WHEN TRUST MATTERS

Guidance Document 1: CO_2 Storage Life Cycle and Risk Management

Jørg Aarnes - Lead – Hydrogen and CCS, Offshore Norge
Johnathon Osmond - Senior Consultant - CO_2 Storage, DNV

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Scope of GD1

Objective: Guide operators and competent authorities (CAs) on how to interpret the requirements in the CCS Directive for responsible risk management practices to demonstrate and verify conformance with the purpose:

Environmentally safe geological storage of CO_2 is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health

Outline

- Legislative context for CO_2 storage risk management under the CCS Directive
- Interpretation of key terms that are used in the CCS Directive
- Main phases of a CO_2 storage project, the associated key activities for CAs and operators, and the main points of interaction between CAs and operators
- Overall approach to risk management for CO_2 storage sites
- How to demonstrate that there is no significant risk of leakage, and that no significant environmental or health risks exist

Legislative context
EU CCS Directive

Directive establishes a legal framework for the environmentally safe geological storage of carbon dioxide (CO_2) to contribute to the fight against climate change

The purpose […] is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health

Legislative context
Risk assessment

The following items in the CCS Directive:

- Article 4(4): a geological formation shall only be selected as a storage site if, if under the proposed conditions of use there is no significant:
  a) Leakage risk
  b) Environmental risk
  c) Human health risk
- Annex I, Step 3.3: Risk assessment
  - 3.3.1 - Hazard characterisation
  - 3.3.2 - Exposure assessment
  - 3.3.3 - Effects assessment
  - 3.3.4 - Risk characterisation

Legislative context
Inclusions & exclusions

- Article 2(4): the storage of CO_2 in the water column shall not be permitted
- The CCS Directive allows for storage in sedimentary and igneous aquifers, hydrocarbon fields, coal seams, and in principle other options such as salt caverns, provided Article 4(4) is met
- If CO_2 is injected into the subsurface as part of enhanced hydrocarbon recovery (EHR) operations or as part of geothermal operations, then a risk-based approach suited for CO_2 storage projects should be used
- When is a CO_2 storage permit required in the context of EHR?
  - Primary aim: permanent and environmentally safe storage of CO_2,
  - Prerequisites: fulfilment of all requirements of the CCS Directive, additional to that of petroleum operations
- When is a CO_2 storage permit required in the context of geothermal operations?
  - Primary aim: reducing GHG emissions
  - Prerequisites: fulfilment of all requirements of the CCS Directive, additional to that of geothermal operations.
  - Exclusions: cases where the CO_2, originating exclusively from the same aquifer, is reinjected in a closed cycle system, being contained within the system for the entire operation

Key terms

Storage site

Definition in CCS Directive	Comments
A defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities	The subsurface component of the storage site is comprised of the geological stratum (or strata) into which CO_2 stream(s) are injected. This volume shall be: • contained within the storage complex; and • delineated by lateral boundaries on an area map. The surface and injection facilities considered to be part of the storage site should include all wells associated with CO_2 injection operations or monitoring, and may include associated infrastructure such as pipelines, CO_2 conditioning systems, storage tanks, offshore platforms and floating (storage and) injection units. **Note:** It is generally understood that the “surface and injection facilities” start where the transport system ends. This can for onshore projects be at custody transfer meters for each CO_2 stream receiving line. For offshore projects, however, such custody transfer meters can be onshore, prior to loading of a ship or injection into the offshore pipeline. It is therefore proposed to define the limits of the surface facilities to be the facilities after any custody transfer that exist within the *surrounding area*.

Storage complex

Definition in CCS Directive	Comments
The storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations	Storage complex shall: • be contained within license area; • include the volume where a CO_2 plume may be present; and • include all legacy wells within the surrounding area that have potential to provide **leakage** pathways. Elevated pressure may extend beyond the limits of the storage complex. Vertically, the complex will normally incorporate shallower geological formations that provide physical trapping of buoyant formation fluids, including any CO_2 plume. The storage complex also contains the subsurface component of the storage site, which can include several geological formation(s) / stratigraphic interval(s) into which CO_2 is injected.

