ECOS 2026: Using the waste management hierarchy for the evaluation of CO_2 management pathways: a resource- and footprint-oriented scenario analysis

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Abstract:

This study develops a Carbon Capture and Storage (CCS)-specific assessment framework for CO_2 management through a comparative governance analysis of waste and CO_2 management. The EU waste hierarchy is used as an initial reference point within this broader comparison but is not transferred as a normative ordering principle for CO_2 management. Cross-domain analytical dimensions are translated into five core key performance indicators (KPIs) under harmonised system boundaries for 2030 and 2050: (1) specific energy requirement, (2) CO_2 avoidance efficiency, (3) CO_2 transport logistics, (4) monitoring, reporting and verification (MRV), together with long-term regulatory obligations, and (5) levelized cost of CO_2 management (LCOM). Benchmark post-combustion monoethanolamine (MEA) cases indicate total capture-and-compression requirements of 3.21–4.08 GJ/tCO_2. CO_2 avoidance efficiency varies from 65 to 93% in 2030 and from 68 to 99% in 2050, depending mainly on the heat supply configuration. The coal boiler case shows the lowest CO_2-avoidance efficiency, whereas the high-temperature heat pump (HTHP) case achieves the strongest improvement. LCOM ranges from 44.0 to 118.4 €/tCO_2 stored across the selected case configurations, with the onshore natural gas combined cycle (NGCC) single plant-single sink case appearing the most economically constrained within this comparison. The 2030 results are driven mainly by infrastructure availability, offshore storage access, permitting conditions, and MRV obligations. By contrast, the 2050 results for CCS reflect the assumed system maturation, infrastructure scale-up, and lower-carbon energy supply. Overall, CCS assessment does not follow a fixed hierarchical ranking but depends on the technical, infrastructural, and regulatory conditions under which CCS is implemented and evaluated.

Keywords:

Carbon Capture and Storage; CO_2 Management; Comparative Governance Analysis; KPI Framework; Waste Hierarchy.

1. Introduction

In the European Union, waste is regulated through a legally defined hierarchy that guides priority setting in prevention and management decisions [1]. Prevention has the highest priority, followed by reuse, recycling, recovery, and finally, controlled disposal to protect public health and environmental quality [2]. By contrast, CO_2 is primarily addressed through emission reduction, abatement, and climate-mitigation strategies within industrial decarbonisation and carbon management frameworks [3-4]. In these frameworks, CCS is treated as a mitigation and carbon-management option among broader decarbonisation measures. CCS is particularly relevant in sectors with process-related emissions, where full abatement through electrification or fuel switching is limited [3-4]. Therefore, this study differentiates between two analytical perspectives on CO_2: CO_2 as an emission to be reduced, and CO_2 as a residual carbon stream that may require management [5] under defined technical, infrastructural, monitoring, and regulatory conditions [6].

Existing studies on CO_2 and carbon management can be grouped into four categories. First, synthesis and pathway studies examine the role of CCS within sectoral mitigation and industrial decarbonisation pathways [3]. Second, technical and techno-economic studies analyse capture performance, retrofit conditions, energy requirements and cost implications [7], along with plant-specific integration [8] and the role of transport and storage costs in decarbonisation pathways [9]. Third, studies on CO_2 utilisation examine pathway-specific product categories and show that deployment is constrained by market size, regulation, and energy-system conditions [10]. Fourth, policy-oriented prioritisation studies rank CCS applications according to defined criteria. For example, the E3G CCS Ladder [11] evaluates applications for 2030 and 2050 in terms of competition from alternatives, mitigation potential, feasibility, and CO_2 source characteristics.

A smaller body of literature directly addresses governance analogies. Buck [5] considers whether carbon removal can be understood from a waste-management perspective and uses the historical evolution of solid and liquid waste governance to reflect on how a future regime for gaseous carbon management might develop. Rossati [12] compares the regulatory regime for geological CO_2 storage with radioactive waste management, with an emphasis on long-term containment and stewardship. These studies show that cross-domain analogies are analytically viable in governance research. However, they do not develop a structured set of analytical categories for CO_2 management based on a systematic comparison with waste governance.

The present study addresses this gap by using the EU waste hierarchy [1] as a comparative starting point within a broader governance perspective on waste and CO_2 management. The waste perspective is used heuristically to derive a set of analytical categories that can be examined across domains rather than transferred as a normative ordering principle for CO_2 management. This comparison is analytically relevant because both domains concern the management of residual streams [5]. Taken together, the reviewed sources indicate that both waste and CO_2 management involve decisions on handling [1,5] and responsibility allocation [5-6], while CO_2 management additionally requires decisions on monitoring and containment under storage-specific regulatory conditions [6]. At the same time, the two domains differ in management logic [1,5], permanence [5-6], and use pathways [10].

This paper develops and applies a CCS-specific KPI framework derived from a comparative governance analysis of waste and CO_2 management to assess whether, and under which conditions, CCS can function as a management route for residual CO_2 streams in 2030 and 2050 scenarios.

