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Assessment and Communication of Leakage Risk in Underground CO_2 Storage

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Abstract

As commonly known, carbon dioxide is one of the climate gases that contribute to greenhouse effect on the earth, thereby causing serious climate issues.

So, to prevent large release of the gas into the atmosphere, storage is an option. CO_2 storage is the process of capturing waste carbon dioxide (CO_2) from big point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it does not reach the atmosphere, usually an underground geological formation. A geological formation could be an abandoned oil or gas reservoir, a salt formation or any other impermeable formation. A major concern is to ensure the possibility of leakage from these underground storages is small, when being plugged and abandoned.

Most of the risk assessment methods for underground storage methods focus more on consequences and probability concept of risk, with little mentioning of quantifying uncertainties. The purpose of this thesis is to provide an overview of risk assessment methods for underground storage that has already taken place and to establish the basis for a risk management framework and risk analysis methods. Communication of risk is vital in the understanding of the situation in question and to support decision-making process; so possible recommendations will be mentioned.

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List of Abbreviations

CBM	Coalbed Methane
CCS	Carbon Capture and Storage
CFA	Certified Framework Approach
CO_2	Carbon dioxide
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
FEHM	Final Element Heat and Mass transfer
FEP	Features, Events and Processes
FID	Final Investment Decision
FMECA	Failure Mode Effects and Criticality Analysis
GHGs	GreenHouse Gas(es)
GSC	Geological Storage of Carbon dioxide
HAZID	Hazard Identification
HAZOP	Hazard and Operability
IEAGHG	International Energy Agency Green House Gas
LNG	Liquefied Natural Gas
MAUT	Multi-Attribute Utility Theory
MCA	Multi-Criteria Assessment
MOF	Metal-Organic Frameworks
MOSAR	Method Organized for a Systematic Analysis of Risk
NORSOK	Norwegian Shelf's Competitive Position
P&R	Performance and Risk
PENS	Predicted Engineered Natural Systems
PSA	Petroleum Safety Authority of Norway
RAL	Risk Acceptance Limit
RISQUE	Risk Identification and Strategy using Quantitative Evaluation
SMA	System Modelling Approach
VEF	Vulnerability Evaluation Framework

1. Introduction

Concentrations of atmospheric CO_2 have continuously increased from the pre-industrial level of 280 ppm to over 370 ppm. The primary causes of this rise are due to coal, oil and natural gas burning. Presently, more than 20 billion tons of CO_2 are emitted globally into the atmosphere. Rising level of atmospheric CO_2 concentrations can upset the earth's climate condition, and inadvertently cause the sea level to rise enough to flood low-lying regions at the coast and damage sensitive ecosystems[1]. In order to cope with this challenge, CO_2 is being captured, transported to the storage site, and injected either into depleted oil and gas reservoirs or into an impermeable coal seams or into any deep salt formation underground. This is referred to as Carbon Capture and Storage (CCS).

There are four (4) step-processes involved in CCS as depicted in the *Figure 1* below. Firstly, a pure CO_2 stream is separated and captured from point sources, such as big fossil fuel facilities, natural gas processing, synthetic fuel plants, which then is compressed to about 100 atm[2]. Then, it is transported to the injection site, and in the final process it is injected deep underground into geological formations like oil and gas reservoirs. CO_2 can then be stored safely for thousands of years or longer depending on the reservoir storage quality and overburden. However, it is important to perform proper during screening of a candidate reservoir for storage [1].

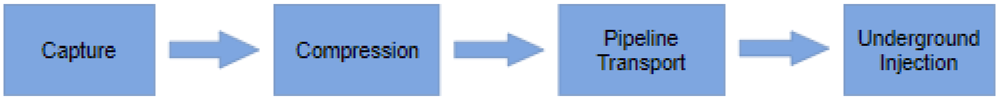

Figure 1: Major steps in the CO_2 Capture and Storage process[1]

Continuous monitoring of storage site is maintained, to ensure leakage of CO_2 is contained[2]. However, there has been no consensus on a standardized method or set of methods of assessing the risk associated with the leakage[3].

This thesis deals with the overview of risk assessment methods for underground storage that has already taken place and to establish the basis for a risk management framework and risk analysis methods. Then it suggests a means of communicating the leakage risks to all stakeholders.

1.1 Background

Great attention has been given to changes in climate in recent years. Changes in temperature that lead to increased sea level and more extreme weather are some of the concerns, calling for individuals, nations and industries becoming more environmentally conscious. Some of the greenhouse gases (GHG) contributing mostly to increased global warming are carbon dioxide (CO_2), methane (CH_4), nitrogen oxide (N_2O) and ozone (O_3). With regards to carbon dioxide (CO_2), being a major contributor, the anthropogenic emissions must be reduced. One viable means to prevent the release of significant amount is through Carbon Capture and Storage (CCS).

1.1.1 Causes of Global Warming

Evidence exists that the earth is now under global warming. Observations, along with other factors, indicate that a major factor in climate change is human CO_2 emissions. CO_2 is a greenhouse gas released into the atmosphere through a number of sources, such as burning coal and oil, and natural gas discharges [4].

The greenhouse gases capture radiation from the sun in the earth's atmosphere, leading to significant warming of the planet. As shown in *Figure 2*, the annual carbon dioxide emissions increased by approximately 80%, from 21 to 38 gigatons, between 1970 and 2004. The increases in the global atmospheric concentrations of CO_2, CH_4 and N_2O are the result of human activities [4].

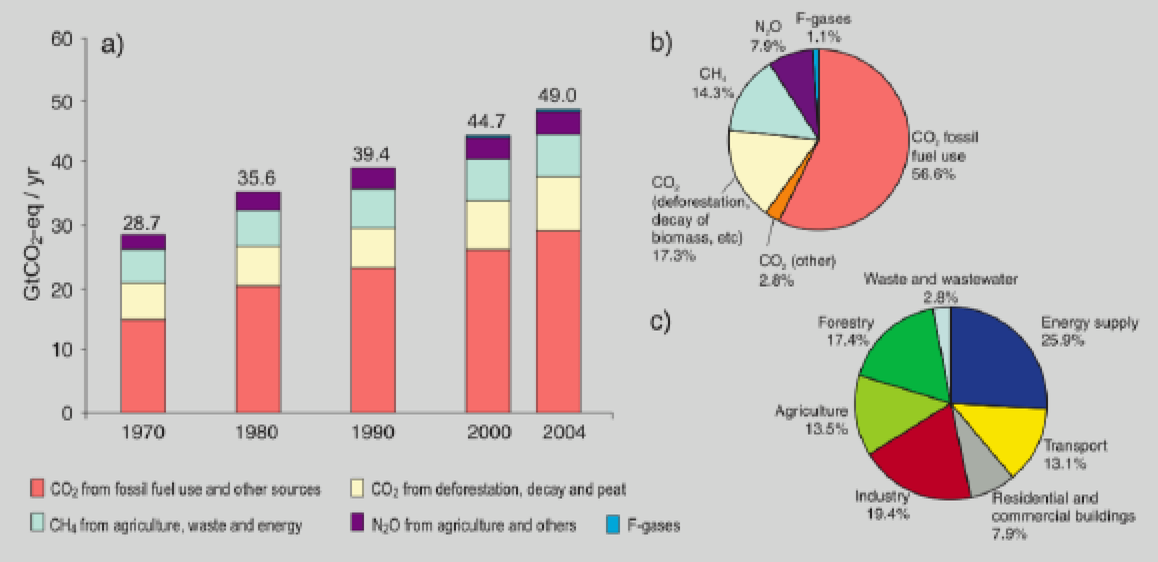

Figure 2: (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004 (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2 equivalents. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2 equivalents[4].

Figure 3 shows CO_2 emission and temperature development over time century. The data was taken from different regions. The plot clearly demonstrates and is an evidence for CO_2 gas contribution for global warming.

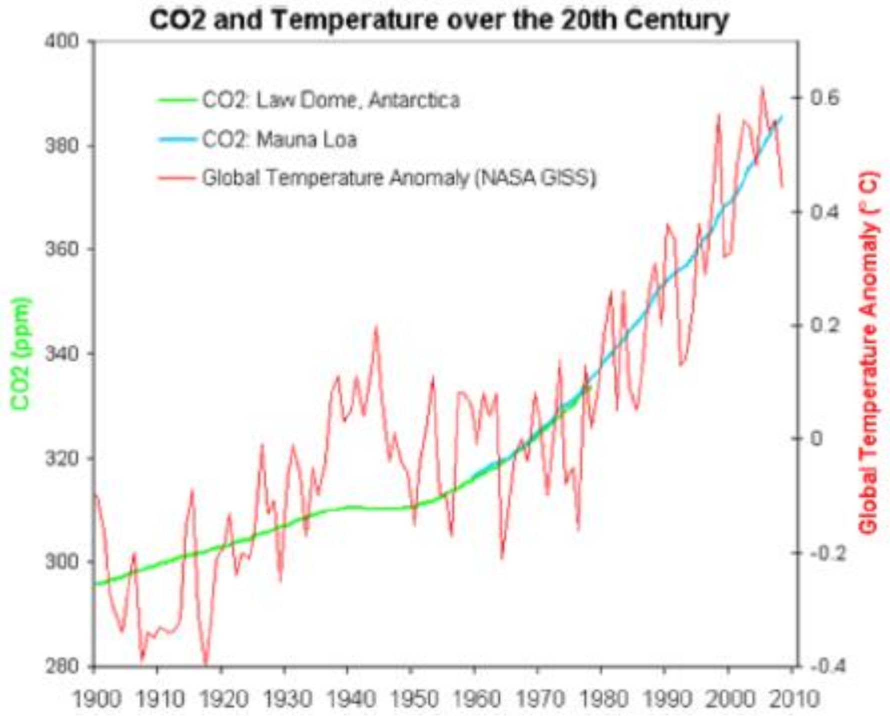

Figure 3: Carbon dioxide levels along with annual global temperature anomaly[5].

1.1.2 Effects of Climate Change

Excessive emissions of CO_2 and other GHG gases have negative consequences on the environment. Some of these are:[6]

- Extremely hot days due to air and ocean temperature increase.
- Warmer weather may affect the ecosystem.
- Rise in sea levels, eroding coasts and causing coastal flooding.
- Heat can spread diseases like malaria and yellow fever.

1.1.3 Mitigation

There are various ways of reducing CO_2 emissions - using renewable energy sources such as wind energy, solar energy, tidal energy, geothermal and biomass energy. Nuclear power is also another alternative, but it comes with the public acceptance challenge, largely because of the Chernobyl accident in 1986[7].

Due to the fact that the industrial sectors are not to be avoided, CO_2 can be captured from industrial plants and stored in geological or ocean formations in a process such as carbon capture and storage.

1.1.4 Risk communication

The way risk is translated and communicated is important. Several definitions of risk have been proposed. However, the Petroleum Safety Authority (PSA) defined risk as consequences of an activity with the associated uncertainty. How is this uncertainty measured? By probability! The concept of uncertainty is sometimes difficult to represent using probability in a meaningful way, so there should be less single-minded focus on probability and more focus on what is behind these probabilities [8].