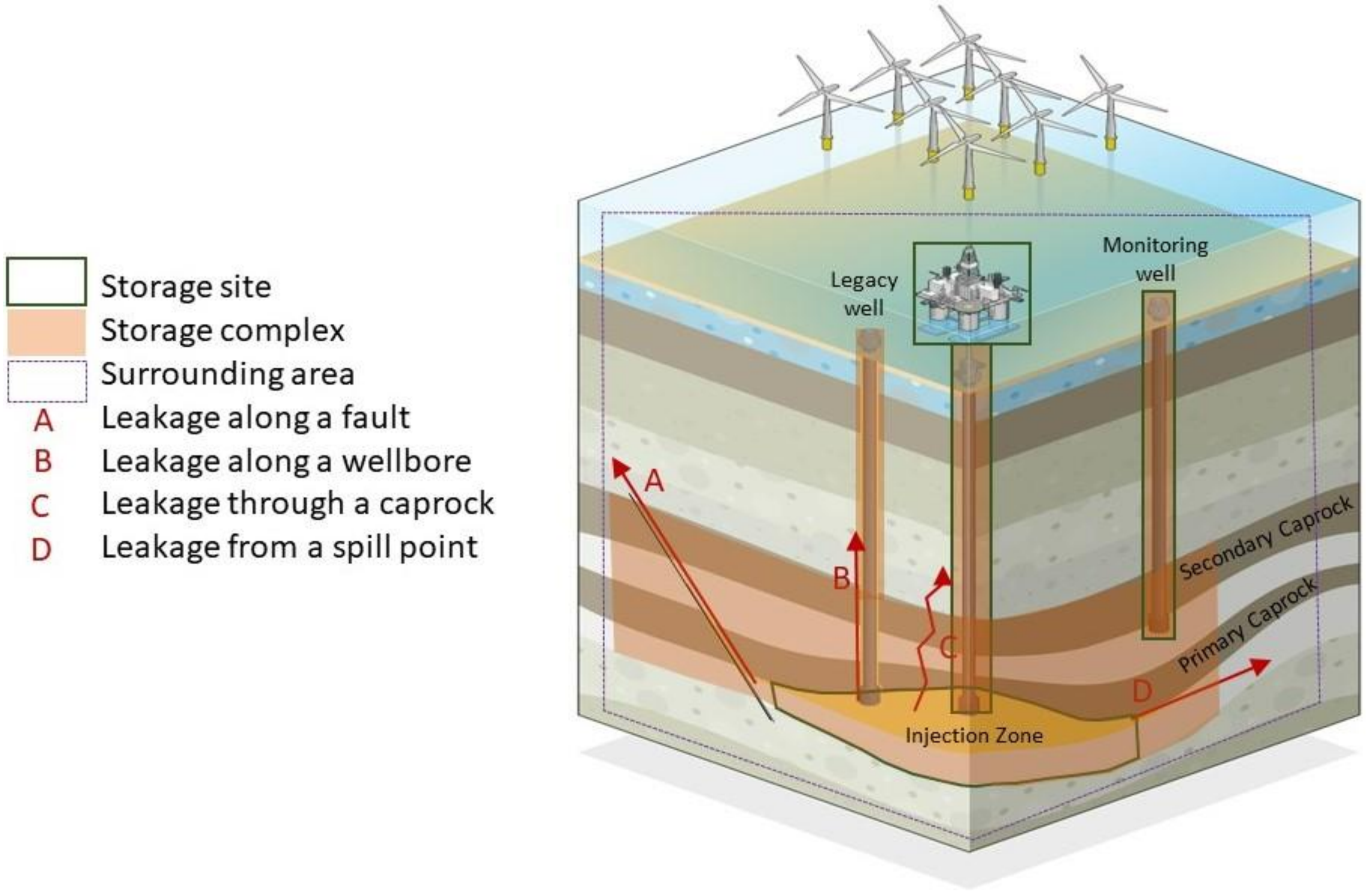
Definition & interpretation of key terms in the Directive

Term	Definition in CCS Directive	Interpretation
Surrounding area	None	Surface and subsurface domain surrounding the storage complex where leakage or negative effects on the environment or human health are realistically possible. Risk assessment should be applied to determine the significance of associated risks, and this should inform the design of the monitoring of the storage complex and surrounding environment. The storage complex and surrounding area should be determined through site characterisation per Annex I and will combined normally encompass the monitoring area.
Hydraulic unit	A hydraulically connected pore space where pressure communication can be measured by technical means and which is bordered by flow barriers, such as faults, salt domes, lithological boundaries, or by the wedging out or outcropping of the formation	The hydraulic unit containing the subsurface volume for the storage site is important for determining the expected pressure build-up from the geological storage project. The hydraulic unit should be mapped and described over an areal extent where material changes in pressure as a result of the CO_2 injection activities can occur. This should also describe other known activities within the hydraulic unit that may impact pressure within the storage site.