2. Methodology

The four-step methodological framework is illustrated in Figure 1.

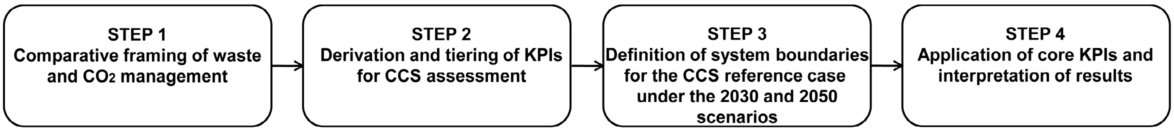

Figure 1. Four-step assessment framework.

The procedure consists of comparative framing of waste and CO_2 management, KPI tiering, definition of system boundaries, and application of core KPIs to the CCS reference case under the 2030 and 2050 scenarios. It translates the analytical dimensions identified in the cross-domain comparison into a CCS-specific assessment structure across technical, infrastructural, regulatory, and economic dimensions.

2.1. Step 1: Comparative framing of waste and CO_2 management

Step 1 uses the EU waste hierarchy as a conceptual entry point for the comparison (Figure 2) [1].

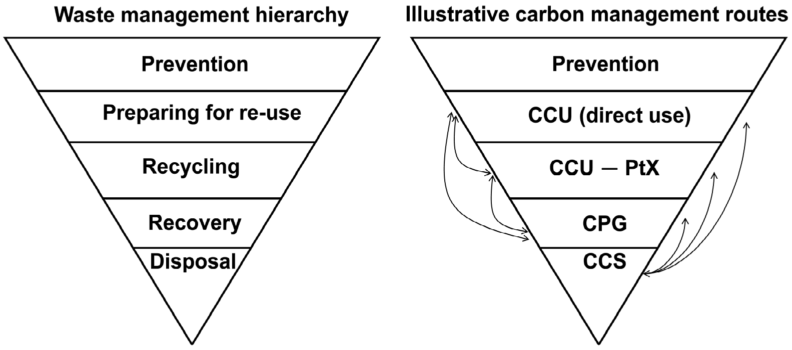

Figure 2. Waste hierarchy as a conceptual point of entry and functional comparison with CO_2 management routes. Left: waste hierarchy based on Directive 2008/98/EC, Art. 4 [1]. Right: author-developed illustrative scheme of functional analogies for CO_2 management routes. Arrows indicate that route prioritisation is conditional and may vary across contexts and time horizons (2030 and 2050 scenarios).

At a functional level, limited analogies can be drawn between waste-management routes and carbon-management options. Geological CO_2 storage is the closest analogue to disposal in terms of long-term containment. Power-to-X (PtX) and other utilisation routes may perform recovery-like functions in a limited sense. CO_2 plume geothermal (CPG) can be understood as a hybrid route combining CO_2 storage with energy use. However, these analogies remain partial. Step 1 therefore extends the comparison to broader cross-domain analytical dimensions that structure the subsequent KPI framework. These dimensions include stream characteristics, hierarchy and handling logic, infrastructure and transport requirements, temporality and reversibility, regulatory structure, and cost implications (Table 1).

The comparison is used to identify comparable governance functions and key differences in management logic, without assuming equivalence between waste and CO_2 streams. Where regulatory and infrastructural dimensions require illustration, the comparison draws in part on CCS, since long-term storage, monitoring, and transfer of responsibility are regulated under the CCS Directive [6].

Table 1. Comparative analytical dimensions of waste and CO_2 management.

Group	Category	Comparable functions	Key difference
Technical and substance-based characteristics	Substance-specific characteristics	In both domains, residual streams require specific handling and treatment routes that depend on their characteristics [13-14].	Waste management includes material- and product-related waste streams with varying characteristics and treatment requirements [13]. CO_2 transport and storage systems manage a pressure- and temperature-sensitive stream whose phase behavior, impurities, and corrosion effects directly influence transport and storage performance [7,14].
	Energy-use logic	In both domains, some management routes have an energy-related dimension [1,10].	Waste management includes energy-recovery routes [1]. CO_2 is non-flammable [15] and cannot serve as a direct fuel. Pathways producing CO_2-derived fuels require substantial external energy input [10].
	Stream management logic	In both domains, residual streams can be managed through specific routes [1,3].	Waste management follows a legally codified priority order, where disposal (landfilling) is a last-resort option and should be minimised [1,16]. CO_2 management has no directly equivalent hierarchy. Geological storage is functionally comparable to disposal. It is regulated as a long-term containment route for residual CO_2 streams [6], while CCS is framed primarily as an option to reduce emissions from large-scale energy and industrial sources [3].
	Transport and infrastructure logic	Both domains require organised transport and infrastructure [1,14].	Waste transport can largely rely on existing transport infrastructure and longer distances may be economically preferable to undersizing treatment facilities [17]. CO_2 transport commonly relies on dedicated chains (e.g., pipelines) operated under controlled conditions to manage phase behaviour and avoid two-phase flow [14].
Governance & regulatory design	Temporality and permanence	Both domains include long-term management routes that require containment and follow-up control beyond the operational phase [6,17].	Landfills provide long-term engineered containment and can become a potential resource stock via landfill mining [17]. Geological CO_2 storage is regulated as long-term containment with post-closure monitoring obligations and "complete and permanent containment" [6]. Non-storage CO_2 routes differ in their carbon-retention profiles; re-emission is especially relevant for fuel and some chemical pathways [10].
	Legal framework	Both domains are governed through formal regulatory frameworks that define permitted routes, operator obligations, and compliance requirements [1,6].	Waste management is primarily governed through waste and circular-economy law [1]. CO_2 management is governed through climate and industrial regulation, notably the EU Emissions Trading System (ETS) monitoring and reporting rules for quantified CO_2 flows [18] and the CCS Directive for geological storage obligations [6].
Economic factors	Cost structure	Both domains depend on infrastructure-intensive systems and cost-optimised system design [14,17].	Waste-system economics are shaped by investments in treatment facilities and by logistics design [17]. CO_2-management economics are shaped by capture costs in addition to transport, storage or utilisation costs [14].