The concept of probability is of great importance in risk and safety settings, and therefore meaning and interpretation of probability needs to be clearly communicated and understood, in order to help in decision making. There are basically two extreme lines of thought, the objective probability and the subjective probability. The objective probability, which in most cases referred to as frequentist probability, denoted as $P_f(A)$, and defined as the fraction of times event A will occur if the situation considered were repeated (hypothetically) an infinite number of times[9]. This is complicated and not suitable for realistic or practical situations. However, the other class, that is, the subjective probability is more acceptable and practical, as it reflects the belief of an assessor regarding an event. Subjective probability is largely based on the popular Bayesian theorem, which combines beliefs, which maybe pre-existing, with observations or new data/information about an event to update a pre-existing probability [10]. Although assigned probabilities and expected values are important in risk analysis, because they express information about the situation, uncertainties and degree of belief; the strength of knowledge on which the probability values are based is an important component of risk description. If the background knowledge changes, then the probability assignment might also change[10].

1.1.5 Risk Description

A risk description is a risk assessment output. One always starts with some concept of risk such as (A,C,U) which is in compliance with the definition given by PSA, where *C* is the consequence of an initiating event *A*, with corresponding uncertainty *U [11]*. The assessment method is chosen according to how much information that is needed for decision support and the analyst's preferences. For example, considering the uncertainty regarding the event *A*, and choosing to describe this with the probability of *A*, the risk assessment will simply be the process of assigning the probability P(*A*). On the basis of (A,C,U), by letting Q be the measure used to represent U, an intuitive description of the risk concept is (A´,C´,Q) where A´ and C´ are descriptions of respectively the initiating event A and the consequence C. However, one cannot obtain Q, A´ or C´ without background knowledge K. Hence, background knowledge should also be a part of the description. The risk description is then (A´,C´,Q,K) [10].

1.1.6 Knowledge dimension

The risk analyst may obtain and combine a set of probabilities for particular activities with distinct loss classifications, but these figures must be seen in relation to the strength of knowledge that promotes the probabilities [12]. Knowledge background could be weak, medium or strong. According to Aven and Vinnen, care must be taken when using such probability-based boundaries (or criteria), since they can readily lead to incorrect focus, fulfilling requirements rather than finding the best general arrangements and measures. However, in order to simplify decision process using the criteria, in relation to the strength of knowledge supporting the probability, an adjusted procedure as suggested by Aven is as follows [12]:

1. If risk is found acceptable according to probability with large margins, the risk is judged as acceptable unless the strength of knowledge is weak (in this case the probability-based approach should not be given much weight).

2. If risk is found acceptable according to probability, and the strength of knowledge is strong, the risk is judged as acceptable.
3. If risk is found acceptable according to probability with moderate or small margins, and the strength of knowledge is not strong, the risk is judged as unacceptable and measures are required to reduce risk.
4. If risk is found unacceptable according to probability, the risk is judged as unacceptable and measures are required to reduce risk.

Table 1 also shows how the knowledge dimension is used to understand better the concept of the probability-based thinking. This is to put the above four adjusted procedures in a better picture for easier understanding and communication[10].

Probability-based justification	***Above limits***	Unacceptable risk	Unacceptable risk	Unacceptable risk
	Small margin below	Unacceptable risk	Unacceptable risk	Acceptable risk
	Large margins	Further considerations needed	Acceptable risk	Acceptable risk
		Weak	***Moderate***	***Strong***
		Strength of Knowledge		

Table 1: Adjusted procedure for use of risk acceptance criteria in view of considerations of the strength of knowledge[12].

1.2 Problem Statement

Once the CO_2 is injected into the formation, it is important to understand and evaluate the integrity of the formation with respect to leakage to the surface. Most of the risk assessment methods for underground storage methods focus more on consequences and probability concept of risk, with little mentioning of quantifying uncertainties. The problem to be addressed in this thesis is as follows:

- The concepts and options available for carbon storage
- Overview of different methodologies to evaluate leakage risk
- Comparison of the methodologies
- Communication of results and how to support decision-making

1.3 Objective

The primary objective of the thesis is to show the comparison among some of the methods used to evaluate leakage risk of an underground storage of CO_2 and a way to communicate the risk to all stakeholders in order to influence decision-making.

2. The concept of Carbon Storage

In order to accomplish noteworthy reductions in the atmospheric release of anthropogenic greenhouse gases, it is vital to engage technologies in capturing carbon dioxide (CO_2) and storing it in geological formations. In any case, deep saline aquifers have the greatest potential for CO_2 sequestration in geological sites in terms of quantity, duration and minimum or zero environmental impact[13]. In this chapter, different storage options will be described, so also the mechanism of the storage and challenges involved.

2.1 Geologic storage

Geological storage of CO_2 is one of the various forms of carbon sequestration. It is a prospective way to mitigate the contributions of fossil fuel emissions to global warming and ocean acidification[14]. This is the process where the gas goes through separation, transportation by pipelines to inject on site and compression processes prior to re-injection into geological storage formations where it is stored for at least thousands of years [14]. This technology is often referred to as Carbon Capture and Storage (CCS). Already in the 1970s it was suggested that CO_2 storage could be utilized to reduce emissions of carbon fueled energy, but the idea was dismissed. The idea did not become popular before the early 1990s [15]. Sleipner West was the world's first industrial-scale storage project which commenced in 1996 [16]. More storage projects in various locations around the world have been introduced since then and others are in the developing phase today. In the last 15 years CO_2 storage has gone from a controversial and limited area of interest to a promising and important mitigation option [15]. The success of these pioneering projects has paved way to the future of geological storage of CO_2 as a way of reducing greenhouse gas emissions.

2.1.1 CO_2 Injection Process

Generally, CO_2 is injected into, most likely, sandstone dominated reservoirs at depths greater than 800 meters in a supercritical state. These reservoirs are also likely to be confined by a sealing cap rock. At above critical temperature of 31.1°C and critical pressure of 73.9 bar, CO_2 attains a supercritical state as indicated in *Figure 4* [17]. This state is important for CO_2 storage because the density is favorable more than the gaseous or liquid state. At supercritical state, CO_2 acts both as gas and liquid and can occupy the same pores that a less dense gas would, and it won't split into two phases so long it is kept above the critical temperature and pressure. Therefore, CO_2 is most often injected at formation depths where it can retain these properties[15].

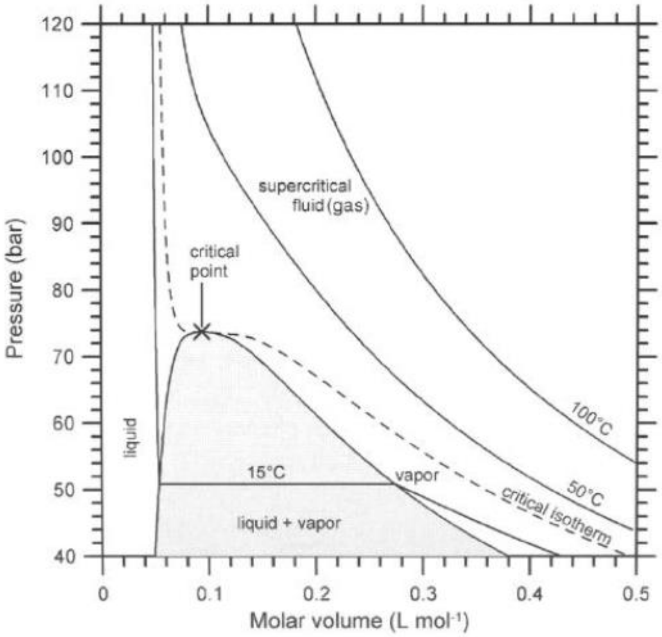

Figure 4: Simplified PV Diagram for CO_2 [17].

Another advantage is that supercritical CO_2 is more stable than the gaseous CO_2 [18]. Supercritical CO_2 has a density of 400-700 kg/m3 *(see Figure 5)*, which in most cases are less dense than the surrounding formation (unless it is a gas reservoir, where CO_2 is denser than the natural gas). Since the supercritical CO_2 is still less dense than the surrounding aquifer the CO_2 will rise buoyantly until it is trapped by an overlying seal[19].

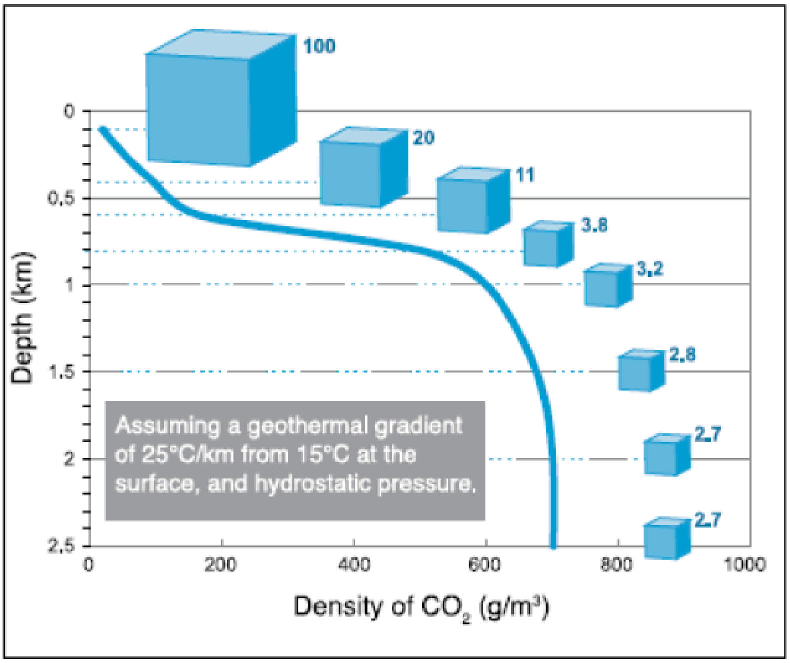

Figure 5: Density of Injected CO_2 with Assumed Geothermal Gradient of 25^0C/km, Surface Temperature of 15^0C and Hydrostatic Pressure[15].

During CO_2 injection, it is important to monitor the injection pressure. Pressure build-up can potentially reduce the estimated storage capacity in saline aquifers. Production of hydrocarbons relieves pressure build-up but this is not the case for saline aquifers, which do not have hydrocarbons[20].

2.2 Mineral storage

Another form of carbon sequestration involves the conversion of the gaseous carbon dioxide to stable carbonates. In this process, CO_2 reacts exothermically with available metal oxides, after which stable carbonates (e.g. calcite, magnesite) are subsequently produced. The process is a natural occurrence over many years and is responsible for a substantial quantity of surface limestone[21].

2.3 Storage Mechanisms

When buoyant CO_2 accumulates beneath the cap rock, a combination of physical and chemical trapping mechanisms work together to ensure that the CO_2 does not migrate from the reservoir for at least thousands of years[15]. In the most desirable conditions, the buoyant CO_2 plume is immovable under a thick and low-permeability cap rock, where a fraction of the injected volume is dissolved and later converted to carbonate minerals.

2.3.1 Physical Trapping Mechanisms

Physical trapping involves storage of CO_2 while keeping the physical properties it had at the beginning of injection [15]. Structural traps are formed by weathered rocks that acts as primary trapping mechanisms. These traps exist in most storage scenarios [15, 18]. Structural traps are in most cases overlying barriers that prevent CO_2 from further upward migration. However, faults that exist close to a storage site can potentially provide leakage pathways for CO_2 flow [15].

Hydrodynamic trapping, or residual trapping, is another form of physical trapping that is often observed in saline formations, where fluid flows very slowly [15]. The aquifer effectively blocks some of the CO_2 from further migration and consequently traps it within the sealing formation as residual CO_2 saturation. Hydrodynamic trapping is sometimes present without an overlying seal, and is in such cases the primary trapping mechanism [22]. Hydrodynamic traps also have the potential of leaking, if they are not properly sealed [23].

