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INVITED REVIEW PAPER

Optimal strategy for carbon capture and storage infrastructure: A review

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Abstract−To effectively reduce CO_2, CO_2 mitigation technologies should be employed tactically. This paper focuses on carbon capture and storage (CCS) as the most promising CO_2 reduction technology and investigates how to establish CCS strategy suitably. We confirm a major part of the optimal strategy for CCS infrastructure planning through a literature review according to mathematical optimization criteria associated with facility location models. In particular, the feasibility of large scale CCS infrastructure is evaluated through economic, environmental, and technical assessment. The current state-of-the-art optimization techniques for CCS infrastructure planning are also addressed while taking numerous factors into account. Finally, a list of issues for future research is highlighted.

Key words: Carbon Capture and Storage, Infrastructure Planning, Optimization, Feasibility Evaluation

INTRODUCTION

With increasing concern about climate change arising from greenhouse gas (GHG) emissions, various methods for reduction of GHG emissions to the atmosphere have been presented. Carbon dioxide is the most important GHG, produced primarily by the combustion of fossil fuels as the most abundant energy source [1]. Although CO_2 emissions to the atmosphere can be reduced by using alternative non-carbon energy sources, there are some barriers (the high cost and technical realization of renewable energies, the high efficiency of fossil fuels) for transiting our society away from fossil fuels and into a new alternative energy economy. Carbon capture and storage (CCS) is currently being researched as a promising approach that may help to reduce CO_2 emissions while maintaining the main energy source [2]. The CCS methodology comprises three technologies: CO_2 capture, transportation and storage (Fig. 1) [3]. In principle, CO_2 is first captured, mainly from point sources in the industry and power sector, compressed, transported and then sequestered in deep underground formations.

Commercialization of these CCS technologies requires construction of a macro-scale infrastructure supporting CCS based on answers to the following questions [3]: (i) Which CCS facilities should be used? (ii) Where and how much CO_2 should be captured, stored and transported from which CCS facilities to meet the given CO_2 mitigation target? It is similar to a general facility location problem [4], so we review the literature on the optimal strategy for CCS infrastructure associated with mathematical optimization criteria within facility location research. The criteria can be divided into three parts: economic, environmental, and technical assessment [5,6]. The economic assessment methodology essentially assesses the costs or benefits of facilities over an investment term while meeting the decision maker's goals to select the best facilities. The environmental assessment is a study required to establish all the impacts, either positive or negative, about one facility, which consists of the natural, social and economic impact of the facility. The technical assessment is the process of analyzing the impacts of exposure to loss arising from activities such as defects of design and engineering, operator errors in manufacturing, and equipment failure caused by environmental disasters.

Past research efforts were directed toward analyzing individual sub-processes (e.g., capture, storage, and transport) of technologies within the CCS infrastructure [7-9], while recent attention has increasingly focused on the optimal design and operation of the CCS infrastructure as a whole [3,10]. Thus, it is a grand attempt to find the direction of future research from a review of the current state-of-the-art optimization techniques for CCS infrastructure planning. Moreover, the feasibility of large scale CCS infrastructure has not been evaluated considering the viability of the comprehensive and systematic methodologies.

Therefore, the purpose of this paper is to review such comprehensive and systematic methodologies for feasibility assessment of CCS infrastructure and to support decision makers to determine better strategies to select optimal CCS infrastructure.

The paper is organized as follows: Section 2 focuses on the techno-economic assessment of CCS infrastructure. Section 3 is devoted to providing some insight into the environmental effects of CCS infrastructure. Section 4 reviews optimization methods for analyzing the technical risks or assessing their performance related to the CCS infrastructure. Finally, some critical conclusions and possible directions for future research are highlighted.

TECHNO-ECONOMIC ASSESSMENT

Techno-economic assessment (TEA) in principle is a cost-benefit comparison using different methods such as static cost benefit assessment, annuity method, net cash flow table, net present value, and internal rate of return [11]. The TEA for optimal strategy of CCS infrastructure is typically based on net present value (NPV), which is calculated by discounting expected future cash flows by the discount rate and by summing over the project period [12]:

$$\mathrm{NPV}=\sum_{1}^{N}\frac{\mathrm{NCF}}{(1+\mathrm{d})^{n}} \tag{1}$$

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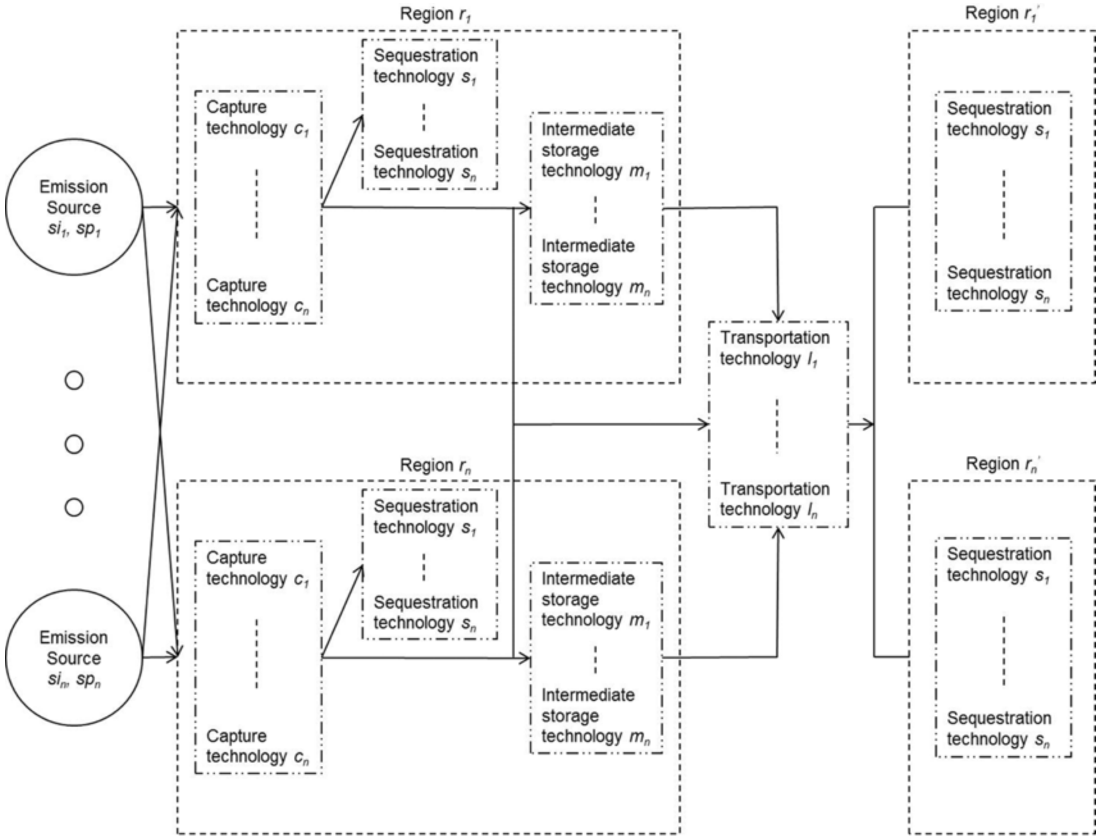

Fig. 1. Schematic diagram of CO_2 infrastructure [3].

Table 1. Various projects and studies using NPV

Article	Cost	Benefit	Profit[a]
[13]	○		
[14]	○		
[15]	○		
[16]	○		
[17]	○		
[18]	○		
[19]	○		
[32]	○		
[33]	○		
[20]	○	○	
[21]	○	○	
[22]	○		
[23]	○	○	
[3]	○	○	○
[7]	○		
[24]	○	○	
[25]	○	○	
[26]	○	○	
[27]	○	○	○
[28]	○	○	○
[29]	○		
[30]	○	○	○
[31]	○	○	○

[a]Profit=benefit−cost

where NCF is net cash flow and calculated as all benefits received minus costs paid for every year of the project period n starting with the project development until the end of technical lifetime; d is the discount rate over the project period.

The NPV is especially useful for predicting how much the project will increase the investor's property over the whole project period in today's money value. For example, if the NPV is positive, a project should be undertaken; otherwise the project is not to be realized since a negative NPV means the investor's property will be decreased. Therefore, NPV should be at least zero. This approach has been used in various projects and studies (Table 1) [3,7,13-33].

Most of the various projects and studies using NPV contain the objective function of minimizing cost [3,7,13-33] or maximizing benefit [3,20,21,23-28,30,31]. There are, however, relatively few projects and studies considering the objective function of maximizing profit, which is calculated as the difference between cost generated and benefit obtained in the process. In general, when we create an advantage in trading, we make sure that our gains are much larger than our losses. It implies that well-planned profit objectives are the best way to provide a relatively low-cost way to provide a much larger benefit. Thus, it is more desirable to maximize the profit of CCS infrastructure including the value added of the utilization of CCS such as acquisition of carbon credit from CO_2 reduction and product sale (e.g., biofuel or 'green' polymer) made from CO_2.