Based on the comparison in Table 1, both domains require regulated management routes and infrastructure systems, but differ across several dimensions, including physical characteristics, temporal dynamics, and energy-use options. In addition to the key differences summarized in Table 1, waste management addresses ongoing residual material streams and, in some global projections, rising waste volumes over time [19]. CO_2 management is embedded in mitigation pathways that aim to reduce emissions progressively toward net zero, even if residual emissions remain relevant in some sectors [3]. In waste management, failures of collection and disposal tend to create local material problems [2]. By contrast, the warming effect of CO_2 emissions is cumulative and unfolds over much longer timescales [20]. These differences indicate that governance concepts from waste management cannot be transferred directly to CO_2 management without adaptation. Accordingly, the comparative analysis in Step 1 provides the basis for Step 2, where the KPI framework for CCS assessment is derived.

2.2. Step 2: Derivation and tiering of KPIs for CCS assessment

Step 2 translates the cross-domain analytical dimensions identified in Step 1 (Table 1) into a structured KPI set for CCS assessment. The translation is limited to indicators that can be consistently defined and classified for the CCS reference case under specific system boundaries and the 2030 and 2050 scenarios. Following OECD guidance on indicator design [21], the indicator set is tiered into core, complementary, and contextual indicators (Table 2). Only core KPIs are operationalised and assessed under harmonised system boundaries. Complementary and contextual indicators are used selectively for interpretation and boundary specification. The core KPIs are grouped into technical characteristics (KPIs 1–3), governance and regulatory design (KPI 4), and economic conditions (KPI 5).

Table 2. Classification of KPIs for CCS assessment.

OECD tier	KPI
Technical and substance-based characteristics	
core (KPI 1)	Specific energy requirement
core (KPI 2)	CO_2 avoidance efficiency
core (KPI 3)	CO_2 transport and infrastructure logistics
complementary	Permanence
	Leakage risk indicator
	Storage capacity and injectivity
contextual	Transport distance & mode availability
	CO_2 purity and specification
Governance & regulatory design	
core (KPI 4)	Monitoring, Reporting and Verification (MRV) and long-term regulatory obligations
complementary	Time-to-deploy (lead time)
contextual	Permitting & liability complexity
Economic factors	
core (KPI 5)	Levelized Cost of CO_2 Management (LCOM)
complementary	Cost structure
	CAPEX intensity
	Scale and throughput sensitivity
contextual	Energy prices

To operationalise the selected core KPIs consistently, Step 3 defines the harmonised system boundaries and reference case assumptions for the 2030 and 2050 scenarios.

2.3. Step 3: Definition of system boundaries for the CCS reference case under the 2030 and 2050 scenarios

The assessed chain includes CO_2 capture, compression, transport, and geological storage (Figure 3). The functional output of the assessed chain is defined as 1 tCO_2 stored. Accounting-relevant distinctions, including the difference between captured and avoided CO_2 where relevant to KPI definition, are specified in line with [14]. Geological storage is defined in accordance with CCS Directive [6]. KPI classes are reported separately for 2030 and 2050 using an ordinal scale (Low, Medium, and High), with KPI-specific classification criteria defined in the respective KPI definitions.

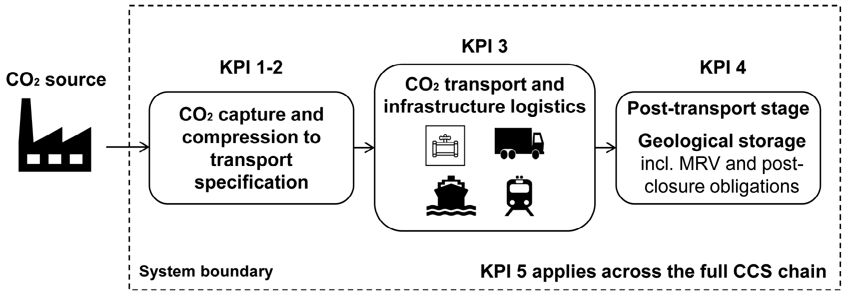

Figure 3. System boundary of the CCS reference case and core KPI mapping.