2.3.2 Geochemical Trapping Mechanisms

When the CO_2 plume is stagnated in the reservoir beneath the cap rock, some of it will eventually begin to dissolve in the formation water. This process is called solubility trapping [15]. When CO_2 dissolves in the formation water, the following reactions take place[24].

1) Gaseous CO_2 → aqueous CO_2:

$$CO_2(g) \rightarrow CO_2(aq)$$

2) Dissolved CO_2 → carbonic acid:

$$CO_2(g) + H_2O \rightarrow H_2CO_3$$

3) The overall reaction:

$$CO_2(g) + H_2O \rightarrow H_2CO_3^*$$

where H_2CO_3* is the sum of CO_2(aq) and H_2CO_3. The solubility of CO_2 in water has been shown to depend on temperature, pressure and salinity (see *Figures 6 and 7*) [25].

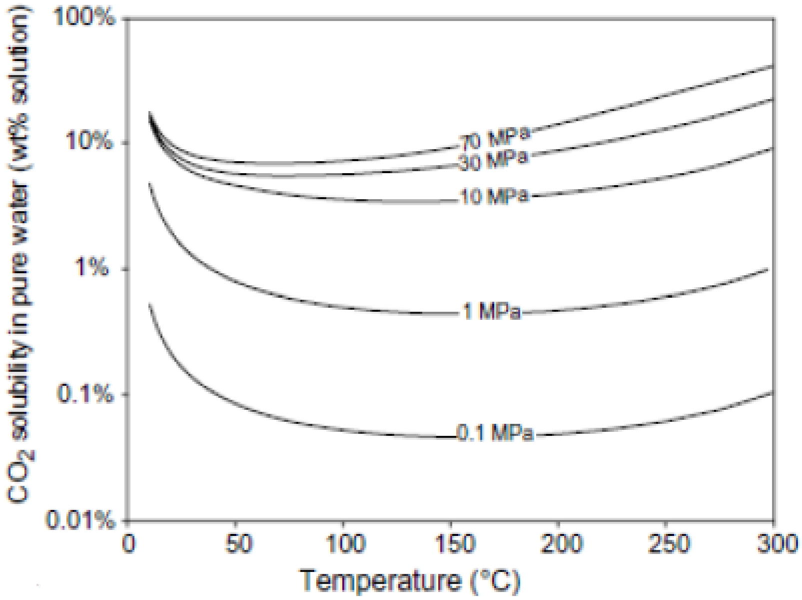

Figure 6: CO_2 Solubility in Water Dependent on Temperature and Pressure[25]

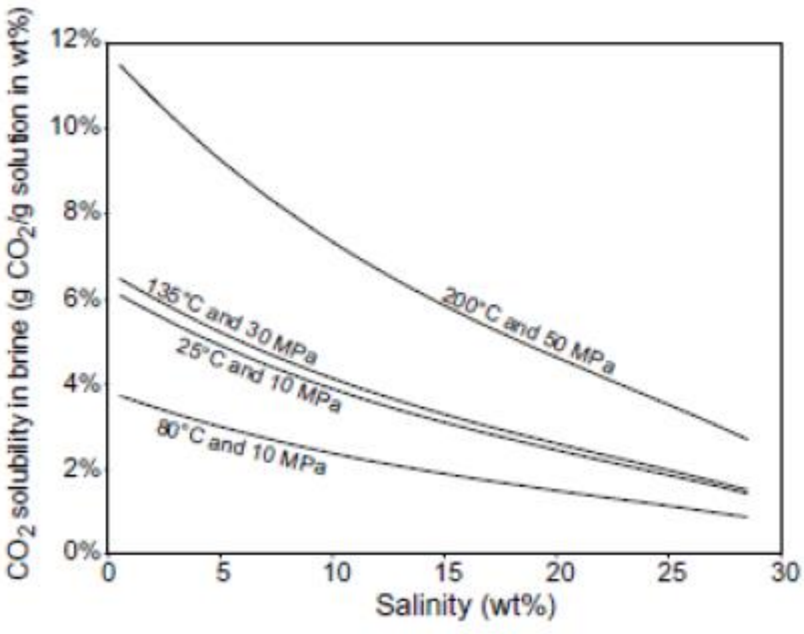

Figure 7: CO_2 Solubility in Water Dependent on Salinity[25]

As the rock dissolves, ionic species are formed and pH rises[15]. A part of the dissolved CO_2 can be involved in precipitation of secondary carbonate minerals that may permanently store CO_2. This trapping mechanism is known as mineral trapping and is a very slow process that can take thousands of years, or even longer. Since mineral trapping involves permanent trapping of CO_2 it is regarded as the safest way of long-term storage.

2.4 Examples of Storage Options

Storage of CO_2 can be conducted in various settings, including depleted oil and gas fields which often involves EOR-processes, deep saline aquifers and coal seams (see *Figure 8*). These settings vary in size, composition, and storage capacity, but are currently regarded as the most realistic and safe environments for permanent CO_2 storage [15].

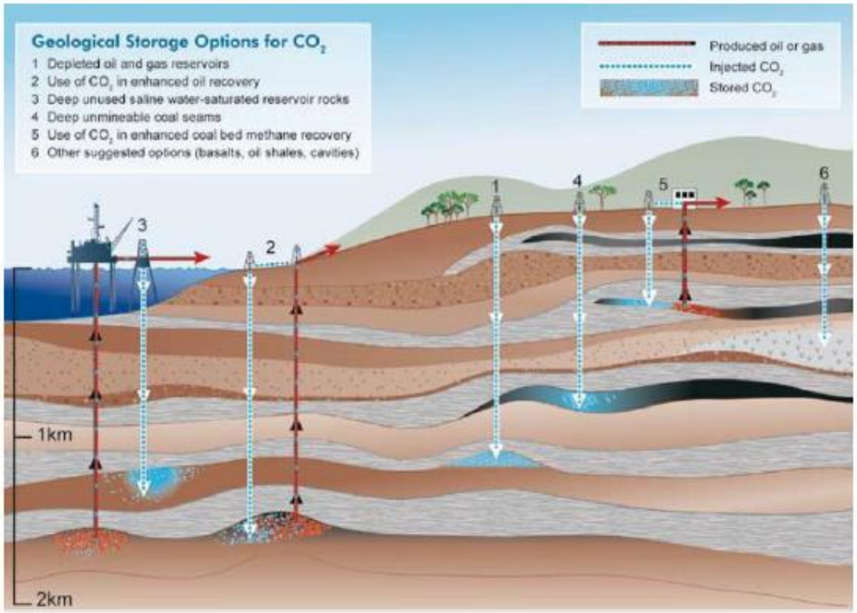

Figure 8: Options for CO_2 Storage[15].

2.4.1 Depleted Oil and Gas Reservoirs Including CO_2-EOR and CO_2-EGR

Mature sedimentary basins are good storage sites. Some of the mature fields are depleted or nearing depletion. These sites have been explored, studied and produced, which indicates existence of a successful seal. In addition, these sites may already contain the infrastructure needed for CO_2 transport and injection [15]. Global estimates of the storage capacity in oil reservoirs vary from 126-400 $GtCO_2$. For depleted gas reservoirs the storage capacity is estimated to 800 $GtCO_2$ [18].

Depleted oil reservoirs are considered as promising and safe locations for storage of CO_2 [18]. When combined with CO_2-EOR, injected CO_2 will also yield extra production of hydrocarbons and thus relieve pressure build-up, together with the obvious added economic benefit. Although CO_2-EOR only accounts for 0.3 % of the world's total oil production, the global storage potential of CO_2-EOR is estimated to lie within the range of 61-123 $GtCO_2$ [14, 15]. This translates to a global average incremental oil production of 13.2 % [15]. A challenge remains to optimize CO_2-EOR for CO_2 storage[26].

In CO_2-EOR, the carbon dioxide is stored due to the injected CO_2 being trapped by capillary forces and other mechanisms within the pore spaces that are previously occupied by reservoir fluid. When assessing the storage capacity of a project it is often assumed that all pore space previously occupied by hydrocarbons can be utilized to store CO_2. Research suggests that this might not always be the case, as some residual water saturation may be present because of capillary forces and water influx, which will ultimately reduce the estimated storage capacity[25].

CO_2-EOR can be performed either during miscible (or near miscible) temperature and pressure conditions where the CO_2 mixes and dissolves in the oil to enhance oil production, or at immiscible temperature and pressure conditions where CO_2 flows above the oil and increases the amount of oil recovery by gravity displacement [27]. Some of the CO_2 is permanently trapped in the reservoir in a CO_2-EOR process, while the rest is reproduced until the field is abandoned[26]. All the CO_2 is stored in the geological formation after completion unless some of it is needed for other purposes.

Depleted gas reservoirs are also regarded as very safe for CO_2 storage purposes. This is because the natural gas has been stagnated in these reservoirs for thousands of years, indicating presence of a sealing cap rock[18]. In CO_2-EGR projects CO_2 is primarily used for pressure support to prevent subsidence and water intrusion [27].

2.4.1.1 Weyburn-Midale CO_2-EOR Project (Canada)

The Weyburn-Midale CO_2-EOR project is one of the world's largest commercial storage sites, located in Saskatchewan, Canada. It is a CO_2-EOR project where the purpose is to increase the amount of heavy oil recovery from a depleted carbonate reservoir where hydrocarbons have been produced for 50 years [28]. CO_2 is injected into the two reservoirs at 59°C and 1 500 meters depth. CO_2 injection started in the year 2000 and approximately ten years later, 16 Mt of CO_2 had been stored in the reservoir (Whittaker et al. 2011). CO_2 injection will possibly continue until 2035 and beyond. Oil production has increased by 60%, yielding 155 million barrels of incremental oil recovery. Injection into the adjacent Midale Oil Field was started five years later in 2005. By 2010, 2 Mt of CO_2 had been stored at this location and it is estimated that injection will last 30-40 years with 60 million barrels of incremental oil production [20, 28].

2.4.2 Deep Saline Aquifers

Deep saline aquifers holds the largest potential storage capacity, which is thought to be at least 1000 $GtCO_2$, possibly as high as 10 000 $GtCO_2$ [15]. Capacity estimations of saline aquifers are notoriously difficult because of the interplay between different trapping mechanisms operating at different time scales, and limited availability of seismic data. Current estimations are based on discovered fields but could be 25 % higher if undiscovered fields are considered. This is also the case for the other storage options[22].

Aquifers that are too saline to be considered as drinkable groundwater are called deep saline aquifers[22]. These aquifers are porous and permeable rock formations generally found at depths greater than 800 meters where CO_2 acts supercritical. CO_2 in this condition is immiscible with the formation water[15]. Buoyancy drive in saline formations is strong because of the density differences between the supercritical CO_2 and the surrounding aquifer are large (30-50%). Storage mechanisms related to deep saline aquifers include structural trapping, hydrodynamic trapping and mineral trapping[29].

A significant challenge related to storage of CO_2 in deep saline aquifers is pressure build-up that occurs since no fluids are produced. Such pressure build-ups and potential fracturing can cause severe CO_2 leakage. Because of these risks the pressure build-up is a limiting factor for the storage capacity, meaning that the actual capacity can be less than the initial potential estimate[20].

