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Identifying and Structuring Risks in CCS Infrastructures - A Systematic Literature Review

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A Systematic Literature Review

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Abstract:

Large-scale CCS infrastructures link capture, conditioning, transport, and geological storage into a tightly coupled value chain. This working paper examines how the associated risks can be systematically identified and structured. It is based on a literature analysis of 76 full-text publications. The identified risks were assigned to five CCS stages and seven risk categories and consolidated into 35 risk clusters. A CCS value chain risk matrix enables their structured positioning, while a risk register documents causes, impacts, mitigation measures, and the underlying literature. The results show that storage constraints, capacity deviations, technical interfaces, and coordination problems in particular have effects beyond individual process stages. The instruments developed provide a transparent basis for project-specific analyses but do not replace quantitative risk assessment. Further research is needed on empirical validation, the modeling of interdependencies, and a stronger consideration of social acceptance.

Kurzzusammenfassung:

Großskalige CCS-Infrastrukturen verbinden Abscheidung, Konditionierung, Transport und geologische Speicherung zu einer eng gekoppelten Wertschöpfungskette. Das Arbeitspapier untersucht, wie die damit verbundenen Risiken systematisch identifiziert und strukturiert werden können. Grundlage ist eine Literaturanalyse von 76 Volltextpublikationen. Die identifizierten Risiken wurden fünf CCS-Stufen und sieben Risikokategorien zugeordnet und zu 35 Risikoclustern konsolidiert. Eine Risikomatrix der CCS-Wertschöpfungskette ermöglicht deren strukturierte Verortung, während ein Risikoregister Ursachen, Auswirkungen, Minderungsmaßnahmen und Literaturgrundlagen dokumentiert. Die Ergebnisse zeigen, dass insbesondere Speicherrestriktionen, Kapazitätsabweichungen, technische Schnittstellen und Koordinationsprobleme über einzelne Prozessstufen hinauswirken. Die entwickelten Instrumente schaffen eine transparente Grundlage für projektspezifische Analysen, ersetzen jedoch keine quantitative Risikobewertung. Weiterer Forschungsbedarf besteht bei der empirischen Validierung, der Modellierung von Wechselwirkungen und der stärkeren Berücksichtigung gesellschaftlicher Akzeptanz.

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Abstract

Large-scale CCS infrastructures link capture, conditioning, transport, and geological storage into a tightly coupled value chain. This working paper examines how the associated risks can be systematically identified and structured. It is based on a literature analysis of 76 full-text publications. The identified risks were assigned to five CCS stages and seven risk categories and consolidated into 35 risk clusters. A CCS value chain risk matrix enables their structured positioning, while a risk register documents causes, impacts, mitigation measures, and the underlying literature. The results show that storage constraints, capacity deviations, technical interfaces, and coordination problems in particular have effects beyond individual process stages. The instruments developed provide a transparent basis for project-specific analyses but do not replace quantitative risk assessment. Further research is needed on empirical validation, the modeling of interdependencies, and a stronger consideration of social acceptance.

1 Introduction

Reducing anthropogenic CO_2 emissions is a key prerequisite for achieving national and international climate neutrality targets (Lecocq et al. 2022). Despite progress in energy efficiency, electrification, and the expansion of renewable energy, hard-to-abate emissions remain, particularly in the cement, steel, refining, and chemical industries. These arise, among other things, from process-related reactions and the demand for high-temperature heat and therefore cannot be fully avoided through conventional decarbonization measures (European Commission Joint Research Centre 2025; d'Amore et al. 2021; Regufe et al. 2021).

Carbon capture and storage (CCS) refers to the capture of anthropogenic CO_2 at an emission source, its processing and transport, and its permanent storage in suitable geological formations. The CCS value chain thus comprises capture, conditioning and compression, transport, injection, and geological storage (Folger 2013). Unlike carbon capture, utilization and storage, in CCS the captured CO_2 is not put to any further use but is stored permanently (Regufe et al. 2021).

Large-scale deployment of CCS requires not only individual capture plants but a spatially and temporally coordinated infrastructure. Emission sources must be connected via transport links to suitable storage sites. Moving from individual source-to-sink connections towards shared networks with multiple sources and sinks can yield economies of scale. At the same time, however, the number of technical, operational, economic, and institutional interfaces increases (Wetenhall et al. 2017; Gunawan et al. 2024).

The individual process stages therefore cannot be considered in isolation. Changes in the available CO_2 volumes, the stream composition, or storage performance can affect the design and operation of upstream and downstream infrastructure components (Middleton, Keating, et al. 2012; Porter et al. 2016; Wetenhall et al. 2017). This coupling gives rise to a multidimensional risk landscape. It comprises technical and operational risks as well as environmental and safety-related, economic, regulatory and legal, social, and systemic risks (Lee et al. 2017; Heffron et al. 2018; Kabir et al. 2024). These risks can occur within individual process stages but can also propagate across interfaces and thereby affect the functionality, safety, economic viability, and scalability of the entire infrastructure (Middleton, Keating, et al. 2012; Middleton and Yaw 2018; Wetenhall et al. 2017).