Step 4 applies the framework developed in Steps 1–3 to the CCS reference case. The resulting assessment is presented in Section 3.

3. Application and Results

3.1. Core KPI 1 — Specific energy requirement

CO_2 capture is generally associated with a high energy demand. For power plants with CCS, the additional energy requirement is roughly 10–40% relative to a plant of equivalent output without CCS. Most of this penalty arises from capture and compression [14]. KPI 1 characterises the specific energy demand of CO_2 capture, including compression to the transport pressure level, under the stated system boundary. Transport and downstream stages are excluded in order to isolate capture-system performance from infrastructure-dependent effects.

The main point-source capture routes commonly differentiated in the literature are post-combustion, pre-combustion, and oxy-fuel combustion [14]. In the present study, post-combustion MEA absorption is used as the operational benchmark because MEA-based systems have long served as the benchmark technology in post-combustion capture studies [14,22]. More recent benchmark updates also include advanced solvent systems beyond conventional MEA. For AMP/PZ-based systems such as CESAR1, i.e. blends of 2-amino-2-methyl-1-propanol (AMP) and piperazine (PZ), reboiler-duty values around 2.9–3.1 GJ/tCO_2 have been reported [22]. However, CESAR1 remains documented mainly in pilot and development contexts [23]. Proprietary systems such as OASE® blue likewise indicate improved energy performance. Pilot-scale documentation indicates a specific energy demand for OASE® blue of about 2.5 GJ/tCO_2, approximately 30% below the conventional MEA benchmark [24]. However, such systems are less suitable as transparent reference cases because detailed open performance data remain limited.

For post-combustion CCS, additional concepts such as phase-change solvents and electro-swing adsorption are included as indicative cases in Table 3. Phase-change solvents are reported in the literature as promising low-energy alternatives for CO_2 capture [25]. Some electrochemically driven concepts, such as electro-swing adsorption, also indicate low-energy potential for CO_2 capture [26]. Other concepts, including membrane- and cryogenic-based separation, are relevant for CCS in principle [14] but are not operationalised here because of boundary heterogeneity and limited comparability. In addition, membrane-based post-combustion capture is regarded as a promising but still second-generation option [27].

Table 3. Quantitative evidence for KPI 1 under a harmonised capture and compression boundary.

Capture case	Heat demand (GJ/tCO_2)	Electricity demand (GJ/tCO_2)	Compression to ~110 bar (GJ/tCO_2)	Total energy demand (GJ/tCO_2)	Indicative maturity
Post-combustion (MEA), coal power	2.7–3.3	0.06–0.11	0.45	3.21–3.86	benchmark
Post-combustion (MEA), NGCC	2.7–3.3	0.21–0.33	0.45	3.36–4.08	benchmark
Post-combustion (MEA), cement plant flue gas	3.79	0.4416	included	4.232	detailed process study
Post-combustion (phase-change solvent, ex.1)	2.77	not reported	0.45	3.22	laboratory–pilot exemplar
Post-combustion (phase-change solvent, ex.2)	2.2	not reported	0.45	2.65	laboratory–pilot exemplar
Electro-swing adsorption (post-combustion range)	not applicable	0.91–2.05	0.45	1.36–2.5	laboratory–pilot exemplar

Note: Sources by row: coal power [14]; NGCC [14]; cement plant flue gas [28]; phase-change solvent, ex.1 [29]; phase-change solvent, ex.2 [25]; electro-swing adsorption [26]. Where compression was not reported separately, 0.45 GJ/tCO_2 to ~110 bar was added for boundary harmonisation [7]. Total energy demand was calculated by the author under the harmonised capture-and-compression boundary.

Across the cases considered in Table 3, KPI 1 remains in the High class for 2030, as energy demand is still elevated under currently available post-combustion capture configurations. For 2050, a shift to the Medium class is assumed for cases in which lower-energy carbon capture concepts move beyond pilot application and become deployable at larger scale. KPI 1, however, captures energy quantity only. The climate relevance of this energy demand is addressed in KPI 2.

3.2. Core KPI 2 — CO_2 avoidance efficiency

KPI 2 defines the CO_2 avoidance efficiency under the stated boundary, limited to capture and compression to the transport specification (Figure 3). Transport and downstream stages are assessed separately (KPI 3–5) to avoid mixing capture-related penalty emissions with downstream effects. The conceptual difference between CO_2 captured and net CO_2 avoided follows [14].