2.4.2.1 Sleipner West (Norway)

Sleipner became operational in 1996, and as the first offshore commercial-scale injection site in the world the Sleipner project is a pioneer within CO_2 storage in deep saline aquifers. It is located on the Norwegian Continental Shelf, where carbon dioxide is injected into the extremely large Utsira Sand formation at a depth between 700-1000 meters (see *Figure 9*) with a rate of approximately 1 Mt/year[30]. CO_2-rich natural gas is produced from a reservoir located at a depth of 3 500 meters, and the CO_2 content must be reduced to meet government regulations before the natural gas can be sold[20].

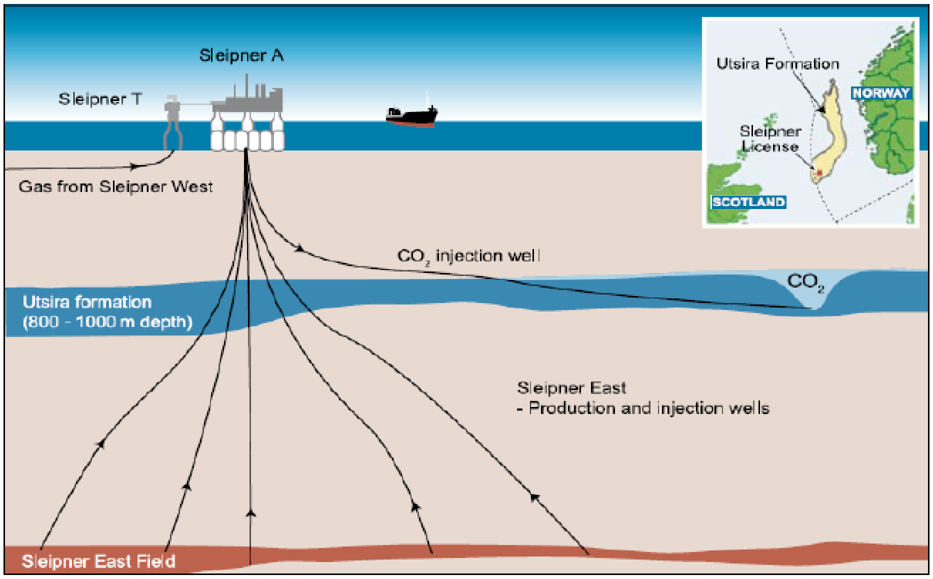

Figure 9: Schematic of the Sleipner project [15].

The Utsira Sand formation has inter-fingering layers of shale or clay that influences the movement of the CO_2 plume [19]. Above the aquifer the Nordland Shale cap rock prevents the CO_2 from migrating to the ocean floor. Nordland Shale is a 200-250 meters thick cap rock with a porosity of 5-10 % [30, 31]. More than 16 million tonnes of CO_2 has been stored since 1996 in the Utsira formation[32].

2.4.2.2 The In Salah Gas Project (Algeria)

The In Salah project in Algeria was the first industrial-scale CO_2 storage project in a gas reservoir in the world[15]. The project became operational in 2004 and involves re-injecting produced CO_2 from the natural gas into the Krechba carboniferous sandstone, which is a 20m-thick aquifer located at a depth of 1900 meters (see *Figure 10*). Natural gas containing up to 10% of CO_2 is reduced to at least 0.3% before it is sold[33]. CO_2 is injected in horizontal wells at a rate of 1.2 $MtCO_2$ per year. Approximately 17 $MtCO_2$ was stored, which translated to a cost of 6 dollar/ton CO_2 being avoided[15, 20].

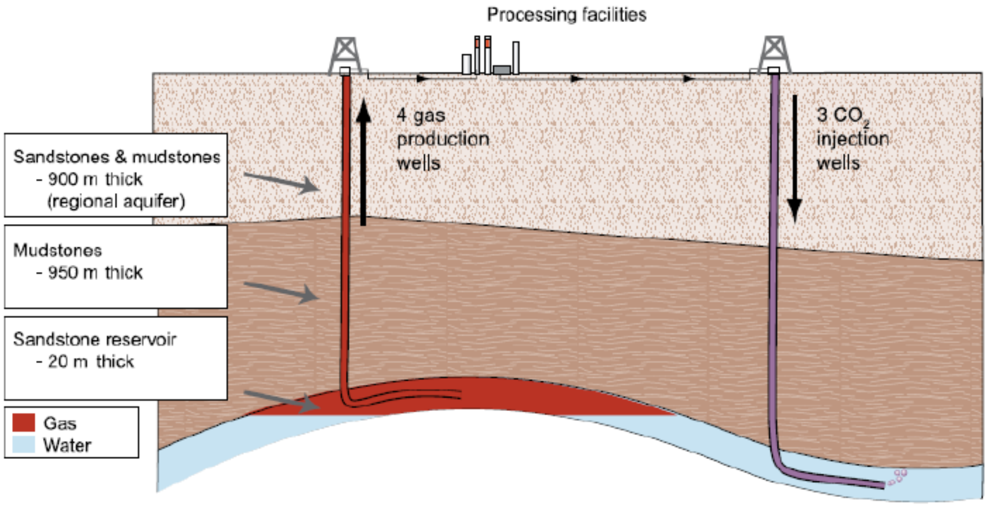

Figure 10: Schematic of the In Salah Gas Project storage site [15].

2.4.3 Coal Seams

Coal has fractures that alter the permeability of the coal seams. Gas molecules diffuse into micro-pores located between these fractures and strongly adsorb onto the coal, which is the main trapping mechanism in such storage environments[15]. Storage capacity is determined by the coal thickness, CO_2 adsorption isotherms, recovery factor and completion factor[29]. When CO_2 interacts with coal beds there will be adsorption and desorption of gases that were previously adsorbed on the coal as well as shrinking and swelling of the coal. The global storage capacity is thought to lie between 60-200 $GtCO_2$ [15]. However, assuming that CO_2 will only be stored in coal seams when recovering coal bed methane the theoretical storage capacity is reduced to 3-15 $GtCO_2$ [15, 29].

2.4.3.1 The Allison Unit CO_2-ECBMR Pilot (USA)

CO_2 injection lasted from April 1995 until the year 2001 with the purpose of enhancing coal bed methane recovery[15]. The Allison unit is located in the San Juan Basin in USA and has a CBM resource estimated to be 242 million m3/km2. CO_2 was injected into a 13m thick reservoir at a depth of 950 meters. After six years of injection 270,000-ton CO_2 had been stored. Although methane recovery increased from 77% of IGIP to 95% of IGIP, incremental methane recovery was reduced, and project cost escalated due to a significant permeability reduction[15].

2.5 Issues and Challenges for CO_2 Storage

In the following section, various key issues and challenges facing the implementation of CO_2 storage are highlighted with examples.

2.5.1 Integrity of the bounding seal system

A key to the long-term storage achievement in depleted oil and gas reservoirs is the hydraulic integrity of both the geological formations that bind it, and the wellbores that penetrate it. Although this “bounding seal” system’s integrity is controlled by geological factors, it is eventually influenced by different mechanical, chemical and thermal forces acting during exploration, development, oil production and secondary recovery operations, CO_2 injection, and also during the subsequent CO_2 storage phase. For illustration purposes, a number of leakage scenarios are illustrated *Figure 11*. However, it should be observed that leakage from the reservoir does not necessarily lead to leakage to the surface[13].

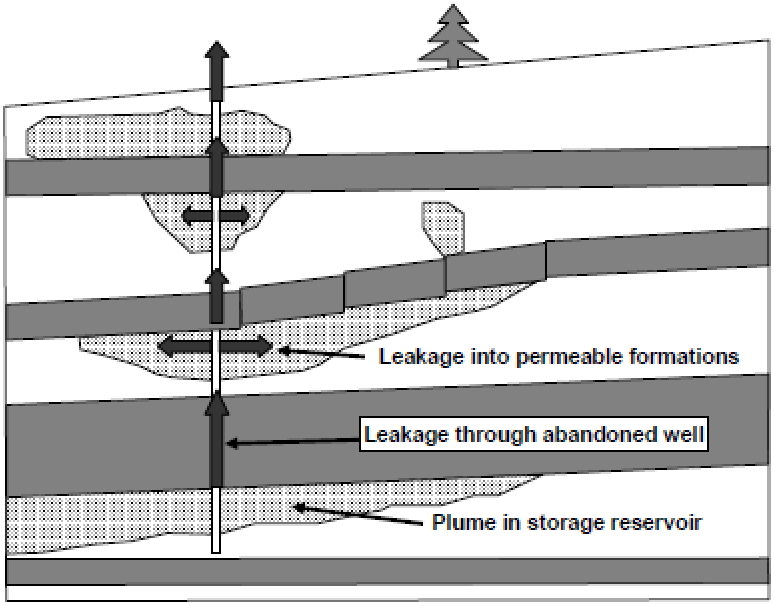

Figure 11: Possible CO_2 leakage pathways: Wellbores and/or faults and fractures [13].

2.5.2 Data availability and analysis

The wealthy subsurface data sets with respect to oil and gas fields will provide an underlying basis for evaluating CO_2 storage possibilities in depleted or near-depleted oil and gas formations, as well as allowing comprehensive research on regional subsurface geology. However, this inheritance information will be less useful in the analysis of other possible storage options, including saline formations[34].

Jurisdictions with public ownership of resources prior to production is a factor to consider, as countries such as Australia, Canada, the UK and nations with production sharing contracts tend to have more accessible and comprehensive data sets as the resource is a state asset. This easier accessibility to data set helps to accelerate further understanding and thereby mitigate preliminary exploration and evaluation costs. It is therefore recommended that 'data reporting and regulations need to be reviewed in order that CCS regulators are able to consult relevant data' and develop a 'deep understanding' of the basin's geological framework[34].

2.5.3 Storage Sink Location and Selection

In the initial demonstration part of CCS development, there is a compelling economic driver to find storage locations (or 'sinks') near emitting sources. In areas with scarce repository potential, long-distance transport by ship or pipeline can be viable over the long-term if wide-scale deployment of CCS underpins the scale efficiencies needed to reduce CO_2 transport cost over longer distances[34].

Geological factors, such as the danger earthquake and the lateral and vertical sealing effectiveness of the rocks surrounding the storage structure need to be considered before selecting CO_2 storage location. The potential interaction between geological CO_2 storage and the production of subsurface resources of fossil fuels, water and geothermal resources also require to be carefully considered[34]. Non-geological variables, including socio-political considerations, are often also significant factors in the choice and evaluation of storage site and must be taken into account at the early phases of a project[34].

2.5.4 Costs of storage

Investment in offshore pre-injection storage and actual construction of the storage infrastructure entails tens of millions or more of dollars. For instance, the Gorgon LNG project in Australia has spent more than AU$150 million on site-assessment operations for its CO_2 injection component within an existing hydrocarbon province prior to FID [34].

Although every project is distinctive in detail, in order to advance from small scale to injection-readiness, extra geophysical acquisition, drilling, well testing, predictive reservoir and containment modelling and laboratory analyses is required to investigate work during the operational and post-injection phases. This amount of data and analysis would also be needed to satisfy the regulatory and public requirements, and to show that the risks of leakage and other possible impacts on the environmental, health and safety, and other underground resources can be contained properly. Development and operating costs are highly vulnerable to aquifer/reservoir quality, mainly owing to the number of injection wells needed in lower quality reservoirs [34].