Existing research already examines many of these risks in detail. Technical and operational studies focus in particular on transport and storage, while other studies address economic decisions, regulatory frameworks, societal impacts, or cross-stage infrastructure issues. In addition, there are various approaches to structuring risk-related information, including cause-and-effect models, project-specific risk registers, category-based classifications, and technical mapping methods (A. Brown et al. 2017; Luna-Ortiz 2022; Szklarczyk-Marshall et al. 2025).

Within the literature base examined, however, a combination of systematic risk identification, consistent assignment to the relevant CCS stages and risk categories, and in-depth documentation of the identified risks is evident only to a limited extent. The research gap therefore lies not in a lack of individual CCS risk analyses but in the consistent integration of heterogeneous findings within a common structuring system.

The aim of this study is therefore to develop a risk concept based on two complementary instruments. A CCS value chain risk matrix serves to position the identified risk clusters in a structured way by CCS stage and risk category. A complementary risk register elaborates on these clusters in terms of their causes, potential impacts, and possible mitigation measures. This leads to the following research question:

> *How can risks of CCS infrastructures be systematically identified, structured, and transparently presented?*

2 Methodology

2.1 Research design

The study follows a literature-based and conceptual research design. The literature analysis served three functions: identifying relevant risks, classifying them within a systematic structure along the CCS value chain, and extracting information on causes, impacts, and mitigation measures. The results of the literature analysis feed, on the one hand, into a matrix representation of the risks along the CCS value chain stages and, on the other hand, into a risk register.

The rows of the matrix are based on the five stages of the CCS value chain: capture, conditioning and compression, transport, geological storage, and infrastructure and system integration. The risk categories were guided in particular by the categories of Lawrence (2024) and the principles of risk management according to ISO (2018). The final column order is: technical, operational, environmental and safety-related, economic, regulatory and legal, social, and systemic risks. The order follows a content-based presentation logic, from technical functionality via operation, possible consequences, and implementation conditions through to system integration. It does not represent a prioritization or ranking of the risk categories.

2.2 Database selection and search strategy

The search strategy was developed iteratively between 12 and 18 June 2026. Test queries were carried out in Semantic Scholar, Google Scholar, and Scopus. In the test queries, Semantic Scholar returned the largest share of suitable publications and was therefore used as the primary database. The final search string was last run on 18 June 2026.

The research question was broken down into three term blocks: CCS or CCUS, risk, and infrastructure. Narrower search variants proved too restrictive. The final query was:

```
("carbon capture and storage" OR CCS OR
CCUS)
AND (risk* OR uncertaint* OR challenge*)
AND (infrastructure OR network OR pipeline
OR transport OR storage)
```

2.3 Literature selection and classification

Literature selection was carried out in several stages. First, the titles and abstracts of the identified publications were screened. Contributions addressing risks, uncertainties, barriers, or comparable challenges in connection with CCS infrastructures were included. In addition, publications were included that address questions of planning, implementation, scaling, or operation of CCS systems or that relate to transport networks, storage sites, and infrastructure development.

For inclusion in the further analysis, at least one of the following aspects had to be the main focus:

- technical, operational, environmental and safety-related, economic, regulatory, or social risks,
- uncertainties and implementation barriers,
- challenges in infrastructure planning or system integration.

After screening, the publications were classified according to their relevance to the research question. Publications that explicitly examine risks or uncertainties, identify several specific risks, or make a methodological contribution to risk, resilience, or decision analysis were classified as core papers. Supporting papers provided additional expertise on individual risk areas, while background papers mainly served for general contextualization. Systematic risk extraction was based exclusively on the full texts classified as core papers.

2.4 Risk extraction, assignment, and clustering

All risk-relevant issues were systematically extracted from the selected core publications. This included not only aspects explicitly labeled as risks but also uncertainties, hazards, technical challenges, operational problems, bottlenecks, and potential barriers, provided that a negative influence on the planning, construction, operation, safety, economic viability, or scaling of CCS infrastructures was plausibly described. The risks were initially documented at the most granular level possible. Terms were merged only where they were clearly synonymous.

As a rule, individual risks were assigned to a CCS stage based on their primary subject reference and to a risk category based on their dominant risk mechanism. Multiple assignments were possible in justified cases. The aim was not to capture all interdependencies but to structure the literature findings consistently. Within each combination of CCS stage and risk category, related individual risks were condensed into an overarching risk cluster, while different risk mechanisms were kept separate.

The resulting risk clusters form the basis of the risk matrix. For the risk register, all full texts assigned to a cluster were re-analyzed, and information on causes, potential impacts, and possible mitigation measures was consolidated. The risk register thus complements the structural classification provided by the matrix with substantive information on the key risk mechanisms and the options for action discussed in the literature.

3 Results

3.1 Descriptive results of the literature search

The literature search initially identified 274 potentially relevant publications. After screening titles and abstracts, 149 contributions remained for further assessment. Of these, 102 publications were classified as core papers. Following full-text review, 26 contributions could not be used for risk extraction because full access was not possible or no additional risk-relevant information could be extracted. The final data basis therefore comprises 76 full-text publications. Figure 1 summarizes the literature selection process.