TEA of CCS infrastructure can also be performed using more advanced methodologies and decision criteria than the static NPV approach. The matrix in Table 2 illustrates sixteen different valuation models, with regards to their treatment of uncertainty, deci-

Table 2. Techno-economic assessment matrix

	Decision		Uncertainty		Variable		Constraint		Model type
	Static	Dynamic	Deterministic	Stochastic	Discrete	Continuous	Linear	Nonlinear	
1	✓		✓		✓		✓		StaticDeterministic ILP
2	✓		✓		✓			✓	StaticDeterministic INLP
3	✓		✓			✓	✓		StaticDeterministic LP
4	✓		✓			✓		✓	StaticDeterministic NLP
5	✓			✓	✓		✓		Static StochasticILP
6	✓			✓	✓			✓	Static Stochastic INLP
7	✓			✓		✓	✓		Static StochasticLP
8	✓			✓		✓		✓	Static StochasticNLP
9		✓	✓		✓		✓		Dynamic Deterministic ILP
10		✓	✓		✓			✓	Dynamic Deterministic INLP
11		✓	✓			✓	✓		Dynamic Deterministic LP
12		✓	✓			✓		✓	Dynamic Deterministic NLP
13		✓		✓	✓		✓		Dynamic StochasticILP
14		✓		✓	✓			✓	Dynamic Stochastic INLP
15		✓		✓		✓	✓		Dynamic StochasticLP
16		✓		✓		✓		✓	Dynamic StochasticNLP

Table 3. Classification of techno-economic assessment research

	Deterministic		Stochastic	
	Static	Dynamic	Static	Dynamic
LP	[3,14,19-23,27,91]	[13,16-18,30,32,33]	[7,15,28,29,31]	[24-26]
ILP	[3,19-23,27,92]	[13,30]	[7,28,29,31]	[25]

sions, constraints and variables.

For example, the 15th model, dynamic stochastic LP, includes the time-variant structure, uncertainty, and continuous and linear variables. It is possible to find the valuation model to match detailed strategic CCS planning in Table 2, with regard to the these properties. Table 3 also shows TEA studies classified by valuation model types.

In fact, the literature has dealt with deterministic models more than stochastic models considering the uncertainty. Static models, not considering the evolution of design and operation of CCS infrastructure over time, have been used in more projects and studies than dynamic models. In the static model a time-invariant CO_2 reduction target is assumed, but the CCS infrastructure design can be adapted to target variation by introducing capacity expansions. The CCS infrastructure design should cover a fixed time horizon divided in several periods of time accounting for CO_2 emission and reduction target variations. Moreover, few nonlinear problems were studied in the CCS infrastructure model.

Meanwhile, uncertainty including the variance of operational decisions is one of the most important decision-making problems in the CCS infrastructure planning because the information of cost and benefit in the future is not sufficient and clear; thus these data can

Table 4. Types of uncertainty for stochastic model

Uncertainty	Article
CO_2 emission	[24,28,29]
Carbon tax	[24-26]
Operating cost	[24,25,31]
Price	[31]

Table 5. Compilation of CCS cost estimates for different case studies on large scale CCS infrastructure

Location	CO_2 capacity	Estimated costs	Comments
United States - California [19]	1,752 Kt/yr	Capture costs: 44.17 $/tCO_2$ Storage costs: 3.60 $/tCO_2$	37 Sources (22 power plants, 10 oil refineries, and 5 cement manufacturers) 14 Sinks (depleted oil fields).
Europe - Nederland [34]	74 Mt/yr	Transport costs: 3.69€/tCO_2 Storage costs: 1.89€/tCO_2	40 Sources (24 power plants, 16 industrial plants) 171 Sinks (35 aquifers, 5 oilfields, 131 gasfields)
Korea - East coast [3]	1,850 Kt/yr	Capture costs: 38.75 $/tCO_2$ Transport costs: 3.84 $/tCO_2$ Storage costs: 7.67 $/tCO_2$	20 Sources (8 power plants, 5 steel plants, 5 oil refineries, and 2 petrochemical plants) 3 Sinks (2 depleted oil fields, 1 saline aquifer).

affect operational decisions. In particular, stochastic models considering the uncertainty (e.g., CO_2 emission, carbon tax, operating cost and price) can be seen in Table 4 [24-26,28,29,31].