2.5.5 Skills and Experience

Parts of skill sets needed for storage assessment and development are subsurface geoscience and engineering skills and project management. In the oil, public and other energy sectors, these skills are already in high demand. The skills involved in translating large-scale projects such as Gorgon, In-Salah and Sleipner from concept to full-scale operation are therefore in short supply[34].

Also, while many of the abilities needed for carbon storage can be transferred from the hydrocarbon industries, some skills need to be enhanced before being deployed to carbon storage projects. Since most resource sectors are concerned with resources extraction, however, these procedures need to be adapted to large-scale injection and each site certainly has distinctive requirements.

As legislation is enacted to allow access to storage locations, worldwide regulatory shortages of skills and experience will continue for a while, especially in the areas of well integrity and measurement, monitoring and verification. [34].

2.5.6 Public Perception

The likelihood for injection-induced fault reactivation in relation to industrial injection operations is an important debate, not only from a safety point of view, but also from a public approval standpoint. Although the carbon capture and storage (CCS) has been identified as a promising alternative to reduce the CO_2 emission into the atmosphere, there are questions relating to the potential for prompting notable seismic activities and how the long-term integrity of a CO_2 storehouse might be affected by such activities, as well as how it might impact the general public insight of geological carbon sequestration [35].

3. Methods of Assessment of CO_2 Leakage Risk

In this section, a broad review of the most popular risk assessment methodologies pertaining to geologic storage of carbon dioxide will be highlighted. It should be noted that, since the proposal of CCS as a mitigating opportunity for reducing anthropogenic CO_2 emissions, many attempts have been made at studying the potential risks of long-term storage of CO_2 in geologic formations. Despite these attempts, there is currently no standardized technique or sets of procedures for evaluating risk and/or uncertainty for GSC projects.

However, there is need to mention the framework for which risk management exercise is carried out. Followed the framework is the overview of the methods risk of assessment.

3.1 Frameworks for Risk Management

Despite different frameworks found in standards and literatures on how to undertake risk management and risk analysis, most come to an agreement on what should be the necessary elements in the risk management process [36]. *Figure 12* describes the general framework for risk management according to NORSOK Z-013 [37], while *Figure 13* shows that of a risk analysis according to T. Aven in "Foundations of Risk Analysis". It should be noted that Aven's is an expansion of the risk analysis part of NORZOK Z-013 [38].

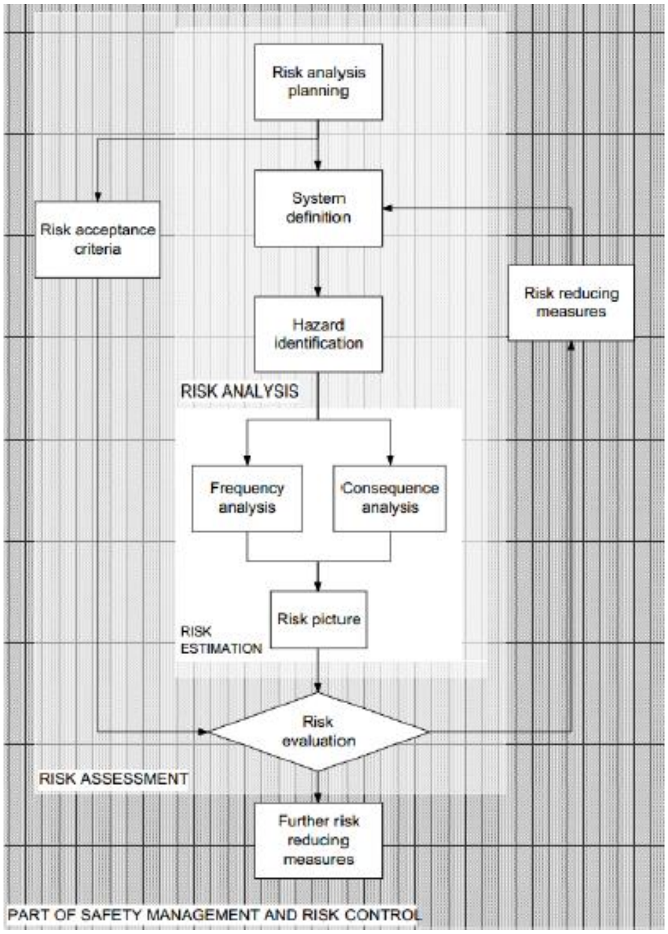

Figure 12: The risk management process as advocated in NORSOK Z-013 [36].

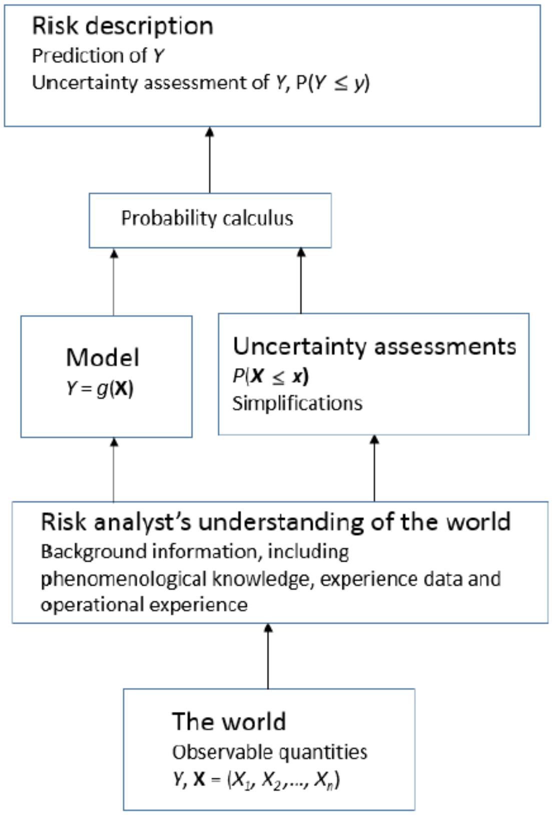

Figure 13: Framework for risk analysis from Aven's "Foundations on risk analysis" [38].

These two frameworks are general frameworks for an arbitrary case and have also implemented the updated definition of risk by the Petroleum Safety Authority (PSA) of Norway as, "risk can be defined as the consequences of an activity with the associated uncertainty"[8], which is against the classical definition as *risk* = *probability* x *consequence.*

For specific case of post-production leakage of oil and natural gas storage, DNV GL suggested *Figure 14* as a framework, while IEAGHG suggested *Figure 15* as framework for underground CO_2 storage. DNV GL has a clear link to NORSOK Z-013, but no explicit reference to probabilities or frequencies, focusing on only consequences.

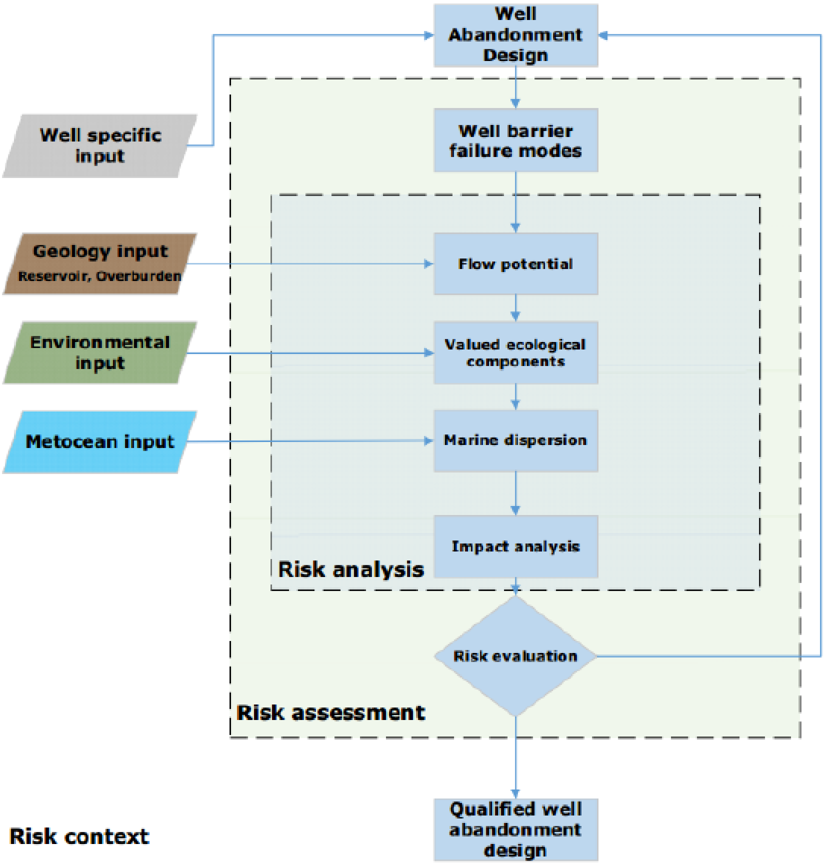

Figure 14: Framework for "risk-based abandonment of offshore wells" suggested by DNV GL[36]

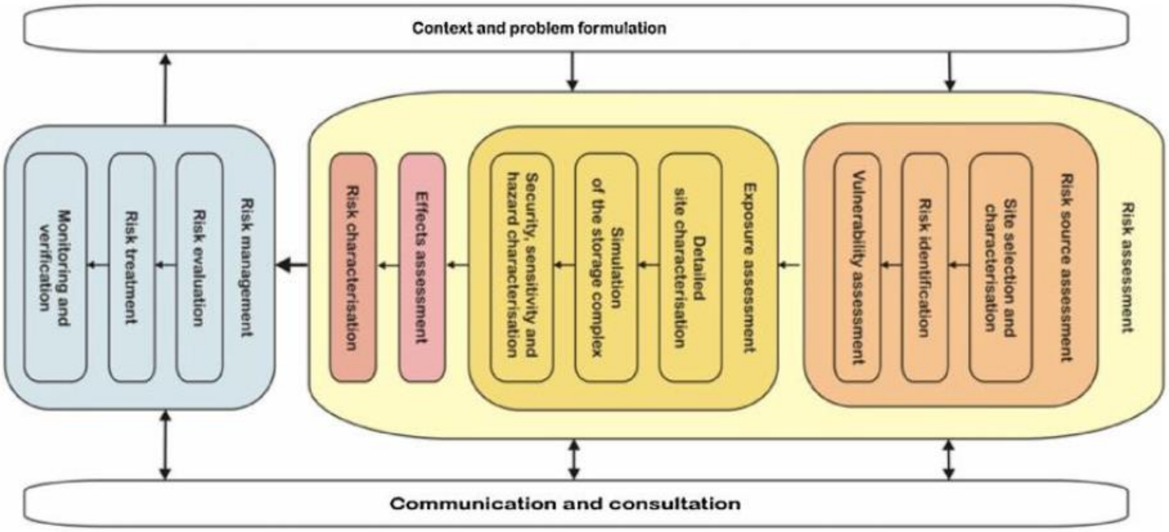

Figure 15: Recommended risk assessment, management and communication framework for CO_2 storage projects by IEAGHG [36].

3.2 The Features, Events and Processes (FEP)

This method is a qualitative risk assessment of different conceivable situations and consists of a rundown of relevant factors that portray the present state and likely future development of a site. Features consists of explicit on-site parameters like cap rock porosity, reservoir permeability, number of wells, etc. Events are processes such as seismic and well-blowouts. Processes could be physical and/or chemical, for example geo-mechanical or geochemical processes and multi-phase flow behavior. FEP analysis can be utilized in two different, but similar ways, bottom-up or top-down (see *Figure 16*). The bottom-up method utilizes the database specifically to build up the assessment models. In the top-down method the database is utilized as a review tool to make sure all applicable FEPs are incorporated in the models and to document the reason others have not been considered. The FEP analysis is handy in the licensing and certification phases of project development. As a disadvantage, it is a tedious strategy that requires extensive site specific information[3].