The publications considered span the period from the late 1990s to 2026. Around one-fifth of the core publications analyzed were published in or after 2024. The literature base thus combines established findings of CCS research with recent contributions on infrastructure development, system integration, and scaling. In terms of publication type, the 37 journal articles predominate. The sample is supplemented by 23 conference papers and 16 scientific reports.

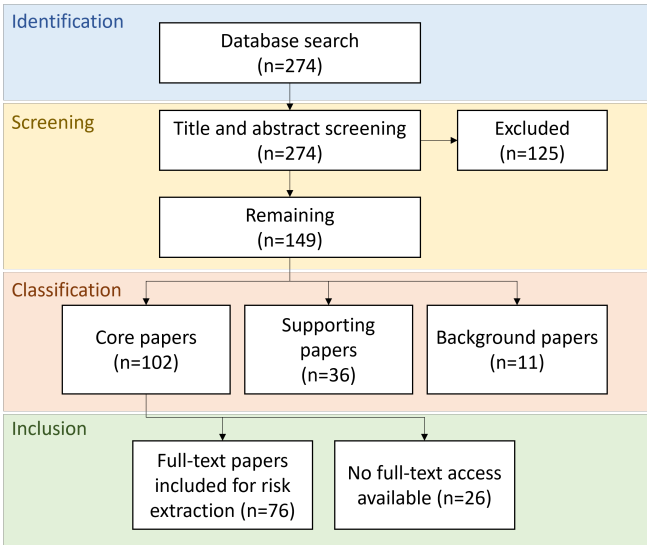


Figure 1: Literature selection process.

Thematically, the literature focuses on transport, geological storage, and infrastructure and system integration. In the transport domain, the main topics are pipeline design, material behavior, corrosion, flow assurance, safety, and network planning (Onyebuchi et al. 2018; Demofonti et al. 2011; Vianello et al. 2016). The storage literature addresses geological suitability, storage capacity, injectivity, pressure management, and long-term integrity (Middleton, Keating, et al. 2012; Bandilla et al. 2017; Worth et al. 2014). Cross-stage studies examine network development, source-sink matching, shared infrastructure concepts, and capacity alignment (Wetenhall et al. 2017; Middleton, Kuby, et al. 2012; Olson et al. 2025). Capture as well as conditioning and compression, by contrast, are comparatively rarely addressed as research foci in their own right. Social aspects likewise feature less prominently than technical, operational, and economic issues (Gunawan et al. 2024).

3.2 Key findings

For each combination of the five CCS stages and seven risk categories, one cluster was formed on the basis of the risk register. The 5×7 matrix presents the 35 clusters in condensed form (Figure 2). Its columns follow the presentation logic *technology – operation – environment and safety – economics – governance – acceptance – system integration*. This order serves solely to guide the reader; the matrix depicts neither a prioritization nor causal relationships between the clusters. A complete overview of all risk clusters with a brief description and literature assignment is provided in Table 1 in the appendix.

The substantive results are summarized below column by column, i.e., by risk category. First, causes and impacts are explained in the order of the matrix. The mitigation measures are then summarized across clusters, as many measures address several risks and CCS stages at once. An additional row-by-row presentation of the risk register is omitted.

3.2.1 Technical integrity and performance

The functionality of a CCS chain requires that its components deliver the intended performance permanently under the respective operating conditions. Technical data gaps and insufficient alignment with downstream infrastructure stages

	Risk category						
CCS value chain	Technical integrity and performance	Operations and monitoring	Environment, health and safety	Economics and investment	Regulation, law and governance	Social acceptance and stakeholders	System integration and scaling
CO_2 Capture	Capture efficiency and plant performance	Process stability and operational flexibility	CO_2 quality and downstream integrity	Investment and design	Emission standards and verification	Acceptance and trust	Capacity alignment and plant integration
CO_2 Conditioning and Compression	Compression integrity and corrosion	Operational efficiency and energy demand	Impurities and stream quality	Energy and operating costs	Safety standards and permittability	Exposure and safety concerns	Interface compatibility and stream transfer
Transport	Pipeline integrity and corrosion	Transport capacity and flow stability	CO_2 leakage and exposure	Investment and cost overruns	Permitting and regulatory delays	Public opposition and routing conflicts	Network expansion and capacity development
Storage	Reservoir and wellbore integrity	Monitoring and anomaly detection	Leakage and induced seismicity	Liability and post-closure costs	Permitting and long-term liability	Local acceptance and siting conflicts	Storage availability and system upstream effects
Infrastructure/ System Integration	Network integrity and technical compatibility	Operational coordination and system availability	System integrity and environmental impacts	Network investment and underdimensioning	Regulatory fragmentation and governance	Stakeholder and actor coordination	Scalability and overall integration

Figure 2: Matrix of risk clusters by CCS stage and risk category. The column order follows a content-based presentation logic and does not represent a ranking.

can already limit the usable performance of capture plants (Lee et al. 2017; Gunawan et al. 2024; Middleton, Kuby, et al. 2012).