There are techno-economic assessments of CCS costs for the United States [19], Europe [34] and Korea [3] (Table 5). These based on representative geological characteristics for the regions show a fairly wide range of cost estimates. It is due primarily to especially the design, operating and financing characteristics of the CO_2 emission sources in which CO_2 capture facilities are used; the required distances and quantities involved in CO_2 transport; and the type and characteristics of the CO_2 storage. In addition, precise cost estimates of future CCS technology components are rarely so; thus uncertainty still remains about the cost estimates of integrated CCS systems.

From the above remarks, we can identify the direction of future projects and research for the CCS infrastructure. The dynamic stochastic model should be studied considering both time and uncertainty simultaneously. Since the insights obtained in the numerical analysis might change according to the input data [35], the model introduced is general enough to be adapted to any particular situation. One of its main values is the inclusion of all possible technologies available at the moment for CCS infrastructure planning into a single mathematical model that is able to evaluate all their possible combinations, considering several periods of time and in the face of uncertainties.

The dynamic stochastic model for the optimal CCS infrastructure can be formulated as follows:

$$NPV_{t,s} = benefit_{t,s} - cost_{t,s} \quad \forall t,s \tag{2}$$

As described previously, NPV can be calculated from the difference of benefit and cost, but variables of time t and uncertain scenarios *s* are specially added in the model.

Thus, the average NPV over total time t and scenario r can be calculated by multiplying NPV(t, s) at each time and scenario by the probability of occurrence:

$$\begin{aligned} &\text{Max} \ \sum_{t,s} prob_s \times NPV_{t,s} \\ &\text{s.t.} \\ &\text{Overall mass balance constraints} \\ &\text{Capacity constratints} \\ &\vdots \end{aligned} \tag{3}$$

where $prob_s$ is the probability of occurrence of the uncertain scenario.

The major advantage of this approach is that the decision-maker can gain more valuable insights into planning the investment strategy for CCS infrastructure in the uncertain environment.

ENVIRONMENTAL ASSESSMENT

Although CCS systems are used to prevent global warming, they have problems of significantly high energy usage and emissions of other pollutants. To evaluate these environmental problems of CCS infrastructure, life cycle assessment (LCA), which is a holistic approach, has been used generally. LCA investigates the overall environmental impacts over the whole life cycle of products, processes or systems [36]. In 1990, the specific principles and guidelines of LCA were defined and developed by the Society for Environmental Toxicology and Chemistry (SETAC) [37,38] and the International Organization for Standardization (ISO) [39]. According to them, the methodological framework for conducting LCA is classified into four steps: goal and scope, inventory analysis, impact assessment, and interpretation (Fig. 2) [37].

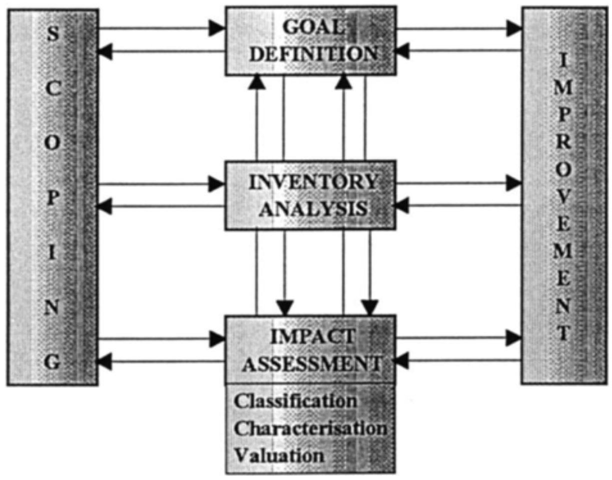

Fig. 2. Interactions between LCA stages [37].

In principal, system boundary and functional unit are first defined in goal and scope definition step. Next, material and energy balances of the system are analyzed, and the life cycle inventories are quantified in the inventory analysis step. After that, within the impact assessment step, the overall environmental impacts are calculated in several impact scores or aggregated into a single score by weighting their relative importance. Finally, the interpretation step attempts to identify improvements or innovations through performing sensitivity analysis.