Definition & interpretation of key terms in the Directive

Term	Definition in CCS Directive	Comments
Leakage	Any release of CO_2 from the storage complex	This refers to CO_2 in free-phase, i.e., it does not include CO_2 that has been dissolved in water, mineralised or otherwise transformed through chemical reactions. However, assessment and quantification of leakage shall include the potential for any exsolution of CO_2 outside the storage complex. Specifically, if CO_2 charged water is displaced to the water column, then it shall be counted as leakage.
CO_2 plume	The dispersing volume of CO_2 in the geological formation	This refers to CO_2 in free-phase within the geological formation where CO_2 is being injected and shall be contained. CO_2 that is fully dissolved in water, or otherwise transformed through chemical reactions is therefore not included in the CO_2 plume.
Migration	Movement of CO_2 within the storage complex.	Movement of free-phase CO_2 within storage complex.
Significant risk	A combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of the CCS Directive for the storage site concerned	The risk of leakage and possible negative local effects on the environment or human health should be established for each storage site based on a project specific assessment. Combinations of probability of occurrence and magnitude of damage that can represent significant risk will be discussed.

Storage site, storage complex, & surrounding area



Main phases of a CO_2 storage project

CO_2 storage life-cycle risk management framework

- Risk management is an ongoing and iterative process through each phase of a CO_2 storage project
- The EU CCS Directive relates to 6 major phases and 5 major milestones

Phase		Milestone	Typical duration
Phase 1	Screening and regional assessment of storage capacity	Award of exploration permit	0.5–2 years
Phase 2	Characterisation and assessment of the storage complex	Award of storage permit	2–5 years
Phase 3	Development	Start of operations	2–4 years
Phase 4	Operations	Closure	10–30 years
Phase 5	Post-closure/pre-transfer	Transfer of responsibility	5–20 years
Phase 6	Post-transfer	n/a	5–30 years

Phases & activities

Phase/milestone	CA activities	Key operator activities
Screening and regional capacity assessments	Assess storage capacity available in the country and/or region and define areas available for storage site exploration or where exploration may not be required	Perform storage site screening and risk assessment to inform site feasibility evaluation and prepare Exploration Permit Application(s)
	Award of Exploration Permit	
Characterisation and storage permit application preparations	Review storage permit applications and provide feedback on acceptable risk levels based on risk assessment results	Perform site characterisation and prepare project development plans and design, including plans for monitoring and corrective measures and the environmental impact assessment (EIA)
	Award of Storage Permit	Investment decision for storage project
Development	Oversee baseline monitoring in accordance with approved monitoring plan	Construct facilities, drill project wells, remediate existing infrastructure and wells if required, baseline surveys, Front-End Engineering Design (FEED)
Operations	Undertake inspections, approve reporting and updates to monitoring and corrective measures plan, ensure corrective measures are implemented, approve adjustment of financial security	Injection operations and monitoring, reporting, update as required models, risk assessment, and plans for monitoring and corrective measures
Closure	Authorise closure	End of injection operations
Post-closure/pre-transfer	Undertake inspections, approve reporting and updates to monitoring and corrective measures plan, ensure corrective measures are implemented, approve adjustment of financial security	Monitoring, reporting, update as required models, risk assessment, and plans for monitoring and corrective measures, remove injection facilities, seal site
Transfer of responsibility (ToR)	Approve or reasoned rejection of transfer of responsibility considering any opinion of the Commission, and accept the responsibility for all legal obligations per Article 18(1)	Submit transfer report and make financial contribution available to CA (Article 20)
Post-transfer	Long term stewardship of site by Member State (MS)	

Interaction between operators & competent authorities

- An ongoing and active dialogue between the operator and competent authority is recommended
- Member States (MS) are encouraged to develop guidance on their expectations to operators on:
  - The level of interaction
  - Timing and frequency of interactions
  - The extent of written inputs required
- Guidance can include providing a standardised report structure for reports under Article 14, detailing the content to be included

Risk management framework

Risk management principles

- Risk assessment for CO_2 geological storage shall consider the site-specific context, e.g., reflect:
  - Geological conditions
  - Local population density
  - Local biosphere and hydrosphere
  - Nature/magnitude of scenarios involving dispersal of CO_2 into the atmosphere or water column
  - Onshore or offshore location
  - CO_2 composition
- The level of risk should be **as low as reasonably practicable** (ALARP)
- Some risks may be contingently acceptable/tolerable if:
  a) Effort or burden of additional risk controls is disproportional to the level of risk reduction
  b) The risk can be maintained at an insignificant level
- Positive effects should not be outweighed by risk of negative impacts (risks$\ngeq$benefits)
- Documentation of risk assessment and management should be transparent and traceable