In conditioning and transport, corrosion and material degradation are key risk areas. Free water phases, reactive impurities, and pressure and temperature fluctuations can promote wall thickness loss and material failure (Morland 2021; Onyebuchi et al. 2018; Liu et al. 2025). When existing pipelines are repurposed, uncertainties about the original design and the current material condition are added (Luna-Ortiz 2022). Hybrid CO_2-H_2 transport concepts place additional demands on material integrity due to varying gas compositions (Sotoodeh 2026).

In storage, reservoir heterogeneity, permeability, storage capacity, and pressure conditions influence the achievable injection performance (Middleton, Keating, et al. 2012). Deviations from planning assumptions may necessitate additional wells or adjustments to the injection strategy (Middleton, Keating, et al. 2012).

Moreover, as multiple sources, transport routes, and storage sites are connected, the requirements for compatible stream compositions and aligned pressure and temperature conditions between the infrastructure stages increase (Harkin et al. 2017; Lothe et al. 2025; Rütters et al. 2021).

3.2.2 Operation and monitoring

Stable operation of the CCS chain requires that fluctuations in CO_2 volumes and constraints at individual process stages are managed. Variable source flows, load changes, and constraints of the transport or storage infrastructure can cause curtailments and operational interruptions (Jensen et al. 2014; Wetenhall et al. 2017).

Deviations in stream composition may necessitate additional drying, purification, or compression steps and reduce operational efficiency (Porter et al. 2016; Rütters et al. 2021). In transport, fluctuating throughputs, pressure losses, and changing stream properties can impair flow stability (Onyebuchi et al. 2018; Wetenhall et al. 2017). An inadequate flow assurance design can cause unstable flow conditions, reduced transport capacities, and operational interruptions (Onyebuchi et al. 2018; Szklarczyk-Marshall et al. 2025).

Insufficient monitoring can hamper the early detection of operational deviations, losses of integrity, and unexpected storage developments (Xu et al. 2024; Worth et al. 2014).

3.2.3 Environment, health, and safety

Environmental and safety risks arise in particular when the safe containment of CO_2 cannot be ensured. During transport operation, corrosion, material defects, external impacts, and unsuitable operating conditions can impair pipeline integrity and cause leaks or ruptures (Demofonti et al. 2011; Onyebuchi et al. 2018; Vianello et al. 2016). Owing to possible phase changes, rapid depressurization influences the course of the release and the dispersion of the CO_2 (Demofonti et al. 2011; Onyebuchi et al. 2018). The damage potential depends on the quantity released, the pressure and dispersion conditions, and the surroundings of the pipeline (Vianello et al. 2016).

In geological storage, the properties of the reservoir and caprock, well integrity, and pressure evolution determine the safe containment of the CO_2 (Middleton, Keating, et al. 2012; Bandilla et al. 2017). Uncertainties regarding storage capacity and injectivity can lead to critical pressure conditions and adjustments to the injection strategy (Middleton, Keating, et al. 2012; Bandilla et al. 2017). Since the effects of technical deficiencies can propagate across several process stages, environmental, health, and safety risks should be assessed across the whole system (A. Brown et al. 2017; Rütters et al. 2021).

3.2.4 Economics and investment

In CCS infrastructures, high upfront investments meet uncertain utilization trajectories, long planning horizons, and long-term capital commitment. Since capture, transport, and storage are interdependent in terms of timing and capacity, economic viability cannot be assessed for individual facilities in isolation (Chrysostomidis et al. 2009; Lee et al. 2017; Middleton, Kuby, et al. 2012; Middleton and Yaw 2018).

For capture plants, the relevant question is whether the planned capacity can be utilized on a sustained basis. The investment decision depends on future CO_2 volumes and on transport and storage capacities becoming available in time (Middleton, Kuby, et al. 2012; Middleton and Yaw 2018; Wetenhall et al. 2017). Market and policy risks reinforce this uncertainty, because changes in regulatory incentives or rev-

enue models can affect the profitability of the entire CCS chain (Dosumu et al. 2024; Emanuelsson 2026).

Conditioning and compression incur energy and operating costs, the level of which is influenced in particular by pressurization, drying, purification, and the stream specifications to be met (Porter et al. 2016; Rütters et al. 2021; Onyebuchi et al. 2018). Deviations from the intended composition can necessitate additional treatment steps and thus higher costs (Porter et al. 2016; Rütters et al. 2021).

In transport networks, there is a trade-off between capacity needed in the short term and long-term expandability. Insufficient capacities can cause bottlenecks and later expansion investments, while oversized networks initially remain underutilized and have higher specific costs (Chrysostomidis et al. 2009; Coleman 2009; Middleton, Kuby, et al. 2012; Middleton and Yaw 2018). Shared networks add uncertainties regarding future users, connected volumes, and the allocation of costs and investment risks (Chrysostomidis et al. 2009; Melese et al. 2017).

Geological uncertainties can increase the costs of storage and affect the economic assessment of upstream infrastructure (Middleton, Keating, et al. 2012; Middleton and Yaw 2018).

