EP

United Nations
Environment
Programme

UNEP(DEPI)/MED WG.387/Inf.14
29 July 2013

Original: ENGLISH

MEDITERRANEAN ACTION PLAN

Meeting of the MAP Focal Points

Athens, Greece, 10-12 September 2013

Draft Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations

UNEP/MAP
Athens, 2013

Draft Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations[1]

Intersessional Working Group on Carbon Storage

Rev 1 after MEDPOL FP meeting (Barcelona, June 2013)

---

[1] Geological formations means geological formations in the sub-soil of the Barcelona Convention maritime area, including sub-seabed geological formations.

Draft Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations[2]

Table of contents

PART A. REQUIREMENTS OF THE DUMPING PROTOCOL AND BARCELONA CONVENTION

A.1. Introduction p.04
A.2. Scope p.07
A.3. Definitions and Purpose p.07

PART B. CO_2 STORAGE IN THE MEDITERRANEAN BASIN

B.1. Carbon dioxide capture and storage (CCS) as one of a portfolio of options to effectively reduce future levels of atmospheric CO_2. p.09
B.2. Technical requirements of CCS in sub-seabed geological formations p.10
B.3. Environmental characteristics of the Mediterranean Sea p.12
B.4. Pilot and proposed storage sites in the Mediterranean basin p.14
B.5. Specific risks and potential effects of CCS in the Mediterranean basin p.17

PART C. RISK ASSESSMENT AND MANAGEMENT OF CO_2 STORAGE IN SUB-SEABED GEOLOGICAL FORMATIONS OF THE MEDITERRANEAN BASIN

C.1. Introduction p.20
C.2. Definition of the composition of the CO_2 stream that can be stored p.23
C.3. Risk assessment and management of CO_2 storage in sub-seabed geological formations of the Mediterranean basin p.23
Step 1. Problem formulation: critical scoping step, describing the boundaries of the assessment. p.23
Step 2. Site selection and characterization: collection and evaluation of the data of the site. p.28
Step 3. Exposure Assessment: characterization of the processes and pathways of the movement of the CO_2 within the formation and the environment. p.31
Step 4. Effects assessment: assembly of information to describe and evaluate the response of receptors within the marine

---

[2] Geological formations means geological formations in the sub-soil of the Barcelona Convention maritime area, including sub-seabed geological formations.

environment resulting from the exposure to CO_2. p.35
Step 5. *Risk characterization:* integration of the exposure and effects information to provide an estimate of the likelihood of impacts. p.37
Step 6. *Risk Management (including Monitoring and Mitigation plan):* Including monitoring, mitigation and remediation measures. p.40
C.4. Establishment of an authorization and licensing process p.46
C.5. Liability of CCS in the Mediterranean sea p.47
C.6. Overall conclusions and implications p.48

APPENDIX I. Information needs for Risk Assessment and Management p.51
APPENDIX II. Issues subject to further research to improve the Risk Assessment and Management p.53
APPENDIX III. Glossary, acronyms and abbreviations p.57
APPENDIX IV. Bibliography p.62

PART A:

REQUIREMENTS OF THE BARCELONA CONVENTION AND ITS PROTOCOLS

A.1. Introduction

1.1 The Convention for the Protection of the Mediterranean Sea Against Pollution (the Barcelona Convention) was adopted by the Coastal States of the Mediterranean region for the protection of the Mediterranean Sea.

1.2 The storage of carbon dioxide streams (CO_2) in geological formations under the seabed of the Mediterranean basin have some risks associated with leakage into the marine environment of the CO_2 and any other substances in or mobilized by the CO_2 stream. In general, there are different levels of concern regarding potential leakage that range from the local to the regional over both the short- and long-terms.

1.3 The Barcelona Convention (*the Convention*) is aware of the need of protection of the marine and coastal Mediterranean environment and its biodiversity from the potential impacts of this form of mitigation.