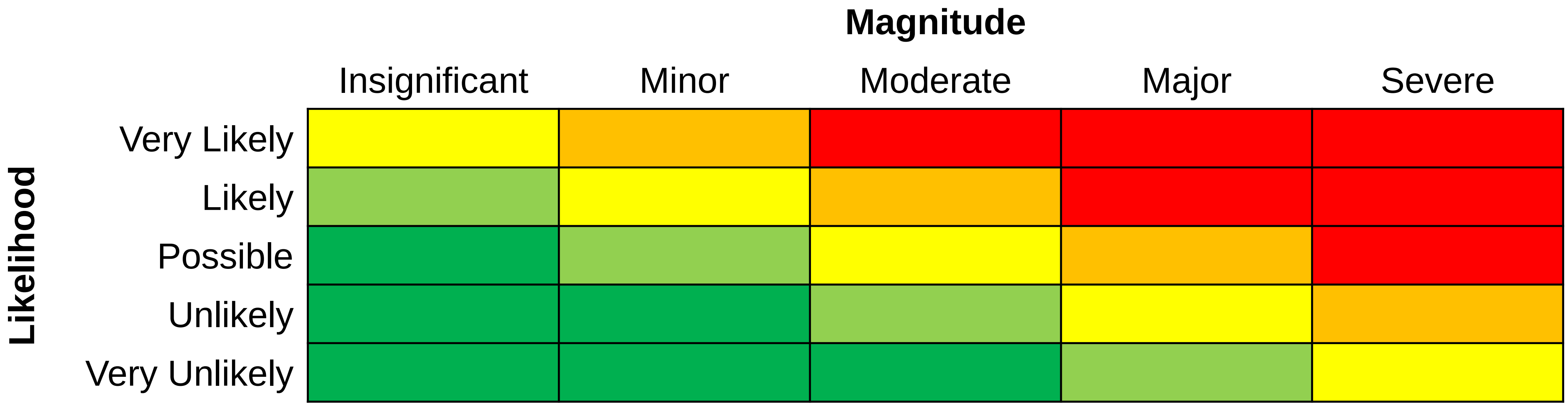
Storage site requirements and risks

- Storage sites must satisfy 3 high-level requirements:
  1. Capacity – sufficient storage volume or can be engineered
  2. Integrity – confidence the site is secure, low risk of leakage and storage impacts
  3. Injectivity – suitable reservoir properties for sustained injection without impacting integrity
- CCS Directive allows for storage in various subsurface formations, but specifies required characteristics of the storage complex
- Operators need to establish confidence in storage integrity
  - Verify that the combination of trapping mechanisms provides permanent containment
  - The timing and effectiveness of trapping mechanisms shall be well understood

Risk evaluation criteria

Risk matrix

- Each cell in the matrix represents a likelihood class and consequence class
- Cells are normally coloured based on the level of significance of risk scenarios in the cell
- Red often represents an unacceptable risk, green an acceptable risk



Risk evaluation criteria: defining the risk matrix

Likelihood classes

- Probability/frequency of an undesirable event, with specification of likelihood ranges (probability/frequency bands) with descriptors
- Descriptors often include a qualitative interpretation to help developers consider relevant empirical data

Consequence classes – human health

- Damage to human health is often described in terms of severity of injuries and number of fatalities, and associated impact on life quality and work performance (e.g., illness, disability, lost worktime, etc.)
- Useful to describe a situation that could cause the associated impacts.

Consequence classes – environment

- Degree of severity of environmental impact depends on:
  - Size of the area being impacted
  - Magnitude and durability of the damage to the environment in the area (flora and fauna)
  - Vulnerability of the flora and fauna that are affected

Level of risk (colours)

- Determination of risk levels should:
  - Be based on the project-specific context
  - Consider the nature of the potential damage, relevant risk acceptance criteria in applicable regulations and corporate policies, and benefits of the CO_2 storage activity.