Heijungs and Sun [40] and Spriensma [41] suggested a method of calculating and aggregating LCA results of different impact categories into a single score. This method provides the opportunity to optimize total environmental impacts of CCS infrastructure. In fact, several studies have performed optimization of LCA score in other fields such as hydrogen networks, process design and supply networks [39,42-44]. The measure of environmental impact score of CCS infrastructure is performed through the mathematical process below. The values of impact indicators $I_{x,n}$, damage indicators D_n, and the final score of LCA (Lscore) can be calculated as follows [40].

$$I_{x,n} = \sum_b v_{b,n,x} \omega_b M \quad \forall n,x \tag{4}$$

$$D_n = \eta_n \sum_x I_{n,x} \quad \forall n \tag{5}$$

$$Lscore = \Sigma_n \vartheta_n D_n \tag{6}$$

where (i) $b \in B$ is the set of the life cycle inventory; (ii) $v_{b,n,x}$ is the damage factor that life cycle inventory b contribute to impact category x of damage category n; (iii) ω_b is the entry of emissions inventory b per 1 unit of CO_2 flow of CCS network; and (iv) M is the amount of CO_2 flow required for CCS network (e.g., ton of CO_2 captured, load and distance of substances transported); and (v) η_n is the normalization factor of damage category n; and (vi) ϑ_n is the weighting factor of damage category n. Damage factor $v_{b,n,x}$, nor-

Table 6. LCA research with system boundary criteria for CCS infrastructure

Study/year	Fuel						Capture routes			Transport		Storage				
	PC	C	LG	NG	BM	SG	PoC	PrC	Oxy	Pp	SH	GE	ER	A	O	Oth
[45]/1995	O			O		O	O	O				O			O	O
[46]/1995				O		O	O	O		O	O	O			O	
[64]/1996	O	O		O			O	O		O	O	O			O	
[66]/2001													O			
[48]/2002		O					O									
[49]/2003				O		O	O	O	O							
[50]/2004		O			O		O									
[51]/2004		O		O	O		O			O		O		O	O	
[52]/2005		O			O		O	O								
[67]/2005													O			
[54]/2006	O						O						O		O	
[53]/2006		O											O			
[8]/2006							O	O								
[55]/2007	O	O		O			O	O		O						
[56]/2007	O		O	O		O	O	O	O	O		O				
[65]/2007										O		O		O		
[57]/2008				O			O	O					O			
[58]/2008	O						O			O						O
[59]/2008	O	O		O			O	O								
[60]/2009			O				O	O	O	O		O				
[61]/2010	O						O									
[62]/2010	O	O		O			O	O	O	O						
[63]/2011				O			O									

PC: pulverized coal, C: coal, L: lignite, NG: natural gas, BM: biomass, SG: syngas, PoC: post combustion, PrC: pre combustion, Oxy: oxy-fuel combustion, Pp: pipeline, SH: ship, GE: geological, ER: enhanced recovery, A: aquifier, O: ocean, Oth: others

malization factor η_n, weighting factor ϑ_n are obtained from several LCA methodology reports or LCA databases such as Eco-indicator 99, CML, Eco-invent and so on.

In the past decades, many studies of LCA for CCS infrastructure have provided life cycle inventory data and environmental impact results. Specifically, most of the studies have focused on the analysis of the CCS system with various types of power plants, which are the most significant CO_2 emission source.

The LCA research is classified in three main categories: LCA system boundary, scope and outcome (Tables 6 and 7). There is a major difference in LCA, caused by different fuel types, routes of capture technologies. The major difference caused by fuel types is the pollution substances which are emitted to air, water and soil. For example, SOx is not emitted from natural gas combined cycle (NGCC) power plants, but pulverized-coal power plants. Also, the capture routes determine the type of capture facilities and the pollution material. For example, NH_3 is emitted from MEA capture facilities, which are used in post-combustion power plant. On the other hand, NH_3 is not emitted from Selexol capture facilities, which are used in pre-combustion power plants.

- LCA System boundary
  - Fuel types of power plants [45-64]
  - CO_2 capture routes [8,45-53,55-63]
  - CO_2 transportation means [46,51,55,56,58,60,62,64,65]
  - CO_2 storage methods [45,46,51,53,54,56-58,60,64-67]
- LCA Scope
  - Material and energy balances [45,46,48,51,52,57,64]
  - Foreground LCA [8,48,56,57,61,62,66]
  - Full LCA [49,50,52-55,58-60,63-65]
- LCA Outcome
  - CO_2, energy and other emissions [8,45-67]
  - GWP (Global Warming Potential) and other impacts [8,45-67]
  - Normalization and aggregation [50,52-54]
  - Uncertainty [8,48,57,58,60,62]
  - Multi analysis [8,45,48,49,51,63,67]

The first different sub-criterion of LCA studies is the fuel type of power plants. Coal and natural gas power plants are considered in 19 studies emphasizing that CO_2 capture is most needed for these fuel types [45-64]. Only three studies considered the biomass fuel in coal power plants [50-52].