CO_2 avoidance efficiency η is defined as:

$$\eta = 1 - p_{total}, \tag{1}$$

where p_{total} is calculated as:

$$p_{total} = q_{th} \cdot CI_{steam} + q_{el} \cdot EF_{el}. \tag{2}$$

The carbon intensity of steam supplied for solvent regeneration depends on the heat-supply configuration. The illustrative cases considered here are: (i) boiler-based steam supply, (ii) electrically driven high-temperature heat-pump (HTHP) supply, and (iii) combined heat and power (CHP)-based steam provision via steam extraction. The corresponding steam carbon intensity is parameterised as follows:

$$CI_{steam,B} = \frac{EF_{fuel}}{\eta_{boiler}}, CI_{steam,HP} = \frac{EF_{el}}{COP_{HP}}, CI_{steam,CHP} = \frac{EF_{fuel}}{\eta_{CHP}} \cdot \sigma. \tag{3}$$

The benchmark assumptions are based on the IEAGHG MEA retrofit assessment [7] and summarised in Table 4. Electricity and steam carbon intensity are treated as boundary conditions and influence the KPI classes for 2030 and 2050. The electricity carbon intensity values for 2030 and 2050 are taken from the KSZ–KS95 transformation scenario as reported in the comparative scenario review by [30]. The underlying scenario is documented in [31]. For the benchmark MEA case, a reboiler temperature of 120 °C is assumed [32], corresponding to a required steam pressure of about 3.1 bar when pressure loss in the branch pipe and the temperature approach in the reboiler are included [33]. In the CHP case, the power-loss effect depends on how this required pressure relates to the IP/LP (intermediate-pressure/low-pressure) crossover pressure of the plant. Accordingly, the power-loss factor σ is used here as a contextual benchmark parameter for steam-extraction power loss and is adopted from the literature [34]. In this study, the CO_2 avoidance efficiency parameter for CHP-based steam provision η_{CHP} is treated as a benchmark parameter [35], while fuel-specific differences are represented by the corresponding emission factors.

In the HTHP case, COP values are treated as contextual boundary assumptions. For industrial applications, the literature reports a Carnot COP of about 4.5–6.0 for target temperatures around 130 °C and a typical efficiency factor of 40–60% [36]. Based on these assumptions, the corresponding COP range is approximately 2.7–3.6. Against this background, COP = 3.0 is used as the benchmark value in this paper.

Table 4. Benchmark inputs used for capture and conditioning penalty calculations.

Parameter	Value, Unit	Source
Reboiler heat for solvent regeneration	$q_{th} = 3.2\ GJ/tCO_2$	[7]
Electricity penalty for auxiliaries and CO_2 compression	$q_{el} = 125\ kWh_{el}/tCO_2$	[7]
Boiler efficiency	$\eta_{boiler} = 0.94$	[7]
Efficiency parameter for CHP-based steam provision	$\eta_{CHP} = 90\ \%$	[35]
Steam-extraction power loss factor	$\sigma = 0.23$	[34]
Fuel emission factor, natural gas	$EF_{gas} = 0.0559\ tCO_2/GJ$	[37]
Fuel emission factor, hard coal	$EF_{coal} = 0.0936\ tCO_2/GJ$	[37]
Grid electricity carbon intensity, 2030	$EF_{el} = 2.33 \cdot 10^{-4}\ tCO_2/kWh_{el}$	[30]
Grid electricity carbon intensity, 2050	$EF_{el} = 1.7 \cdot 10^{-5}\ tCO_2/kWh_{el}$	[30]

Figure 4 summarises KPI 2 for the benchmark heat-supply cases under the stated CCS boundary. Class boundaries for KPI 2 are defined as High ($\eta \geq 0.85$), Medium ($0.70 \leq \eta < 0.85$), and Low ($\eta < 0.70$). The results show that KPI 2 is strongly dependent on the heat-supply configuration. In 2030, the coal-boiler case is classified as Low, the gas-boiler case as Medium, and the CHP and HTHP cases as High. The same class structure remains in 2050, although all cases improve in absolute terms. The strongest improvement is observed for the HTHP case, reflecting the lower electricity carbon intensity in 2050, while both CHP benchmark cases remain in the High class in both scenario years.

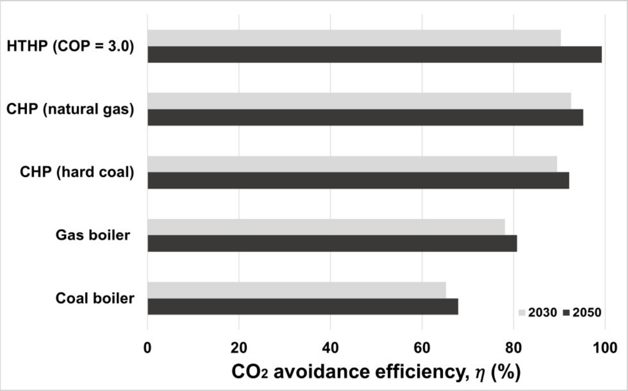

Figure 4. CO_2 avoidance efficiency under alternative heat-supply configurations for the benchmark MEA case in 2030 and 2050.