3.2.5 Regulation, law, and governance

Investments in CCS infrastructures require reliable rules on permitting, safety, liability, and network access. Regulatory uncertainties can hamper the financing of individual components and the coordination of the entire CCS chain (Chrysostomidis et al. 2009; Heffron et al. 2018; Nordhaus et al. 2009).

In conditioning, compression, and transport, regulatory uncertainties concern in particular the requirements for stream quality, pressure, temperature, and materials (Harkin et al. 2017; Rütters et al. 2021). Unclear transfer conditions complicate technical design and the allocation of responsibility in the event of stream deviations (Harkin et al. 2017; Porter et al. 2016).

When transport networks are built, permitting procedures, rights-of-way, and unclear responsibilities can lead to delays (Nordhaus et al. 2009). For shared networks, questions of network access, tariff setting, and capacity allocation also arise (Nordhaus et al. 2009). Cross-border and multimodal transport chains increase the need for coordination, as they link several jurisdictions, operators, and permitting regimes (Heffron et al. 2018; Morbee 2014; Orchard et al. 2021).

In storage, too, unclear institutional responsibilities can impair risk allocation and the financing of the connected infrastructure (Heffron et al. 2018). With increasing interconnection, the need to align technical and institutional arrangements across several process stages therefore grows.

3.2.6 Social Acceptance and Stakeholder

The risk register covers social acceptance less comprehensively than technical, operational, and economic risks. The sources captured primarily allow statements on the societal implications of possible CO_2 releases and on spatial infrastructure decisions.

Concerns about possible releases can influence the perception of transport and storage infrastructures. The technical damage potential depends, among other things, on the quantity released, the dispersion conditions, and the surroundings of the infrastructure (Vianello et al. 2016). However, the societal perception of such hazards must be distinguished from their technical assessment.

Further potential for conflict arises in the spatial planning of transport routes and storage sites. Infrastructure decisions affect land-use, ownership, and siting structures and may distribute burdens spatially differently from the economic or climate policy benefits (Gunawan et al. 2024).

The implementation of regional CCS infrastructures also requires cooperation between emitters, transport and storage operators, and the competent authorities (Connors 2021). However, statements on public participation, institutional trust, and procedural justice are only partially supported by the literature contained in the register.

3.2.7 System integration and scaling

System integration risks arise from the temporal, capacity-related, technical, and institutional interdependencies between capture, conditioning, transport, and storage. Spatial infrastructure models link emission sources, transport routes, and storage sites; their results, however, depend on the underlying assumptions regarding volumes, costs, and storage (Sun et al. 2013; Oei et al. 2014; Lee et al. 2017; Middleton, Keating, et al. 2012).

Capture capacities can only be used if sufficient transport and storage capacities are available at the same time. A lack of synchronization can cause curtailment, underutilization, and subsequent expansions (Middleton, Kuby, et al. 2012; Wetenhall et al. 2017).

At the interfaces, stream composition, pressure, temperature, and transfer conditions must be aligned. Inconsistent specifications can lead to additional treatment steps, capacity losses, and operational disruptions (Harkin et al. 2017; Lothe et al. 2025; Rütters et al. 2021).

In network expansion, there is a trade-off between short-term demand and long-term expandability. Low initial capacities can cause later bottlenecks and expansion investments, while forward-looking sizing may initially lead to underutilization (Middleton, Kuby, et al. 2012; Middleton and Yaw 2018). Storage uncertainties can impair the utilization of upstream facilities and necessitate adjustments to infrastructure and expansion pathways (Middleton, Keating, et al. 2012; Middleton and Yaw 2018).

As individual source-to-sink connections are expanded into networks with multiple sources and storage sites, the number of interfaces, the actors involved, and the possible expansion pathways increase. Without compatible components, coordinated investment timing, and suitable governance structures, fragmented networks, underutilization, and additional adaptation needs can arise (Harkin et al. 2017; Lothe et al. 2025; Olson et al. 2025).

3.3 Approaches to risk mitigation

The risk mitigation measures captured in the risk register operate at the technical, operational, planning, and institutional levels. Since many approaches address several risk categories and CCS stages at once, they are presented jointly. The measures can limit risk drivers or the consequences of damage; however, they cannot fully eliminate uncertainties regarding volumes, storage, and coordination.

Technical risks can be limited in particular through binding stream specifications, suitable materials, and continuous integrity management. Limit values for water content, impurities, pressure, and temperature must be aligned with the operating conditions and the requirements of downstream infrastructure (Harkin et al. 2017; Rütters et al. 2021). Material

selection must be adapted to the expected composition of the CO_2 stream and the permissible operating windows (Liu et al. 2025; Morland 2021). Before existing pipelines are repurposed, the original design, the current material condition, and the suitability for the intended CO_2 conditions must be examined (Luna-Ortiz 2022).

During operation, technical integrity must be maintained through inspection, maintenance, and ongoing condition assessment (Liu et al. 2025; Onyebuchi et al. 2018). Flow assurance analyses take pressure losses, phase behavior, topography, and possible flow instabilities into account as early as the design and operational planning stages (Onyebuchi et al. 2018; Szklarczyk-Marshall et al. 2025). Flexible operating concepts support the handling of fluctuating throughputs and changing transport and injection capacities (Jensen et al. 2014; Wetenhall et al. 2017). Monitoring pressure, temperature, flow rate, and leak indicators enables operational deviations and losses of integrity to be detected at an early stage (Xu et al. 2024).

