absent, although work is performed i this area. β1. In QRA no standardized failure scenarios are formulated. βp. No formal limits for release of CO_2 and impurities. γ. Uniform atmospheric concentration limits for CO_2 to be use in RA. δ. No formally adopted safety distances for CO_2 pipelines.
Storage	P. Characteristics (total amount and speed) of fluxes (e.g. CO_2 and brine) between environmental compartments can be quantified, although with high uncertainty. Maximum release rate from storage activity in reviewed risk assessments is 0.5 t s-1. S. The State (CO_2 concentration, pH) of a compartment is not frequently reported. I. Impact indicators per compartment are reported in RAs although sparsely for risks caused by failure of the geological storage system. No risk contours can be drawn as not all leakage pathways are known. PSI: No clear performance indicators per environmental compartment.	1b. Failure scenarios are typically: leakage along well and wellhead failure, caprock failure and leakage through faults or fractures and leakage along spill point. 2. CO_2 dispersion and transport models, reservoir models are not validated for long-term CO_2 storage. 2. Integration of models for subsurface and biosphere is at an infant stage. 1, 2, 3. See 'Transport' for issues of release and dispersion modelling of CO_2 from the engineered system. RA Tools rely highly on expert panel to (depending on approach): -Identify and select failure scenarios; -Characterize/quantify failure rates; -Characterize consequences.	α. Best practice manuals for CO_2 injection are being develope β1a. Monitoring and reporting guidelines for, and prescription the exact characteristics of the injected CO_2 are not formulate β1b. Standardized methodology for the development of failure scenarios and reporting. βp. Monitoring/reporting standards and limits for fluxes betwe compartments are absent. γ. Monitoring/reporting standards and State limits dependent c compartment are absent. γ. Uniform atmospheric concentration limits CO_2 to be used ir RA δ. Standard Safety distances not formulated.

[a] DPSIR: Driver, Pressure, State, Impact and Response.
[b] 1, 2, 3, 4: Indicate models/tools that are used to measure or model DPSIR indicators. 1 = models to determine linkage between Driver and Pressure; 2 = models to determine linkage between Pressure and State; 3 = models to determine linkage between State and Impact; 4 = models to determine linkage between Impact and Response.
[c] α, β, γ, δ: indicate formal Responses in the form of regulations that regulate Driver, Pressure, State and Impact indicators, respectively.

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