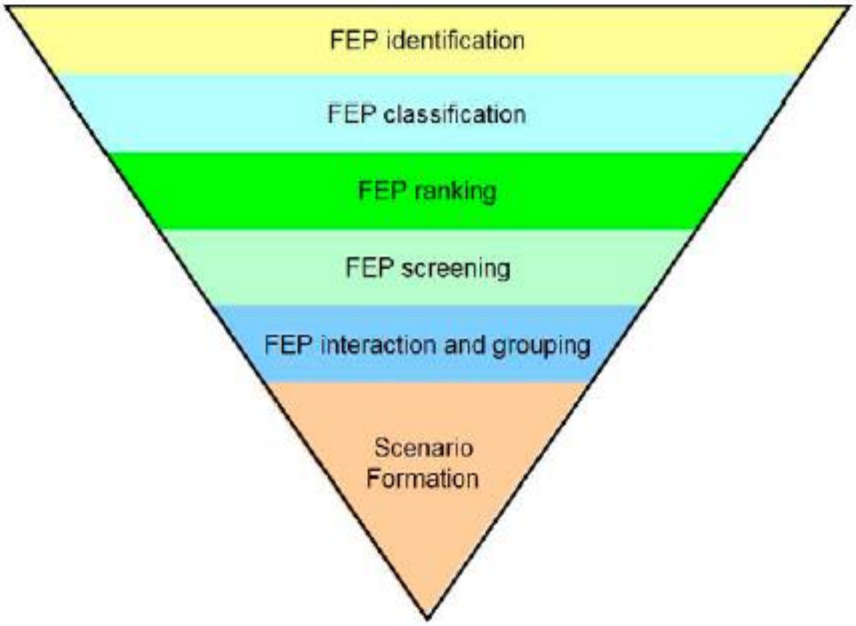

Figure 16: Different stages in FEP analysis, from identification to scenario formation[3]

3.3 The Vulnerability Evaluation Framework (VEF)

This is a qualitative method which methodologically recognizes conditions that could impact positively or negatively the potential for adverse consequences, developed by the U.S. Environmental Protection Agency (EPA), for the geologic sequestration of carbon dioxide. The applied strategy has three (3) main components, shown in columns in *Figure 17*, "the geological storage system and geologic attributes", "spatial area of evaluation", and "potential impact categories and receptors"[39]. The VEF is not intended as a site selection instrument, or established performance norms, or to specify data requirements, but as a conceptual framework to help regulators and technical professionals in framing specific considerations and identifying areas requiring design assessment, specific risk assessment, monitoring, and management. The VEF is somewhat identical to the Certification Framework Approach (CFA) created at the Lawrence Berkeley National Laboratory [3, 40]. Examples of projects where the method was applied are: the

Frio Brine Pilot Experiment in Texas, USA and the Weyburn Enhanced Oil Recovery (EOR) Project in Saskatchewan, Canada[39].

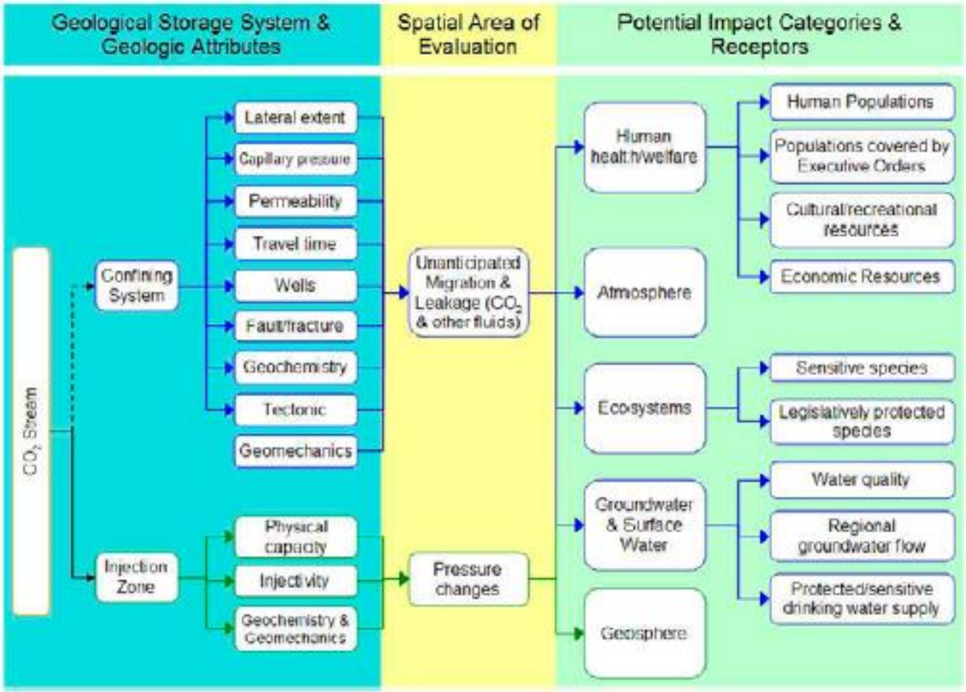

Figure 17: Concept model for the Vulnerability Evaluation Framework, VEF [39]

3.4 The Certification Framework Approach (CFA)

This is simple risk-based assessment approach for evaluating CO_2 and brine leakage risk at GSC sites, taking into account both the probability and impact of CO_2 and brine leakage. The objective is to provide a framework for GSC project advocators, regulators, and the public, to certify startup to decommissioning of geologic CO_2 storage in a simple transparent and acceptable manner[40]. The CF highlights leakage risk with respect to subsurface processes, assuming leakages associated with surface operations (i.e. capture, compression, transportation, and injection-well) are sufficiently taken care of by other frameworks. According to Oldenburg [40], "CF is formulated to be simple utilizing: (1) utilizing proxy concentrations or fluxes for quantifying impact rather than complicated exposure functions, (2) utilizing a catalog of pre-computed CO_2 injection results, and (3) utilizing a simple framework for calculating leakage risk." Certification Framework aims to be clear and accurate in terms of terminology in order to effectively communicate to all the stakeholders, using the following consistent definitions[36, 40]:

- *Effective Trapping* is the proposed overarching requirement for safety and effectiveness.
- *Storage Region* is the 3D volume of the subsurface intended to contain injected CO_2.
- *Leakage* is the migration across the boundary of the storage region.
- *Compartment* is a region containing vulnerable entities (e.g. environment and resources).
- *Impact* is a consequence to a compartment, evaluated by proxy concentrations or fluxes.
- Risk is the product of probability and consequence (impact).
- *CO_2 Leakage Risk* is the probability that negative impacts will occur to compartments due to CO_2 migration.

- *Effective Trapping* implies that CO_2 leakage risk is below agreed-upon threshold.

The CF approach was applied at GSC project in the Texas Gulf Coast, and WESTCARB's Phase III GSC pilot in the southern San Joaquin Valley, California[41]. Generic schematic of compartments and conduits in the CF, and flow chart of the CF approach are shown in *Figure 18* [40].

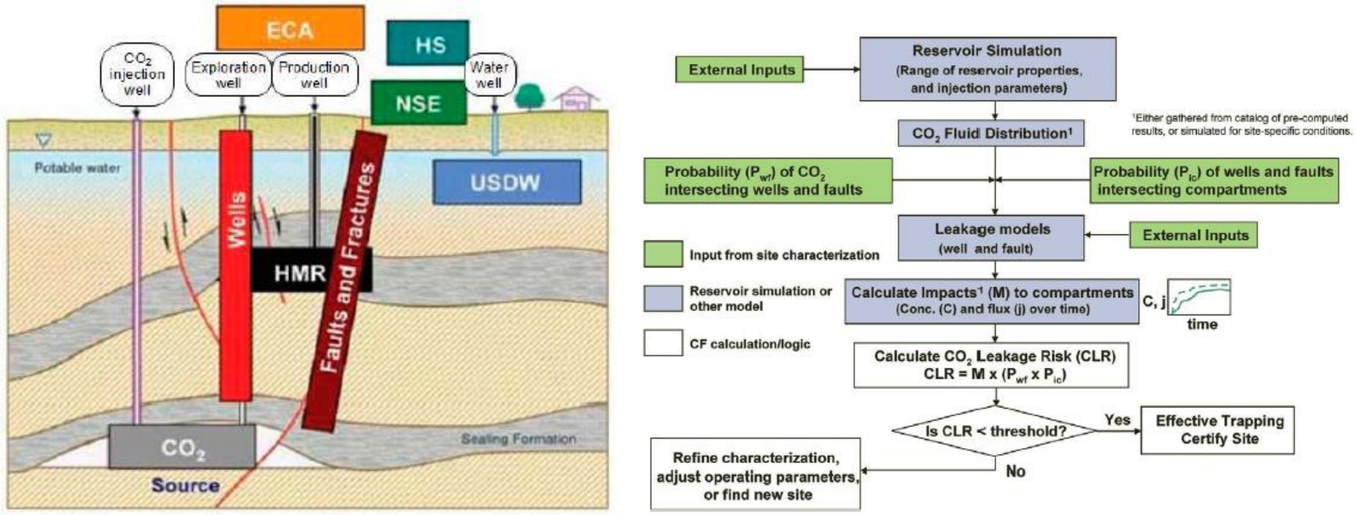

Figure 18: Generic schematic of compartments and conduits in the CF (left-hand side), and flow chart of the CF approach (right-hand side). *[40]*.

3.5 The Multi-Criteria Assessment (MCA)

Multi-criteria assessment includes a spread of non-monetary analysis techniques sharing a fundamental framework within which a number of options are scored against a sequence of outlined criteria and to which users attribute weights that reflect the comparative importance of each criterion[42]. This list of criteria, which can be categorized in groups, is proposed according to the fundamental objectives of the GSC. The MCA method conveys a rich profile of the perspectives and inclinations of stakeholders and thus aids 'mapping' key issues that will influence the prospects for further development. The method is relatively straightforward and can be implemented as a group process or making use of one to one interview as shown in *Figure 19.* As an example, the main storage alternative considered for GSC are oil and gas fields (both disused and with enhanced oil recovery), saline aquifer traps, saline aquifers outside traps and on-shore sites. The comparative performance of the situations along with the storage reservoirs integrated within them was evaluated by a small group of stakeholders in the carbon discuss against a set of socio-economic, industrial and environmental criteria [3].

A comparable technique to MCA is the Multi-Attribute Utility Theory (MAUT), while the primary distinction between them is that MAUT assumes a dependency of preferences of criteria, allowing for the inclusion of subjective elements[3].

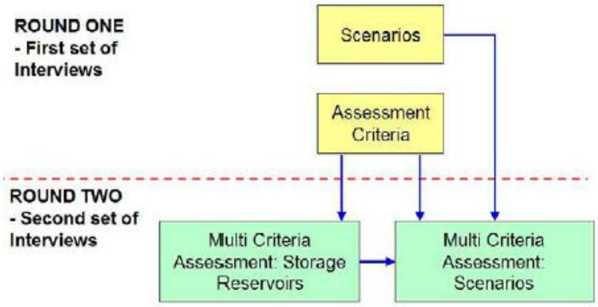

Figure 19: The MCA Interview Concept [3].