The routes of capture technologies also constitute a major differentiation criterion. Mono-ethanolamine (MEA) scrubbing or Selexol capture facilities have been chosen as the main CO_2 capture facilities in every study. These capture facilities with post and pre-combustion technologies are most frequently investigated [8,45-53,55-63], and the oxy-fuel route is described in only four studies [49,56,60,62].

Several LCA studies [46,47,51,55,56,58,60,62,65] have considered the transportation means and storage methods of CO_2. LCA of ships has been studied in only two articles [46,47], while pipelines, which are regarded as the best candidate for transportation because of cost [2], have been more studied. In storage category, the geological, enhanced recovery and ocean sequestration technologies were considered as main storage means for LCA study

Table 7. LCA research with scope and outcome criteria for CCS infrastructure

Study/year	Scope			Outcomes							
	MEB	FG	F	GWP(CO_2)	Energy	Other emission	Normal. step	Other impacts	Aggregation	Uncertainty	Multi comparison
[45]/1995	O			O		O					O (cost)
[46]/1995	O			O	O						
[64]/1996	O		O	O	O	O					
[66]/2001		O		O		O					
[48]/2002	O	O		O		O				O	O (cost)
[49]/2003			O	O		O					O (exergy)
[50]/2004			O	O		O		O	O		
[51]/2004	O			O	O						O (cost)
[52]/2005	O		O	O		O	O	O	O		
[67]/2005				O							O (cost)
[54]/2006			O	O	O	O	O	O	O		
[53]/2006			O	O		O	O	O	O		
[8]/2006		O		O		O				O	O (cost)
[55]/2007			O	O	O	O					
[56]/2007		O		O	O	O					
[65]/2007			O	O	O	O		O			
[57]/2008	O	O		O		O		O		O	
[58]/2008			O	O	O	O		O		O	
[59]/2008			O	O	O	O					
[60]/2009			O	O	O	O		O		O	
[61]/2010		O		O		O		O			
[62]/2010		O		O	O	O		O		O	
[63]/2011			O	O	O						O (cost)

MEB: material and energy balance, FG: foreground LCA, F: full LCA

[8,45-47,51,53,54,56,57,60,65-67].

The LCA scope of CCS systems has been extended in recent years. At the beginning of the scope of the study, an inventory analysis (denoted as background LCA) of simple material and energy balances related to CO_2 emission was performed. However, it has been changed to foreground LCA or complex full LCA recently. The foreground LCA means an inventory analysis to collect the specified data related to manufacturing, use, and final disposal of a targeted product, while the full LCA includes the foreground and background inventory analysis [39]. The crucial different environmental results obtained via complex full LCA involve the environmental impact of not only material and energy balance, but also construction of CCS facilities. For example, steel, sand, alumina and land are used in construction of CCS facilities, but they are not involved in typical LCA, which considers material and energy balance. With this tendency, more various environmental results have been provided such as other emissions, other impact values, normalized and aggregated impacts, and so on.

The LCA methodology has a critical limitation for the study of CCS infrastructure planning. The LCA data is imperfect because of its uncertainties coming from the lack of experience of LCA studies [58]. Some LCA research mentioned about the uncertainty and provided parameters (e.g., the effect of emission substances, spatial and temporal dependency and damage factors) considering this [48, 54,57,58,60,62].

Therefore, a decision maker can consider the dynamic stochastic LCA model, which aims at minimizing average environmental impacts over total time and scenario:

$$\min \sum_{t,s} \text{prob}_s \text{Lscore}_{t,s} \tag{7}$$

This strategy gives the decision maker the most eco-friendly CCS infrastructure. However, the eco-friendly strategy of CCS system should lie within a certain range because an extreme eco-friendly strategy can have significant trade-offs with the extreme economic one. Thus, a combined optimization strategy for CCS infrastructure can support economically and environmentally balanced decisions.

$$\begin{aligned} &\text{Max} \ \sum_{t,s} \text{prob}_s \times \text{NPV}_{t,s} \\ &\text{s.t.} \\ &\text{Lscore}_{low} \le \text{Lscore}_{t,s} \le \text{Lscore}_{upp} \quad \forall t, s \\ &\text{Overall mass balance constraints} \\ &\text{Capacity constratints} \\ &\vdots \end{aligned} \tag{8}$$

where Lscore_{low} and Lscore_{upp} are the lower and upper bound of Lscore considering the CCS system environmentally, respectively.