In storage, monitoring, measurement, and verification concepts serve to capture pressure evolution, the spatial spread of the CO_2, and possible deviations from the expected storage behavior (Worth et al. 2014). The data obtained can be used to update geological models and to adjust injection rates (Worth et al. 2014). In the event of critical pressure build-up, the extraction of formation water or brine is a possible active pressure management measure (Bandilla et al. 2017).

Uncertain CO_2 volumes, connection dates, and storage availability require robust, scenario-based infrastructure planning (Lee et al. 2017; Olson et al. 2025). Spatial and multi-period models make it possible to consider emission sources, transport routes, storage sites, and temporal expansion pathways jointly (Middleton, Kuby, et al. 2012; Oei et al. 2014). A phased expansion can facilitate adaptation to the volumes and connection dates actually realized, although it cannot entirely avoid temporary underutilization of capacities built early (Melese et al. 2017; Middleton, Kuby, et al. 2012; Middleton and Yaw 2018). Risk-sharing models can support the allocation of costs and investment risks in shared networks (Chrysostomidis et al. 2009; Melese et al. 2017).

At the institutional level, shared transport networks require clear rules for network access, tariff setting, and capacity allocation (Nordhaus et al. 2009). Cross-border transport chains require compatible permitting regimes and robust agreements between the states and operators involved (Heffron et al. 2018; Morbee 2014). Joint operating protocols, defined information flows, and clearly assigned responsibilities support the operational coordination of the connected infrastructure stages (Wetenhall et al. 2017).

For social risks, the register contains fewer directly supported measures than for technical and operational risks. Needs for action that can be derived include, in particular, a site-specific assessment of spatial impacts (Gunawan et al. 2024), early clarification of institutional responsibilities (Heffron et al. 2018), and the coordination of the actors involved (Connors 2021). Measures for participation, trust building, and procedural justice, by contrast, are only partially supported by the literature base of the register. This uneven coverage should be interpreted as a limitation of the literature base and not as an indication that social risk mitigation is of little importance.

4 Discussion

4.1 Methodological reflection and limitations of the study

The risk matrix developed and the risk register based on it enable a systematic structuring of heterogeneous risks along the CCS value chain. However, the explanatory power of the results is limited by several methodological constraints.

First, the final literature search is based exclusively on Semantic Scholar, although supplementary test queries were carried out in other databases. Differences in data coverage, document types, and search algorithms may influence the composition of the corpus. Documenting the search string, search date, and selection process increases traceability; however, full reproducibility of the result list cannot be guaranteed.

Second, each identified risk was assigned to one primary CCS stage and one dominant risk category. This classification serves the purpose of structural positioning and does not capture all interdependencies of a risk. The matrix should therefore be understood as an ordering system rather than a complete representation of complex cause-and-effect relationships.

Third, the study does not include an assessment of probabilities of occurrence or magnitudes of damage. Neither the number of literature sources nor the position of a risk within the matrix permits conclusions about its relevance or priority. The risk matrix and risk register serve exclusively to identify, structure, and describe risks.

Finally, cluster formation is based on an interpretive synthesis of literature findings. The causes, impacts, and mitigation measures of a cluster may originate from different sources. Future development could be complemented by second coding, explicit decision rules, and expert validation.

4.2 The systemic nature of CCS risks

The results show that risks in CCS infrastructures arise substantially from the interdependencies between capture, conditioning, transport, and storage. Technical, operational, economic, and regulatory risks therefore rarely occur in isolation but act across several CCS stages.

This becomes particularly evident in the case of storage uncertainties. Limited storage capacities or lower injectivity affect not only storage itself but can also reduce transport capacities, impair the utilization of capture plants, and necessitate additional investments. Similar interdependencies exist for capacity decisions, stream specifications, and investment timing.

The category of systemic risks therefore does not describe a residual group, but rather risks whose causes or impacts affect several infrastructure stages simultaneously. The risk matrix serves their structural classification, while the risk register makes the underlying interdependencies visible.

For planning and risk management, this implies the need for an integrated view of the entire CCS value chain. Infrastructure decisions should not be made on a component-by-component basis but with due consideration of interfaces, expansion pathways, and long-term dependencies. The combination of risk matrix and risk register developed here provides a systematic frame of reference for this, but does not replace a project-specific risk analysis.

4.3 Social acceptance as a research gap

Social acceptance is considered as a separate risk category in the present analysis, but it is covered considerably less well

by the underlying literature base than technical, economic, or regulatory risks. This finding is primarily attributable to the composition of the search corpus and should not be interpreted as an indication of lower practical importance.

The literature analyzed indicates that the perception of CCS projects is not determined by technical safety assessments alone. Transparency, institutional trust, perceived distributional effects, and the involvement of affected stakeholders are equally relevant. Transport routes and storage sites in particular can trigger local conflicts if burdens are spatially concentrated while benefits arise predominantly outside the affected region.