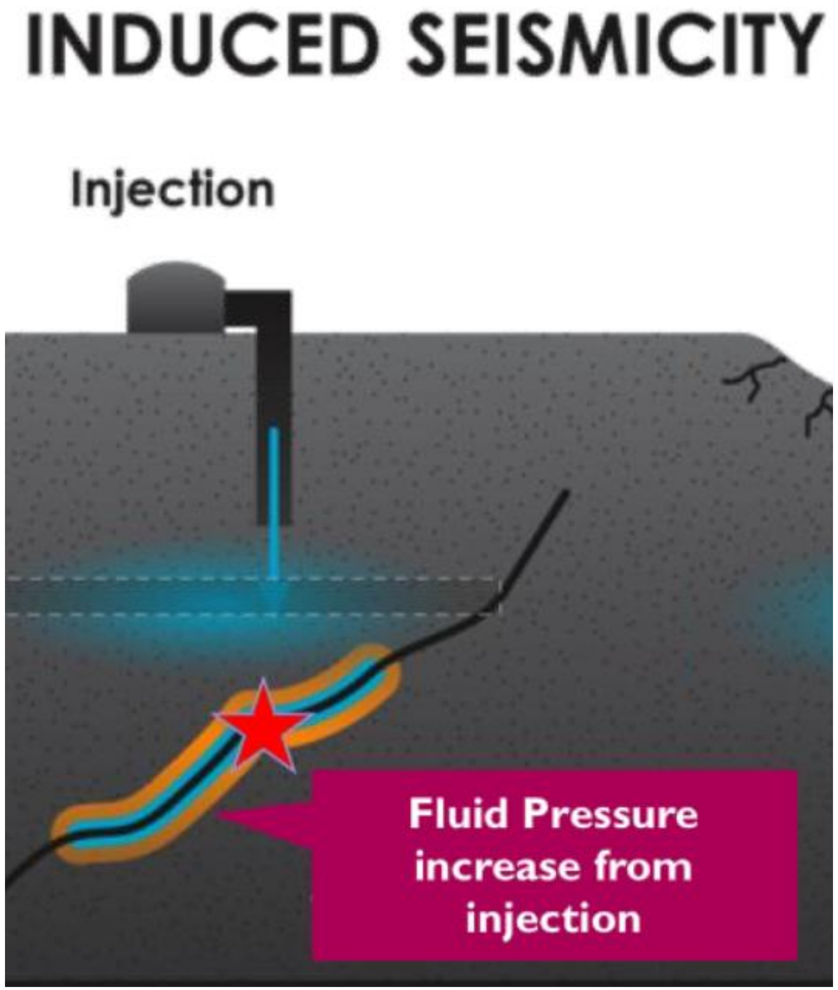
Risk evaluation criteria – example

		CONSEQUENCE				LIKELIHOOD				
						A: Remote	B: Unlikely	C: Possible	D: Probable	A: Certain
		Health and safety (HS) and Environmental protection (E)	Cost (Commercial readiness)	System Performance	Schedule to start-up of operations	Very unlikely to occur during project, no knowledge of similar event occurring in the CCUS industry or in related activities	Unlikely to occur during project, similar event has not occurred in previous CCUS projects by ECO2S team, but has occurred in the CCUS industry or in related activities	Somewhat likely, 50/50 chance of occurring during project, similar event has occurred in previous CCUS projects by ISC team	Likely to occur during project, event expected to occur in similar projects	Very likely to occur during project, event is a common occurrence in similar projects
CONSEQUENCE SEVERITY	E: Very high	HS: On-site exposures/injuries leading to significant irreversible health effect or off-site exposures/injuries leading to long-term or irreversible health effect. E: Persistent severe environmental damage, extensive remediation required. Environment restored > 5 years.	More than $10 million	Major failure in containment or equipment infrastructure requiring significant intervention to remediate and/or restore operations.	More than 12 months	5	10	15	20	25
	D: High	HS: On-site injuries/exposures leading to long-term or irreversible health effect (e.g. loss of limb, hearing loss) with absence from work more than 5 days. E: Severe environmental damage. Remediation measures required. Environment restored 2- 5 years	$1 to $10 million	Equipm… requiring replace / re… to regair… storage…	[illegible]	[illegible]	[illegible]	12	16	20
	C: Medium	HS: Lost time event/on site injury leading to temporary disability and absence from work up to 5 days, or affecting daily life activities more than five days. E: Damage managed by Company response teams, env. restored < 2 years.	$100 to $1000 k	Workover… replaceme… in loss of (… and storag…	[illegible]	[illegible]	[illegible]	9	12	15
	B: Low	HS: Minor injury or health effect – OSHA recordable, reversible health effect requiring treatment and affecting work performance, such as restricting work activities/daily activities for up to 5 days. E: Damage, but no lasting effect.	$10 to $100 k	Maintenance activities that interrupt CCTS activities	1-3 months	2	4	6	8	10
	A: Very low	HS: Slight injury or health effect – Reversible health effect not requiring treatment, and not affecting work performance/daily activities. E: Damage contained within premises.	Less than $10 k	Minor or routine maintenance that does not interrupt CCTS activities.	Less than 1 month	1	2	3	4	5

To be proposed by operator and discussed and calibrated with competent authority

Induced seismicity risk item

- When developing consequence classes, it is recommended to develop one impact example for **leakage events** and one impact example related to **induced seismicity**
- Induced seismicity may lead to annoyance and damage to buildings and infrastructure, which subsequently can cause damage to human health
- Fault slip, which introduces induced seismicity, is also a containment risk. Impacts should reflect damage from both leakage and induced seismicity, i.e., the most severe damage from leakage and ground motion respectively



Risk assessment per Annex I, Step 3.3

Step 3.3.1: hazard characterisation

Characterise hazards to human health or the environment arise from five principal effects				
Leakage (elevated concentration of CO_2 stream components in the overburden, atmosphere, or water column)	Intrusion of CO_2 charged fluids and mobilised elements into groundwater or other receptors	Displacement of fluids by injected CO_2 (e.g., brine or hydrocarbons)	Subsurface deformation and corresponding uplift/subsidence	Natural or induced seismicity and associated knock-on events