3.6 The Method Organized for a Systematic Analysis of Risk (MOSAR)

The method has been developed to analyse the technical risks of a system and to also identify prevention ways to neutralize them, and this system has been adapted to CO_2 geological storage site[2]. It consists of ten interacting sub-steps which are grouped into two major steps, as indicated below in *Figure 20*. The first step 'A' involves the realization of analysis of major risks, while the second step, step 'B' makes a detailed analysis of a system (or installation) and explicitly defines the safety tools associated with the technical dysfunction. The MOSAR method is a step by step approach, in which no step is to be neglected. However, this does not discourage flexibility, because should an unexpected circumstance or a fresh danger source appears, the event can be included without any probing at the start of the technique. The method is based on observations and evidence from the site and not only on complex mathematical models [2, 3].

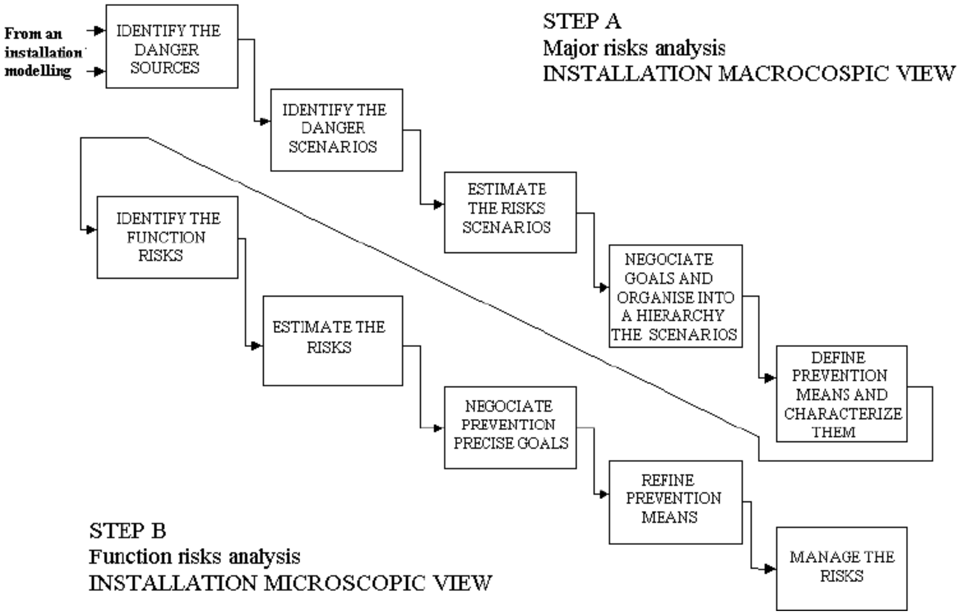

Figure 20: The MOSAR Concept[2].

3.7 The System Modelling Approach (SMA)

This is part of the CO_2-PENS (Predicted Engineered Natural Systems) that was developed in Los Alamos National Laboratory and initially designed to perform probabilistic simulations for the overall CCS chain. The injected CO_2 long-term fate, along with possible migration patterns from the target formation, is simulated through probability distributions [3]. "The model uses a science-based prediction approach by integrating information from process-level laboratory experiments, field experiments/observations and process-level numerical modeling" [36]. Precisely, it can be used to assess well leakage from a CO_2 storage reservoir. The approach is modular and allows easy integration of new models into the framework. According to Arild, the analysis steps are shown in *Figure 21* [36].

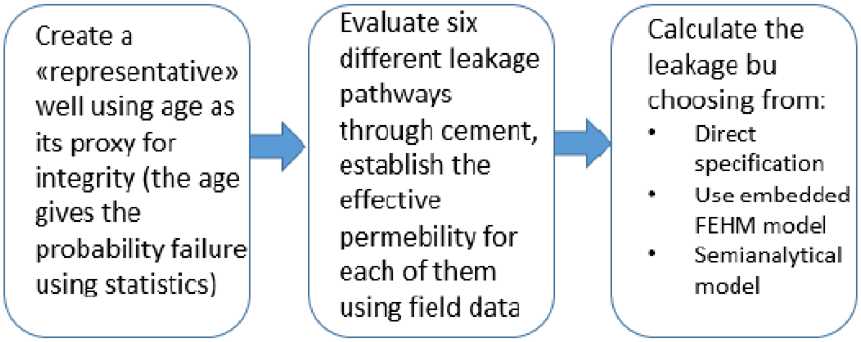

Figure 21: Main Steps in CO_2-PENS[36]

3.8 The Risk Identification and Strategy using Quantitative Evaluation (RISQUE)

This has been used in Australia's GEODISC program. This process systematically evaluates the specific features of a GSC site using expert panel judgments. It utilizes an event-tree technique, that can be interpreted as a list of FEPs. RISQUE utilizes logarithmic square matrices to assess the requirements for acceptability based on six performance indices: containment, self-funding potential, effectiveness, community safety, wider community benefits, and community amenity[43]. *Figure 22* provides an illustration of the criteria for acceptability between containment and effectiveness. This methodology has been validated at four Australian locations: Dongara, Petrel, Gippsland, and Carnavarcon [3, 43].

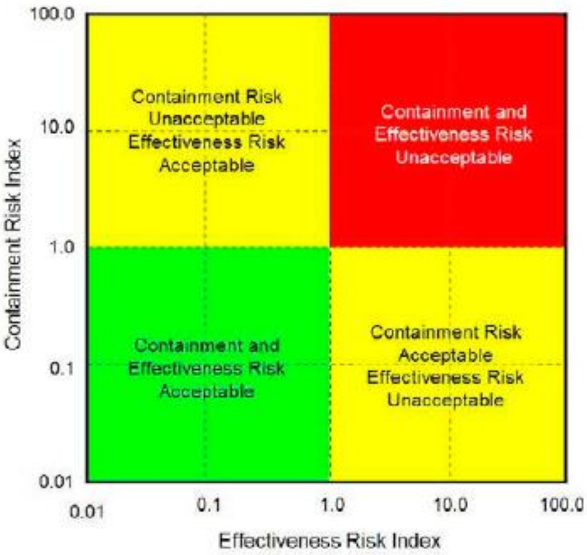

Figure 22: Containment and Effective Risk Matrix[43]

3.9 The Performance and Risk (P&R)

Performance and risk assessment toward well integrity was developed by Schlumberger and OXAND, and the idea is just like the traditional definition of risk (that is, likelihood versus consequence). The systems' uncertainties are transformed into the concept of probability, while the quantity of CO_2 leakage mass is converted into the concept of severity. In parallel, the method incorporated the definition of a Risk Acceptance Limit (RAL), which outlines the requirements for unacceptable risks and corresponding scenarios. See F*igure 23* for the illustration [3].

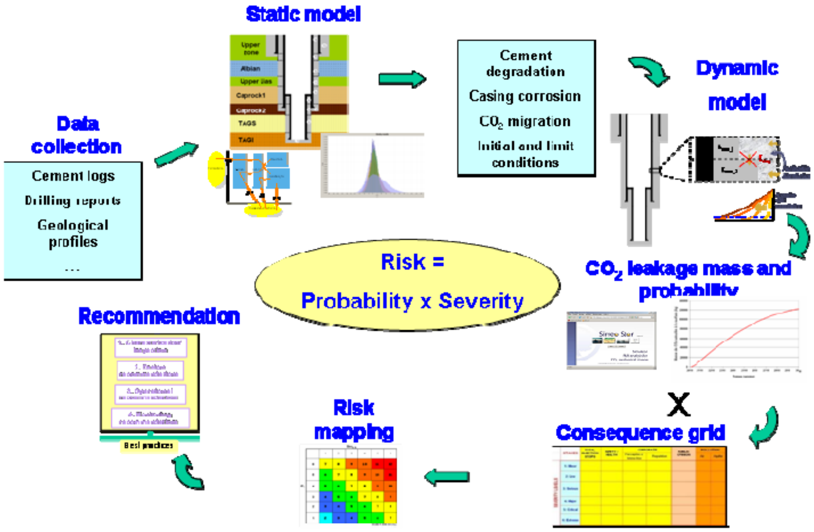

Figure 23: P&R Assessment for Well Integrity[44]

3.10 The Barrier Approach

A safety barrier is considered as a defense system constituted to reduce the risk of accidental events that could cause harm to assets, reputation, humans or the environment. Safety barriers could be classified as technical, organizational or operational. With respect to analysis related to underground CO_2 storage, technical barriers are often considered as due to the physical isolation of the underground storage, thus making it independent of organizational or operational barrier types, unless mitigating events such as intervention are included [45]. The concept of barriers implemented for plug and abandonment operations of oil and gas wells can be implemented for GSC sites as elaborated by PSA in the NORSOK D-010 standard. In designing wells to reduce leakage from a reservoir, whether oil or gas from an abandoned oil and gas field or CO_2 storage reservoir, the approach to well barrier is the similar[45].

Safety barriers are of course part of a risk management context, as they can eventually control and/or impact the amount of risk level. Fault tree, FMECA, event trees and now-ties are typical barrier analysis tools. Bow-tie is commonly used barrier analysis tool on the Norwegian Continental Shelf, used to visualize the risk under consideration and the barriers that are put in place to reduce the effects or eliminate the impact of the risk (see *Figure 24*). In this case, the incident considered is leakage of CO_2 from the storage system, i.e. loss of containment. They analysis proceeds by populating the bow-tie from left to right.

The steps involved in the Barrier analysis approach are: 1) defining and familiarizing with the system; 2) identifying failure modes and causes of failure; 3) constructing reliability models towards well barrier system; 4) conducting a qualitative analysis of the fault tree; 5) conducting a quantitative analysis of the fault tree: and 6) reporting result[45].

An example of a typical fault tree for leakage from an abandoned well can also be seen in appendix A.

The left side of the bow-tie diagram deals with the questions, “What are the main causes initiating a leakage?” and “What are the preventive barriers of the system?” While the right-side answers, “What are the mitigating barriers of the system?” and “What are the consequences, with respect to humans, operations and environment, of a leakage?”

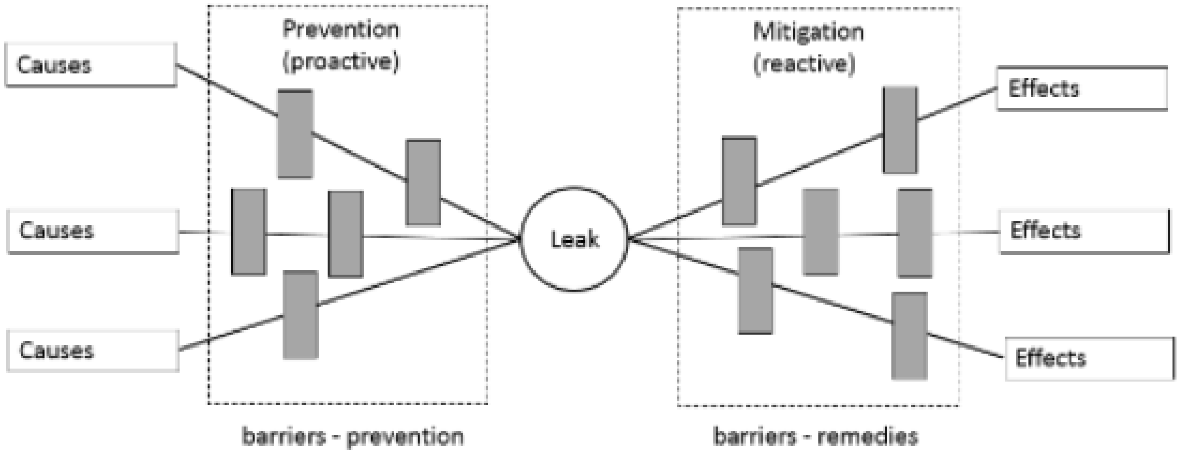

Figure 24: Example of a conceptual bow- tie diagram for a leakage scenario[45]

4. Comparison of the Methodologies

In the previous chapter, some common methodologies used for assessing leakage risk in geological storage of carbon dioxide (GSC) were highlighted. This section focuses on the differences and comparison among the various methodologies mentioned, while highlighting the factors these comparisons were based upon.