TECHNICAL RISK ASSESSMENT

The technical risk assessment (TRA) is a comprehensive, systematic process that assists decision makers in identifying, analyzing, evaluating, and treating all types of risks to health, safety and environment [68]. The TRA is aimed at identifying significant risks and taking an appropriate action to manage these risks. The method of TRA comprises five steps: the analysis, evaluation, treatment, acceptance and communication of risks as follows [69].

- Risk Analysis
  - Risk Source Identification: the recognition of a hazard (What can go wrong?).
  - Risk Estimation: The measurement of the potential threat (How great are the consequences and how often do they occur?).
- Risk Evaluation
  - The meaning attributed to the measurement of threat potential (How important is the estimated risk?).
- Risk Treatment
  - How may we improve the conditions and reduce the risk?
- Risk Acceptance
  - How large an investment must be made and how large are the benefits that will result from the improvement?
- Risk Communication
  - What actions should be activated?

A measure of risk can be a two-dimensional concept involving the possibility of occurrence of an adverse event and the consequence of the occurrence of the adverse event (Fig. 3) [70]. Risk is often defined as a product of possibility and consequence and could be qualitative as well as quantitative. The qualitative risk assessment can calculate relative values of risks, but not allow the security measures to be implemented. However, the quantitative risk assessment can allow their design; thus, this will assign expected losses and cost of risk controls.

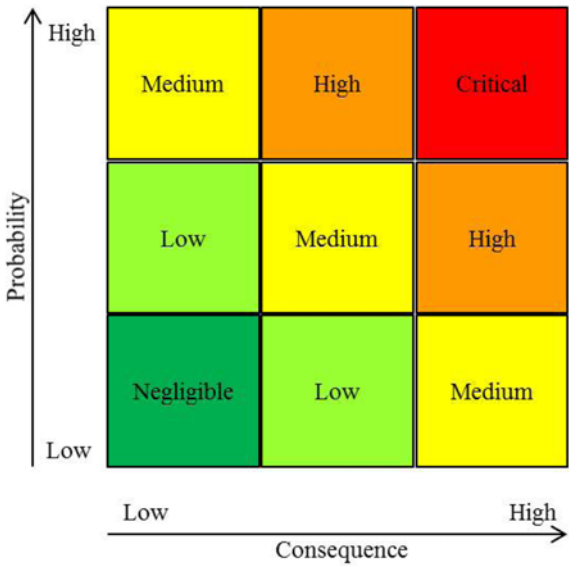

Fig. 3. Risk matrix, based on rankings [70].

Table 8. Risk categories and their impacts for CCS infrastructure

Technology	Risk categories		Risk impacts (annual expected fatalities per activity unit)
	Global	Local	
Capture	• Impurities (NOx, SOx, HCl, HF, etc.) emissions in flue gas with the CO_2 capture process [61,72,73]	• The direct emission of CO_2 by leakage [72] • The direct emission of MEA by leakage [77] • The emission of VOC and NH_3 due to the degradation of the alkanolamine-based solvents [73] • Boiling liquid expanding vapor explosion (BLEVE) when a vessel containing pressurized CO_2 is ruptured or overheated [78-80]	3-14 per 10^5 workers [78-80,93]
Transport	• A failure is caused by third party interference, corrosion, construction or material defects (e.g. welds), ground movement or operator errors		US CO_2 pipelines: 4.0-24 per Mkm [81-84,93]
	• The release of CO_2 due to leakage from pipeline failures [74]	• The leakage from pipeline rupture or puncture (hazards to humans and wildlife), especially in low-lying areas [81-84] • Ships (tankers) and terminals: accidental release through collision [85,86]	US CO_2 ships: 11.4-28.6 Tt^{-1} Nm^{-1} [85,86,93]
Storage	• The leakage by vertical transport into the atmosphere [75,76]	• The leakage by vertical or lateral transport into aquatic ecosystems or underground drinking-water reservoirs [76,87,88] • Local effects (e.g., elevated concentrations in near-surface environment) [89,90]	15-33 per 10^5 workers [76,87,88,93]