Step 3.3.1: hazard characterisation

- Risk identification under the CCS Directive should:
  - Determine threats related to the 5 principle effects
  - Describe the associated risk scenario (i.e., threat-event-consequence sequence)
- For leakage related risk scenarios, the hazard characterisation requires the estimation of the potential leakage rates and duration following various credible modes of containment failure
  - Recommended that operators estimate *expected* magnitude in case risk scenario occurs – worst-case estimates of rate and duration will generally lead to undue exaggeration of magnitude
  - To capture the down- and up-side cases, the operator should determine the uncertainty range for both parameters (rate and duration), and communicate these uncertainty ranges
- If the formation(s) used for storage is within a hydraulic unit used for other activities, the operator should consult with the CA to obtain more information and consider relevant risk scenarios
  - May impact CO_2 storage capacity, subsurface deformation can impact well and seal integrity

Step 3.3.2 & 3.3.3: exposure & effects assessment

- The exposure and effects assessments are elements of risk analysis. Requirements to risk analysis is addressed in Clause 6.7.3 of ISO 27914:2017 and Section 6.3.3 of DNV-RP-J203.
- Potential negative effects to the subsurface environment or resources **within the storage complex** caused by migration of CO_2 is not within the scope of this step
- **Aim:** Increase understanding of both the likelihood and consequence of the identified risk scenarios and uncertainty elements
- (Semi-)quantitative risk analysis approaches should be applied where relevant data to support quantification can be obtained, e.g., based on available empirical data, statistics, or scientific reasoning
- Otherwise, the risk analysis should be supported by judgment of experts who are qualified in terms of applicable professional expertise and project knowledge
- Both quantitative and qualitative approaches can involve modeling in the context of:
  - Scenario analysis: process of analysing a range of possible future events by considering alternative outcomes
  - Reliability analysis: estimation of probability of failure of an engineered system given stochastic loads/characteristics
  - Sensitivity analysis: assessment of sensitivity to variations of key uncertain parameters to performance functions

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Annex I, Step 3.3.4: risk characterisation

- **Aim:** Determine the likelihood of risk scenarios and the severity of possible consequences if they occur, and rank the identified risks using risk evaluation criteria
- Risk evaluation before mitigation sets performance requirements for the risk treatment strategy.
- It is considered best practice to document:
  1. Level of risk prior to implementation of risk treatment
  2. Target level of risk to be achieved following the implementation of risk treatment
  3. Why the selected risk controls will be effective in mitigating the risk
- Uncertainty in the effectiveness of planned risk treatments should also be evaluated/documented
- CCS Directive requires consideration of worst-case impacts:
  - Worst plausible consequences from the risk scenarios
  - Risk level as a best-estimate, along with associated uncertainty
- Be objective and avoid bias without exaggerating the risk unduly

Annex I, Step 3.3.4: risk characterisation

Risk should be characterised and placed in one of two categories:	
Insignificant risks: do not call into question the purpose of the CCS Directive for the storage site	**Significant risks:** must be reduced to insignificant through implementation of risk reducing measures

- The determination significant vs insignificant risk is ultimately subjective, and depends on the risk appetite of the entities that are exposed to risk or will bear responsibility for managing the risk
- Not transferable between sites: a leakage risk scenario with the same likelihood and potential magnitude of leakage may be an insignificant risk at one site and a significant risk at another site