The evaluation has been carried out within the context and compared with the framework for risk management, proposed by NORSOK Z-013 and T.Aven's mentioned in the beginning of Chapter 3, showing the significance of incorporating uncertainty degrees in the assessment of leakage risks. The steps involved are as follows.

1. Establishing the context, including definition of the objectives
2. Establishing the internal and external parameters needed to be taken into consideration, determining the scope and evaluating the risk criteria to be used
3. Identification of sources of risk, and maybe also their causes and potential consequences
4. Risk analysis to understand the identified sources
5. Contextually analyzing risk that would form the basis for better decision making in risk evaluation processes.

4.1 Basis of comparison of the methodologies

This exercise has been based upon the following criteria, while a comprehensive result is shown in *Table 2*.

- Objective of methodology: This describes the purpose of the approach, be it a framework for assessment, identification of relevant situation or an approach to mitigate the risk
- Type of risk analysis (qualitative or quantitative): Basically, risk analysis could be quantitative or quantitative. Qualitative involves evaluating the probability and impacts against a pre-defined scale (such as "high", "medium" and "low"), while quantitative involves assigning numerical values to both the probability and impacts of a potential risk.
- Method or model required: Some assessments require simple models, while others require complex models to understand the science and chemistry of potential risks.
- Input parameters: Models or methods of assessment can only be implemented with the availability of parameters. Parameters could be physical properties, historical data, expert inputs, numerical data or past experimental values.
- Uncertainty focus: How uncertainty is addressed by each method is described here. Measure of uncertainties gives a sense of how the risk is being communicated to aid decision making process.
- Mode of communication: The way risk is communicated and interpreted to the targeted audience is critical to how the approach is accepted and implemented in the decision making.

Model	**Objective**	**Type of analysis**	**Method/Model required**	**Input parameter**	**Uncertainty focus**	**Communication**
FEP	To define relevant scenarios	Qualitative	Interaction matrices; process influence diagrams	Qualitative expert estimation for scenario development	Focus on consequences	Scenarios and risk matrices
VEF	Creating a conceptual framework to be used by regulators and technical experts	Qualitative	Decision-support flowcharts for evaluation of geologic attributes and receptors	Geologic system info. Qualitative expert estimation of areas that require in-dept evaluation	Hazard identification and potential consequences	Framework for regulator guidance
CFA	To estimate risk based on probabilities of occurrence in individual features	Qualitative and quantitative	Proxy concentrations models; migration models	Catalog of pre-computed CO_2 injection results, CBL logs	Likelihood of leakage and consequences	Leakage rates and consequences
MCA	Evaluation of alternatives against multiple criteria	Qualitative and quantitative	Interview of stakeholders	Views and preferences of participants	Focus on consequences	Maps of key issues raised by stakeholders
MOSAR	Identification and prevention of risks	Qualitative and quantitative	Site observations and facts	Danger sources and danger scenarios	Focus on danger identification	Systematic risk analysis
SMA	Risk estimation based on probabilities	Quantitative	Probabilistic simulation – CO_2-PENS, with embedded FEHM model	Process-level laboratory experiment and field data	Focus on consequences	Leakage rate for the pathway
RISQUE	Systematic evaluation using expert panel judgement	Qualitative and quantitative	Event tree, Logarithmic square matrix	Performance indicators	Focus on consequences	Risk matrix (for example containment-effectiveness matrix)
P&R	To map out risk in wellbores using degradation scenarios as criteria	Qualitative and quantitative	Static model, dynamic model, PDF, consequence grid, risk maps	Cement logs, drilling reports, geological profiles	Focus on probability and severity of quantity of leakage	Definition of Risk Acceptance Limit (RAL)
Barrier approach	To mitigate the risk	Qualitative and quantitative	FMECA, event trees, fault trees, bow-tie diagrams	Reliability data	Focus on failure frequencies	Bow-ties and trees

Table 2: Showing comparison of risk assessment methodologies.

Analysis using FEP approach is qualitative, relying on the use of checklists, with regards to the identified features, events and processes involved in CO_2 leakage. In order to structure the relationships between events and processes, interaction matrices and influence diagrams are used, as visualization tools and to simplicity. The outcome of FEP provides the input and directions needed to perform the quantitative consequence analysis of each scenario. However, as a disadvantage, it is a tedious strategy that requires extensive site-specific information.

VEF is not designed as site-selection tool, or established performance standards, or to specify data requirements, but as a conceptual framework, with the intention to assist regulators and/or technical experts. Flowcharts are used to evaluate geologic attributes of the sites, making it a qualitative method. These flowcharts aid in determining if low or high vulnerability may exist, suggesting how that vulnerability may be managed. The geologic attributes that could increase or decrease the vulnerability of a GS system are identified, so also the receptors (i.e. humans or environment) that may be potentially affected in the event of unanticipated migration, leakage, or pressure changes of the underground GSC site.

Just like FEP and VEF, CFA is also a framework for regulators, experts and public to communicate risk in a simple way. It combines both qualitative and quantitative approach using simple terminologies for easier understanding by all stakeholders; dividing the problem into compartments and intersecting pathways, assessing their probability against an established acceptable leakage impact. Risk is expressed in leakage rates and consequences, where the rate is calculated using a catalog of pre-computed CO_2 injection, and the consequences calculated from proxy compartment concentrations and fluxes.

The MCA method is straightforward and involves two stages, which are both qualitative and quantitative. Geologists and non-geologists assign individual scores for all criteria across the geologic storage options and scenarios, constituting the qualitative part. The overall options and scenario ranking are then calculated from the full set of criteria scores and weights. The output is maps of key issues raised by stakeholders' subjective views. MCA conveys a rich but biased profile of the perspectives and inclinations of stakeholders and thus aids 'mapping' key issues that will influence the prospects for further development.

The focus of MOSAR is on the identification and prevention of dangers, based on site observations and evidences. It is a step by step approach, in which no step can be omitted, consisting of complicated mathematical models.

SMA model is a quantitative approach to perform probabilistic simulation of the overall CCS chain. Steps include, creating a representative well for the field under consideration; defining probability density function for effective permeability for six leakage pathways and then calculating the leakage rate using embedded models (such as Finite Element and Mass-Transfer). Uncertainties are quantified from the probability density functions.

RISQUE is both quantitative and qualitative, using experts' judgements in conjunction with event tree to evaluate the acceptability criteria based on six main performance factors: containment, performance, self-funding potential, wider benefits, safety, and amenity. The output of the acceptability criteria is expressed in terms of risk matrix, mapping out two indicators at a time.

In the P&R approach, plug and abandonment data (tubular and cement logs) are used to model degradation of well components that are exposed to CO_2 and the near-wellbore environment over time, that is CO_2 leakage mass rate. To provide an understanding of the possible leakage scenarios, the input variables are assigned probability density functions to include uncertainty.

Barrier analysis approach focus on failure frequencies. The left side of the bow-tie diagram deals with the questions, "What are the main causes initiating a leakage?" and "What are the preventive barriers of the system?" While the right-side answers, "What are the mitigating barriers of the system?" and "What are the consequences, with respect to humans, operations and environment, of a leakage?"

4.2 Communication of Results and How to Support Decision-making

It is important to be able to express the value a risk assessment is creating. The main purpose of corresponding risk is to provide essential, relevant and truthful information in a concise and comprehensible wordage that is targeted toward specific audiences. In the business world, it is a must that the value of a technology be concisely communicated, if the technology is to be accepted. The stakeholders want to see the impact of the assessment, be it economical or environmental. To the operator, economic benefit seems to be the ultimate factor when assessing leakage risk of CO_2 sequestration, while to the public community within the location, hazardous exposure to the potential release of the gas is a big concern, while to the authority, it might be to comply with international requirements for greenhouse emission control. Effective communication of value of risk brings cohesion of all these concerns to the decision-making process and ensures that objectives are being met.

From *Table 2*, we can see the different ways risk is being communicated, depending on the approach and focus on uncertainties. Most of the qualitative, for example FEP, VEP are expressed in terms of risk matrices. Risk matrices use pre-determined scales such "high", "medium" or "low", making it easier for the general public to visualize the consequences involved in leakage. For quantitative approaches, a more systematic way is being implemented, to quantify the effects and consequences of the identified risk, while establishing an acceptable limit of leakage.

It is also noted that for quantitative approach, risk is mostly referred to in terms of probability and severity of quantity of leakage.

5. Concluding Remarks

The goal of performing geologic sequestration of CO_2 is to significantly reduce the amount of atmospheric release of anthropogenic greenhouse gases.

Since geologic storage of CO_2 and concealing it underground can easily be related to plugged and abandoned oil and gas reservoirs, the method of assessment of leakage risk in a plugged and abandoned well can easily be applicable to an underground storage of CO_2.

Injected CO_2 into deep geological formations may leak into well paths, cap rock, geological faults, and fractures, thereby allowing CO_2 to move into the surface or rather into the atmosphere, contaminating shallow underground water, soil, rivers, lakes, and air. This ultimately damages the environment and cause hazards to human health. Therefore, it is necessary to assess the risk of CO_2 leakages from these underground storages.

Many approaches have been suggested on how to assess this leakage risk, with similar objectives, but differ in some ways. Analysis should be simplified, using common terminologies for easier communication with all stakeholders. When assigning probabilities, uncertainties should be considered to account for variations in factors considered. In agreement with Petroleum Safety Authority of Norway (PSA), uncertainty is sometimes difficult to represent using probability in a meaningful way, thus there should be less single-minded focus on probability and more focus on what is behind these probabilities.

Considering the focus on uncertainties and how the notion is incorporated in the risk analysis, “Performance and Risk” and “Barrier Analysis” approaches seem to be preferable methods in assessing leakage risk of an underground CO_2 storage. The focus of P&R is on probability and severity of quantity of leakage; while that of barrier analysis is on failure frequencies, using tools such as bow-tie, fault tree and FMECA.

When doing risk assessment of these geological formations to decide if injection should be carried out or not, communication of the risk is very important because you want all the stakeholders involved to fully understand the risk that is being assessed. Miscommunication in any form can stir up conflicts among the parties. Just like in most projects, for underground storage of CO_2 the following stakeholders should be carried along in the risk analysis and assessment processes: the authority, the project sponsor, project manager, contractors, general public and others.

There is need for improvement on the methodologies in terms of consensus on the use of terminologies. So also more attention needs to be paid to the underlying uncertainties behind the use of probabilities in the expression of risk.

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Appendix A

An example of a fault tree for leakage from an abandoned well