Although CO_2 capture and compression dominate the additional energy penalty of CCS [14], transport remains a critical implementation condition for CCS. While KPI 2 addressed the climate relevance of capture-side energy demand, KPI 3 shifts the assessment to downstream CO_2 transport logistics.

3.3. Core KPI 3 — CO_2 transport and infrastructure logistics

KPI 3 assesses CO_2 transport configurations and transport costs across different distances, volumes, and transport modes. Literature-based cost values are summarised in Table 5. The KPI covers both point-to-point and network CCS transport configurations. The boundary includes CO_2 handling and any mode-specific conditioning required for transport. CO_2 capture components, as well as injection, storage, and MRV, are excluded from KPI 3 (Figure 3).

Table 5. Indicative CO_2 transport costs for different transport configurations and modes.

Transport configuration	Annual CO_2 volume (Mtpa)	Transport distance (km)	Transport mode	Indicative transport cost (€/tCO_2)	Boundary note
Point-to-point [38]	2.5	180	Pipeline (onshore)	5.4	excl. capture-site compression
			Pipeline (offshore)	9.3	
Network [38]	20	180/500/750	Pipeline (onshore)	1.5/3.7/5.3	
Point-to-point [38]	2.5	180	Ship	8.2	excl. liquefaction
Dedicated route [39]	0.3	~100/500	Pipeline (dense phase)	~48/98	TEA incl. conditioning
		~100/500	Pipeline (compressed gas)	~56/165	
		~100/500	Ship	~87/90	TEA incl. terminal chain
		~100/500	Truck	~52/90	TEA incl. handling
		~100/500	Rail	~50/84	

Note: TEA = techno-economic assessment; excl. = excluding; incl. = including.

Industrial-scale CO_2 transport depends mainly on pipelines and ships [14]. Truck and rail are not expected to dominate large-scale rollout [9]. However, trucks can be cost-effective over short distances and small volumes [40]. Table 5 shows that pipelines become more attractive at higher volumes and in shared networks. At the same time, other transport modes can play an important role in early low-volume cases. For shipping, conditioning and terminal-chain requirements can increase unit costs and weaken the effect of distance [38]. Cost differences between transport modes are therefore strongly assumption-dependent, and non-cost factors such as infrastructure availability, permitting, and regulatory approval can become important [39].

In Germany, these logistical conditions are shaped not only by infrastructure availability, but also by the legal and regulatory accessibility of offshore storage and cross-border CO_2 export. The 2024 Carbon Management Strategy identified offshore storage in the German Exclusive Economic Zone (EEZ) and cross-border export as key elements of the emerging framework [41]. This framework was advanced further in January 2026, when the Bundestag adopted legislation to enable offshore CO_2 storage in the German EEZ and to create the legal basis for CO_2 export for offshore storage [42]. At the same time, transboundary CO_2 export under the London Protocol still depends on provisional application [43] and on notified agreements or arrangements between the states concerned [44].

Since pipeline build-out is expected to remain particularly challenging before 2030 [45], near-term logistics are likely to depend strongly on offshore access, port and terminal readiness, as well as cross-border infrastructure and permitting coordination. KPI 3 is therefore classified as High for 2030. By 2050, continued CO_2 network build-out and shared infrastructure can reduce logistical constraints relative to early phases [45]. A shift to the Medium class is therefore plausible for 2050.

While KPI 3 focuses on transport logistics, KPI 4 qualitatively assesses whether a CCS chain remains legally approvable and practically implementable once MRV requirements, permitting constraints, and long-term post-transfer obligations are taken into account.

3.4. Core KPI 4 — MRV and long-term regulatory obligations

The applicable framework is defined primarily by [6]. EU ETS-related monitoring, reporting and verification requirements for transferred, transported and geologically stored CO_2 are further specified in [18,46].

The near-term performance of KPI 4 for CCS depends primarily on the legal approvability of the selected storage route under the applicable regulatory framework. In Germany, this approvability is asymmetric across storage options: offshore storage in the EEZ is legally permissible in principle under the current framework

[42], whereas onshore storage requires an enabling decision by the respective Land [47]. This route-specific permitting asymmetry is particularly relevant for 2030. In addition, the framework includes long-term obligations, including a financial contribution covering at least 30 years of post-transfer monitoring costs [6]. Although Germany is assessed as having substantial geological storage potential in offshore and onshore formations [48], theoretical capacity does not reduce MRV and compliance requirements.

For this KPI, legal accessibility, permitting status, and long-term compliance obligations are more decisive than theoretical storage volume. Accordingly, KPI 4 is classified as High for 2030, reflecting restricted legal accessibility, route-specific permitting asymmetry, and substantial compliance obligations under the applicable framework. For 2050, KPI 4 is classified as Medium under the assumption of a more consolidated regulatory framework and greater operational experience.

While KPI 4 assesses whether a CCS chain is legally and operationally feasible, KPI 5 examines whether it is economically viable under the stated benchmark conditions.