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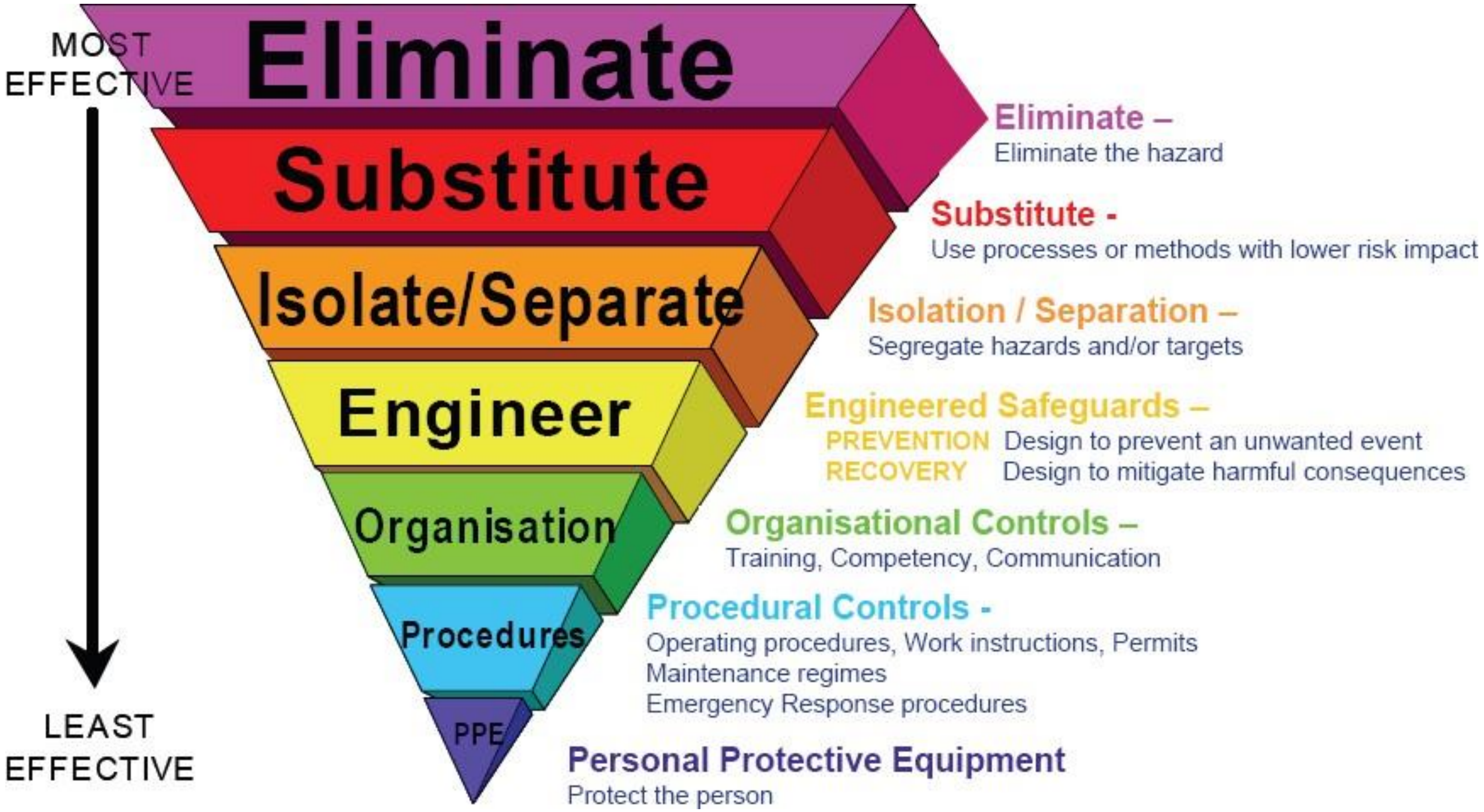
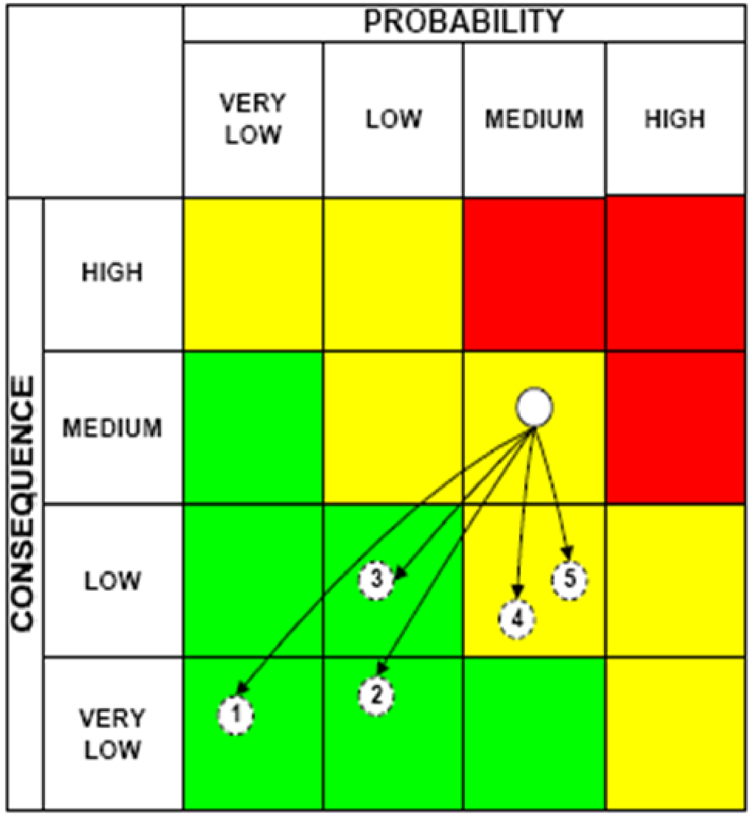
Annex I, Step 3.3.4: risk characterisation