For the further development of the risk register, it therefore appears useful to treat social acceptance more strongly as a cross-cutting issue across the entire CCS value chain. Future work should integrate acceptance, participation, and justice aspects more systematically and examine their interactions with technical and institutional risks.

5 Summary and conclusion

The aim of this working paper was to systematically identify and structure risks along the CCS value chain. Based on 76 full-text publications, risks were assigned to five CCS stages and seven risk categories, condensed into risk clusters, and documented in a risk matrix and a complementary risk register.

The research question can be answered as follows: the combination of the value chain risk matrix and the risk register enables a consistent and traceable structuring of CCS risks. While the matrix allows a systematic positioning of risks by CCS stage and risk category, the register adds information on causes, impacts, and mitigation measures.

The results illustrate that key risk drivers frequently extend beyond individual process stages. Storage uncertainties, capacity deviations, technical interfaces, and coordination requirements in particular create cross-stage dependencies. CCS risks are therefore not solely properties of individual components but arise substantially from the interactions within the infrastructure. The results, consisting of the matrix and the register, are neither a quantitative decision model nor a universally valid risk ranking. They provide a literature-based starting structure for more in-depth analyses.

The contribution of the study lies in integrating heterogeneous literature findings into a common structuring framework. The instruments developed do not replace a project-specific risk assessment, but they provide a transparent basis for identifying relevant risk areas and for further analyses of dependencies and mitigation measures along the CCS value chain.

Further research is needed in particular on the empirical validation of the risk clusters, the modeling of cross-stage interactions, and the more systematic integration of acceptance, participation, and justice aspects.

Research context and funding

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Author contributions

MF: idea generation; conception of the study; writing of the manuscript
SR: conception of the study; writing of the manuscript; further literature work
VB: idea generation; literature search and initial analysis
FS: revision of the manuscript. All authors have read and approved the final version of the manuscript.

Declaration on the use of generative AI

Generative AI tools were used for the linguistic formulation and revision of the manuscript, for structuring and condensing literature content, and for checking terminology, comprehensibility, and consistency. Furthermore, it was used for translations. The literature search made use of, among others, the search platform Semantic Scholar, which integrates AI-supported search, analysis, and recommendation components. The selection of the literature, the risk extraction, the development of the risk concept, the interpretation of the results, and all scientific conclusions were carried out by the author team.

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Table 1: Classification and description of the risk clusters. No complete list of references.

Cluster	Brief description	Source
	Cluster: Technical integrity and performance	
Capture efficiency and plant performance	Scale-up problems, technical data gaps, and insufficient alignment with transport and storage can limit the achievable capture performance.	Middleton, Keating, et al. (2012)
Compression integrity and corrosion	Free water phases, reactive impurities, and unstable operating conditions can cause corrosion, wall thickness loss, and material failure.	Sotoodeh (2026)
Pipeline integrity and corrosion	Moisture, corrosive impurities, and unsuitable materials can gradually impair pipeline integrity. Consequences include wall thickness loss, leaks, and operational interruptions.	Liu et al. (2025)
Reservoir and well integrity	Reservoir pressure, geological uncertainty, and deficiencies in caprock formations or wells can impair safe containment and injection performance.	Bandilla et al. (2017)
Network integrity and technical compatibility	Different technologies, transport modes, and design parameters can lead to incompatible interfaces and inefficient network structures. Compatibility is particularly important for expansions.	Olson et al. (2025)
	Cluster: Operations and monitoring	
Process stability and operational flexibility	Fluctuating source flows and changing operating conditions can impair continuous capture. Limited flexibility at interfaces can cause shutdowns or problems during restart.	Szklarczyk-Marshall et al. (2025)
Operational efficiency and energy demand	Variable CO_2 compositions and additional conditioning requirements can increase energy demand and reduce process efficiency. Shipping and offshore transfers increase operational complexity.	Orchard et al. (2021)
Transport capacity and flow stability	Variable volumes, pressure losses, and storage constraints can reduce the usable transport capacity. An inadequate flow assurance design increases the risk of flow anomalies.	Szklarczyk-Marshall et al. (2025)
Monitoring and anomaly detection	Complex MMV systems, measurement uncertainties, and unfavorable sensor placement can hamper the early detection of leaks or pressure anomalies.	Xu et al. (2024)
Operational coordination and system availability	The CCS stages must be coordinated in terms of volumes, timing, and operating states. Failures or constraints at one stage can limit the availability of the entire value chain.	Emanuelsson (2026)
	Cluster: Environment, health and safety	
CO_2 quality and downstream integrity	Fluctuations in the CO_2 composition and elevated water and impurity contents can promote corrosion and material degradation in downstream components. Stream quality thus influences the safety of the entire CCS chain.	Li et al. (2019)
Impurities and stream quality	Impurities and free water phases can cause acid formation, corrosion, and undesired phase transitions. Inadequate conditioning endangers plant components and downstream processes.	Li et al. (2019)
CO_2 leakage and exposure	Corrosion, material failure, or external impacts can lead to a loss of pipeline integrity and to the release of CO_2. This can result in exposure, safety, and environmental consequences.	Demofonti et al. (2011)
Leakage and induced seismicity	Inadequate geological characterization, pressure build-up, or integrity deficiencies in caprock formations and wells can promote leakage or seismic responses.	Middleton, Keating, et al. (2012)
System integrity and environmental impacts	Differing stream qualities, material requirements, and monitoring standards can reinforce each other across several CCS stages. Local deficiencies can trigger cross-stage losses of integrity and environmental consequences.	Xu et al. (2024)
	Cluster: Economics and investment	
Investment and design	High upfront investments meet uncertain future CO_2 volumes and storage availability. This results in incorrect sizing, underutilization, and the risk of facilities becoming uneconomic in the long term.	Olson et al. (2025)
Energy and operating costs	Compression, drying, and purification entail considerable energy and operating expenditure. Fluctuating stream qualities and demanding purity requirements can further increase this expenditure.	Knoope et al. (2013)