3.5. Core KPI 5 — Levelized Cost of CO_2 Management

KPI 5 for CCS quantifies the full-chain cost of CO_2 management as a levelized cost per tonne of CO_2 permanently stored. LCOM is defined as:

$$LCOM = C_{cap,com} + C_{tr} + C_{st,MRV}. \tag{4}$$

The cost inputs are based on the integrated CCS cases reported by ZEP [38] and the storage-side cost assumptions discussed in ZEP [49], which together provide summarized cost estimates for defined cases on a common Q2 2009 price basis. All ZEP cost values were converted from Q2 2009 EUR to December 2025 EUR using the Harmonised Index of Consumer Prices (HICP, 2015=100), with Q2 2009 approximated by the mean of the April-June 2009 observations. This yields an inflation factor of 129.47 / 91.85 = 1.4096 [50]. The resulting LCOM ranges used in this study are summarized in Table 6. The LCOM differences shown in Table 6 reflect combined case-specific effects rather than a pure comparison between cluster and single-plant options, since plant type, storage setting, and infrastructure configuration are not held constant across the selected cases.

As a consistency check, capture is the dominant CCS cost driver [51], while onshore transport and storage span 4–45 USD/tCO_2 depending on distance, scale, and geology [9].

Table 6. Inflation-adjusted LCOM ranges for selected CCS cases.

Case configuration	Plant type	Storage setting	LCOM (€/tCO_2)
Single plant-single sink	Hard coal	Onshore aquifer	44.0-57.7
Single plant-single sink	NGCC	Onshore aquifer	108.5-118.4
Cluster (network)	Hard coal	Offshore aquifer	73.3-94.4
Cluster (network)	NGCC	Offshore depleted oil and gas field (DOGF)	69.1-78.9

To relate the KPI-5 levelised cost of CO_2 management to an indicative EU ETS break-even carbon price, a literature-based conversion between stored and avoided CO_2 from [51] is applied. The ratio $tCO_2^{stored}/tCO_2^{avoided}$ for post-combustion power-sector CCS systems is reported as 1.240–1.511 for supercritical pulverized coal (SCPC) and 1.16–1.20 for NGCC systems [51], including amine-based post-combustion capture. For conversion purposes, the ZEP hard-coal cases are mapped to the SCPC category, while the ZEP NGCC cases are matched directly to the NGCC category reported by Rubin et al. [51]. This mapping is used for the stored-to-avoided conversion and does not establish equivalence between the respective plant cases. This implies a stored-to-avoided conversion factor:

$$\phi = \frac{tCO_2^{avoided}}{tCO_2^{stored}} = \left(\frac{tCO_2^{stored}}{tCO_2^{avoided}}\right)^{-1}. \tag{5}$$

This yields $\phi = 0.662 - 0.806$ (SCPC) and $\phi = 0.833 - 0.862$ (NGCC). The factor is used as a bounded sensitivity parameter to translate LCOM per tonne stored into an indicative break-even EU Emissions Allowance (EUA) price per tonne CO_2 avoided:

$$p_{EUA}^{*} = \frac{LCOM}{\phi}. \tag{6}$$

A Monte-Carlo-based uncertainty propagation was conducted for each case with N=10,000 draws. The case-specific LCOM was sampled from a uniform distribution bounded by the corresponding literature-based minimum and maximum values. The stored-to-avoided conversion factor ϕ was sampled independently from a uniform distribution bounded by the corresponding SCPC- or NGCC-based range. For each draw, the indicative break-even EUA price was calculated according to Equation 6. Figure 5 indicates the relative economic limitation of the selected CCS cases against the current EU ETS-related benchmark. Points indicate the median, and vertical lines indicate the 5th to 95th percentile (P5-P95) interval. The dashed line marks the EU ETS six-month average allowance price, used here as an indicative benchmark for comparison (August 2025-January 2026: 78.44 €/tCO_2) [52]. Under this benchmark, the cases remain cost-sensitive and strongly case-dependent. The onshore NGCC single plant-single sink case appears to be the most economically constrained, whereas the onshore hard-coal single plant-single sink case lies closest to the benchmark range.

Under the current EU ETS-related benchmark, the selected cases indicate that KPI 5 remains economically constrained and strongly case-dependent in the near term. Accordingly, KPI 5 is classified as High for 2030 under the stated benchmark conditions. The 2050 classification is not derived directly from the Monte-Carlo results, but reflects the scenario assumption of lower full-chain costs under system maturation and infrastructure scale-up in the EU [4,53]. Under this assumption, KPI 5 shifts to Medium.