Risks associated with CCS are broadly divided into two risk impact categories: local and global risks [71]. Global impacts arise from CO_2 leakage and thereby reduce the effectiveness of CO_2 mitigation, while on a local scale there are several ways captured, stored or transported CO_2 may pose a hazard to health, safety and environment as follows:

- Global
  - Release of CO_2 to the atmosphere [61,72-76]
- Local
  - Atmospheric CO_2 exceeds critical value over time (suffocation of humans or animals above ground, etc.) [73,77-80]
  - CO_2 exceeds critical value over time in soils and aqueous systems (mobilization of metals or other contaminants, contamination of potable water, etc.) [76,81-90]

Table 8 shows the examples of hazards for CCS infrastructure and their consequences. For capture, one important hazard is leakage of amines, while for both transport and storage one important hazard is leakage which can lead to loss of life or environmental damage. For each hazard component, a qualitative assessment of the frequencies and consequences is to be performed, and then the result from this risk analysis will be in the form of the expected monetary loss. When the risks on the monetary scale are identified, they will need to be assessed with regards to what is acceptable risk. This implies an optimal strategy of TRA for CCS infrastructure. In other words, the optimal strategy can be considered with the following decisions: 1) how to select major risks and, 2) how to consider the risk control options for risk reduction while meeting a certain level of risk mitigation. However, the optimal strategy of TRA is still imperfect because of its uncertainties coming from the insufficient practice of TRA studies.

Therefore, a decision maker can consider the dynamic stochastic TRA model, which aims at minimizing average expected loss over total time and scenario:

$$\min \sum_{t,s} \text{prob}_s \text{Loss}_{t,s} \tag{9}$$

where $\text{Loss}_{t,s}$ is the expected loss at each time and scenario.

This strategy gives the decision maker the safest CCS infrastructure, and can also assist in comparing the economic aspect with the safety one. Thus, a combined optimization strategy for CCS infrastructure can support decisions that balance economics and safety.

$$\begin{aligned} &\text{Max } \sum_{t,s} \text{prob}_s \times \text{NPV}_{t,s} \\ &\text{s.t.} \\ &\text{Loss}_{low} \leq \text{Loss}_{t,s} \leq \text{Loss}_{upp} \quad \forall t, s \\ &\text{Overall mass balance constraints} \\ &\text{Capacity constratints} \\ &\vdots \end{aligned} \tag{10}$$

where Loss_{low} and Loss_{upp} are the lower and upper bound (e.g., regulations, insurance fess) of Loss considering safety of the CCS system, respectively.

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

In this paper we have reviewed the most recent literature on a comprehensive and analytical optimization framework (i.e., economic, environmental, technical risk assessment) for the strategic planning of CCS infrastructure. This should provide decision makers with high quality and timely information on the optimal strategy for CCS infrastructure.

The results of the literature review will point towards possibilities for a combined optimization strategy for CCS infrastructure that can support economically, environmentally and safely balanced decisions. That is why the extreme eco-friendly strategy or the other safe one can have significant trade-offs with the extreme economic one. Thus, each strategy of CCS system should lie within a certain range and then a comparative analysis of the results is drawn from the study.

As can be easily seen from the various tables and figures throughout the review, many research directions still require intensive research. The literature considering uncertainty and dynamic decisions in CCS infrastructure planning with various assessment methods is still scarce. In particular, very few papers address uncertain parameters within the environmental and technical assessment methods. In an environment with a high level of uncertainty, especially with regards to future technology market, policy and regulations, it is also important to incorporate the strategic changes of CCS infrastructure under the uncertain circumstances. Thus, we need to develop an optimization model with altering conditions (e.g., change in carbon credit prices, emissions regulations or safety requirements) needed for CCS infrastructure planning.

Another focus is the comparative analysis between all assessment methods in the optimal strategy for CCS infrastructure. Multi-perspective CCS chain assessment requires a multi-objective model (e.g., the weighted-sum method or the ε-constraint method) to analyze the performance of a CCS infrastructure. Three main perspectives are selected, and the developed CCS chain assessment methodology reflecting them calculates the comprehensive performance of a CCS infrastructure by summing the economic, environmental or technical impacts.

We can identify the role of this research area is decisive, but future research must include many issues that so far have not received adequate attention. Therefore, new optimization models must be developed for assessing and comparing different CCS infrastructure designs.

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