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Table 1 (continued)

Cluster	Brief description	Source
Investment and cost overruns	Uncertain transport volumes, routing decisions, and storage connections complicate investment planning. Incorrect assumptions can lead to higher specific transport costs, subsequent adjustments, and stranded assets.	Chrysostomidis et al. (2009)
Liability and post-closure costs	Uncertainties about Uncertainties regarding storage capacity, injectivity and long-term storage performance may give rise to additional monitoring, post-closure and remediation costs. Unclear arrangements for the transfer of liability further increase financial uncertainty.	Middleton, Keating, et al. (2012)
Network investment and incorrect sizing	Uncertain connected volumes and storage availability complicate the sizing of shared CO_2 networks. Capacities that are too small or too large can trigger bottlenecks, underutilization, and economic misallocation.	Olson et al. (2025)
	Cluster: Regulation, law and governance	
Emission standards and verification	Uncertain standards, fragmented responsibilities, and complex verification requirements can complicate the permitting and regulatory recognition of capture plants.	Dosumu et al. (2024)
Safety standards and permittability	The lack of CO_2-specific safety standards and unclear limit values for water and impurities complicate safety cases and permits. The transferability of existing standards is limited.	Dbouk et al. (2025)
Permitting and regulatory delays	Unclear permitting responsibilities, rights-of-way, and missing rules for network access and tariffs can delay the expansion of CO_2 transport infrastructures.	Nordhaus et al. (2009)
Permitting and long-term liability	Unclear storage rights, permitting pathways, and rules on long-term liability complicate investment decisions. Transfers of responsibility and the allocation of monitoring and remediation obligations are relevant here.	Heffron et al. (2018)
Regulatory fragmentation and governance	Differing rules for network access, tariffs, liability, and carbon accounting can hinder integrated CCS networks. Unclear responsibilities increase coordination and transaction costs.	Nordhaus et al. (2009)
	Cluster: Social acceptance and stakeholders	
Acceptance and trust	Social acceptance depends on whether benefits, costs, and safety conditions are communicated comprehensibly. A lack of participation and insufficient transparency can reduce trust and delay projects.	L'Orange Seigo et al. (2014)
Exposure and safety concerns	High pressures, large CO_2 inventories, and possible releases can raise safety concerns among workers, emergency responders, and the public. These become socially relevant through perceived exposure hazards and loss of trust.	Vianello et al. (2016)
Public opposition and routing conflicts	Routes through populated or agricultural areas can trigger opposition as well as land-use and right-of-way conflicts. Perceived leakage and health hazards increase the potential for conflict.	Vianello et al. (2016)
Local acceptance and siting conflicts	Concerns about leakage and long-term storage safety can lead to local opposition, particularly at onshore sites. Insufficiently communicated monitoring and safety concepts can exacerbate siting conflicts.	A. Brown et al. (2017)
Stakeholder and actor coordination	CCS infrastructures connect emitters, network operators, storage operators, authorities, and other actors. Unclear roles, asymmetric interests, or a lack of data exchange can delay decisions and favor fragmented infrastructures.	Lothe et al. (2025)
	Cluster: System integration and scaling	
Capacity alignment and plant integration	Capture capacities must be aligned in time and volume with transport and storage capacities. A lack of synchronization can lead to curtailment, underutilization, and retrofits.	Middleton, Keating, et al. (2012)
Interface compatibility and stream transfer	Different CO_2 sources generate streams with varying quality and operating parameters. Missing transfer specifications can cause corrosion, capacity losses, and disruptions.	Lothe et al. (2025)
Network expansion and capacity development	Transport network expansion must balance short-term demand and long-term expandability. Undersizing causes bottlenecks; oversizing causes high specific costs.	Olson et al. (2025)
Storage availability and upstream effects	Uncertain storage capacity or lower injectivity can have repercussions on transport and capture. A lack of capacity can force upstream facilities to curtail operation and trigger additional investments.	Middleton, Keating, et al. (2012)

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Table 1 (continued)

Cluster	Brief description	Source
Scalability and overall integration	Scaling up individual projects into shared CCS networks requires compatible interfaces, coordinated expansion pathways, and overarching coordination. A lack of scalability can cause lock-ins and misinvestments.	Middleton, Keating, et al. (2012)

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