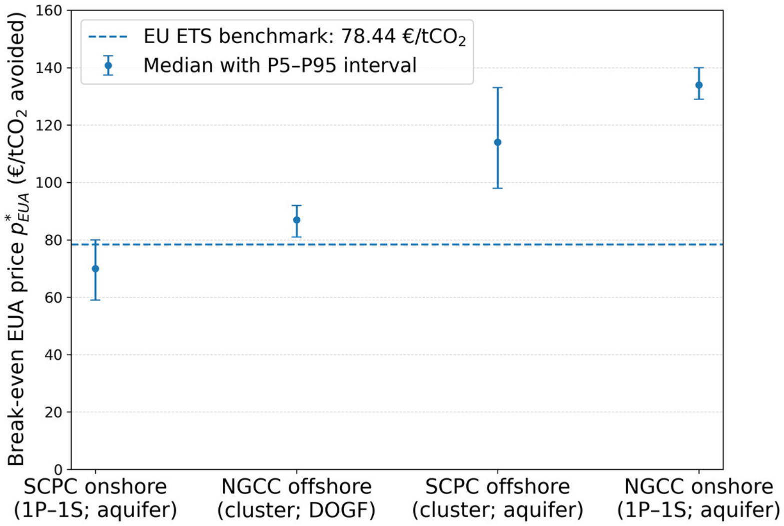

Figure 5. Monte-Carlo-based uncertainty propagation of the indicative break-even EUA price for selected post-combustion CCS cases. Notes: 1P-1S = single plant-single sink.

Taken together, the five core KPIs indicate that CCS performance depends on the interaction of technical, infrastructural, regulatory, and economic conditions across the chain. Table 7 summarises the class-based assessment for the 2030 and 2050 scenarios.

Table 7. Summary classification of core KPIs under the 2030 and 2050 scenarios.

Scenario	KPI 1	KPI 2	KPI 3	KPI 4	KPI 5
2030	High	Low–High*	High	High	High
2050	Medium	Low–High*	Medium	Medium	Medium

* depends on heat-supply configuration

4. Conclusions

This paper develops a CCS-specific KPI framework for CO_2 management through a comparative governance analysis of waste and CO_2 management. Its main contribution lies in translating cross-domain, governance-relevant dimensions into a structured CCS assessment framework operationalised through five core KPIs. The EU waste hierarchy serves as an initial comparative reference, but not as a directly transferable model for CO_2 management. Instead, the analysis shows that waste and CO_2 governance differ in their temporal dynamics, impact visibility, and system conditions. The comparison therefore provides a structured basis for context-specific CCS assessment rather than a fixed hierarchy for CO_2 management. The 2030 and 2050 assessments further show that CCS performance is shaped not only by capture technology, but also by wider technical, regulatory, infrastructural, and economic conditions. In particular, the assessment indicates that near-term feasibility depends strongly on transport availability, permitting conditions, MRV obligations, and broader full-chain implementability. By contrast, longer-term performance improves under assumptions of infrastructure build-out and lower-carbon energy supply. For Germany, this means that near-term CCS feasibility depends less on theoretical storage capacity alone than on whether the full chain can be implemented in practice. In this sense, the value of the comparison lies in clarifying whether, and under which conditions, CCS can serve as a plausible management route for residual CO_2 streams.

Nomenclature

CI_{steam}	steam carbon intensity, tCO_2/GJ
$CI_{steam,B}$	steam carbon intensity for the boiler case, tCO_2/GJ
$CI_{steam,HP}$	steam carbon intensity for the heat-pump case, tCO_2/GJ

$CI_{steam,CHP}$	steam carbon intensity for the CHP case, tCO$_2$/GJ
$C_{cap,com}$	levelized cost contribution of capture and compression, €/tCO$_2$ stored
C_{tr}	levelized transport cost contribution, €/tCO$_2$ stored
$C_{st,MRV}$	levelized storage and MRV cost contribution, €/tCO$_2$ stored
COP_{HP}	coefficient of performance of the high-temperature heat pump
EF_{fuel}	fuel emission factor, tCO$_2$/GJ
EF_{el}	electricity carbon intensity, tCO$_2$/kWh$_{el}$
$LCOM$	levelized cost of CO$_2$ management, €/tCO$_2$ stored
p_{total}	specific penalty emissions per tCO$_2$ captured
p^{*}_{EUA}	indicative break-even EUA price, €/tCO$_{2,\text{ avoided}}$
q_{th}	specific heat demand per tCO$_2$ captured, GJ/tCO$_2$
q_{el}	specific electricity demand per tCO$_2$ captured, kWh$_{el}$/tCO$_2$

Greek symbols

η	CO$_2$ avoidance efficiency
η_{boiler}	boiler efficiency
η_{CHP}	efficiency parameter for CHP-based steam provision
σ	power loss factor for steam extraction
ϕ	stored-to-avoided conversion factor

Subscripts and superscripts

B	boiler case
cap	capture
com	compression
CHP	combined heat and power
el	electricity
EUA	European Union Allowance
HP	heat pump
MRV	monitoring, reporting and verification
st	storage
th	thermal
tr	transport
*	indicative break-even value

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve language quality and to check grammar and spelling. After using this tool, the author(s) reviewed and edited the manuscript as needed and take(s) full responsibility for the content of the published article.

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