- To establish agreement between the operator and CA that risk has been reduced ALARP and that the storage site meets Article 4(4) it is recommended that the operator is transparent about the risk controls that have been considered and why the chosen risk controls were selected





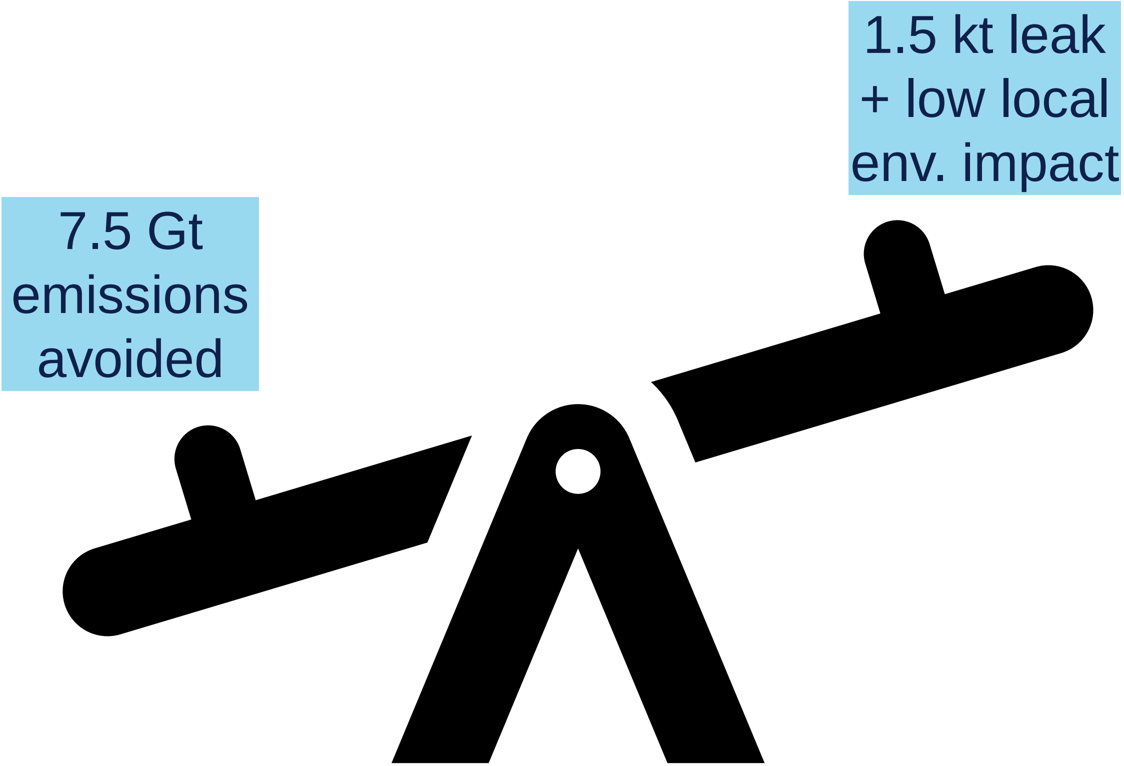
Process to evaluate aggregate risk profile

- Operators and CA need to determine if the aggregate risk profile from all project risk scenarios is acceptable or insignificant. The aggregate risk profile for the project should not outweigh project benefits.
- Since many risk scenarios for CO_2 storage projects have very low likelihood of occurring, it is recommended to compare risk and benefits by considering a portfolio of identical projects:

1. Perform a project-specific risk assessment
2. Establish project risk profile (leakage and consequences to human health and the environment)
3. Establish project benefit related to human health and the environment, incl. CO_2 emission reductions
4. Assume a portfolio of, e.g., 100 identical projects
5. Assume that each risk scenario identified occurs at the assessed frequency in each individual project, and that the assessed impact occurs
6. Evaluate the cumulative damage and cumulative benefit from the portfolio
7. Determine if the damage outweighs the benefit or vice versa

Determination of acceptable risk levels
Example: Project CoCo – offshore storage

- CoCo: 3 injection wells for 3 Mtpa storage, 25 yr
- Risk characterisation estimates that:
  - Likelihood of leakage per well during life of project is 1%
  - If leakage occurs:
    - Magnitude of cumulative leakage per well is <500 t
    - Flora can be affected in a radius of 100 m around the well, but no high value resources. Environmental impact = low
- Principle: 100 projects with identical risk profile:
  - 3 wells will experience a leak during project lifetime
  - Cumulative leakage is <1500 t and environmental impact = low
  - Cumulative storage = 7.5 Gt



Thank you

Jorg.Aarnes@offshorenorge.no
Johnathon.Osmond@dnv.com

www.dnv.com