1.4 Carbon dioxide capture and storage in sub-seabed geological formations (CCS) is not allowed in the Mediterranean under the article 4 of the Protocol for the prevention and elimination of pollution of the Mediterranean Sea by dumping from ships and aircrafts or incineration at sea of the Barcelona Convention (the Dumping Protocol). It allows to only consider for dumping: dredged material, fish wastes, platforms and inert uncontaminated geological materials. In the case that Contracting Parties want to allow CCS in sub-seabed geological formations of the Mediterranean Sea, this article needs to be amended.

1.5 The ‘relevant provisions of the Convention’ include the general obligations in Article 4, in particular the obligation that Contracting Parties shall, in accordance with the provisions of the Convention, take all possible steps to prevent and eliminate pollution and to protect the marine area against the adverse effects of human activities so as to safeguard human health and to conserve marine ecosystems and, when practicable, restore marine areas which have been adversely affected (Article. 4.2,4.3). The Contracting Parties have cooperated in both the formulation and adoption of Protocols, prescribed agreed measures, procedures and standards for the implementation of this Convention

1.6 More specifically, the provisions of Articles 5 and 6 of the Convention, which requires that the Contracting Parties shall take all appropriate measures to prevent, abate and to the fullest possible extent eliminate pollution of the Mediterranean Sea Area caused by dumping (Article 5) and discharges (Article 6) from ships. Also, Article 7 specifies that the Contracting Parties shall take all appropriate measures to prevent, abate, combat and to the fullest possible extent eliminate pollution of the Mediterranean Sea Area resulting from exploration and exploitation of the continental shelf and the seabed and its subsoil. In addition, Article 8 states that measures should be taken to reduce pollution from land-base sources that originating within the territories of the Parties, and reaching the sea through coastal disposal. According to Article 11, the pollution resulting from the transboundary movements of hazardous wastes and their disposal should be reduced to a minimum, and if possible eliminated.

1.7 Also, Article 12 of the Convention requires that The Contracting parties shall endeavour to establish a pollution monitoring system for the Mediterranean Sea and cooperate in the formulation, adoption and implementation of such annexes to the Convention as may be required to prescribe common procedures and standards for pollution monitoring.

1.8 Moreover, Article 3(3c) of the amended Dumping Protocol specifies that ‘dumping’ means any deliberate disposal or storage and burial of wastes or other matter on the seabed or in the marine subsoil from ships or aircraft. Also, Article 3(4b) excludes from the definition of ‘dumping’ the placement of matter for a purpose other than the mere disposal provided that, if the placement is for a purpose other than that for which the matter was originally designed or constructed, it is in accordance with the relevant provisions of the Protocol.

1.9 Furthermore, Article 5 of the Dumping Protocol specifies that the dumping of the wastes or other matter listed in Article 4.2 of the same Protocol requires a prior special permit from the competent national authorities, which in accordance with Article 6 shall be issued only after careful consideration of the factors set forth in the Annex to the Dumping Protocol. Article 6.2 provides that the Contracting Parties shall draw up and adopt criteria, guidelines and procedures for the placement of matter.

1.10 Also, according to the protocol for the protection of the Mediterranean Sea against pollution from land-based sources and activities (the LBS Protocol), under its Article 1 states that Contracting Parties shall take all appropriate measures to prevent, abate, combat and eliminate to the fullest possible extent pollution of the Mediterranean Sea Area caused by discharges from rivers, coastal establishments or outfalls, or emanating from any other land-based sources and activities within their territories, giving priority to the phasing out of inputs of substances that are toxic, persistent and liable to bioaccumulate.

1.11 Moreover, according to Article 4.1(a) of the LBS Protocol, it applies to disposal under the seabed with access from land of discharges originating from land-based point and diffused sources. The General Obligations stated in Article 5, Contracting Parties shall elaborate and implement, individually or jointly, as appropriate, national and regional action plans and programmes, containing measures and timetables for their implementation. Furthermore, in accordance with Article 7, the Parties shall progressively formulate and adopt, in cooperation with the competent international organizations, common guidelines and, as appropriate, standards or criteria.

1.12 Also the LBS Protocol, specifies in Annex I the sectors of activity that will be primarily considered when setting priorities for the preparation of action plans, programmes and measures for the elimination of the pollution from land-based sources and activities (e.g. Energy production, fertilizer production, etc.). This annex also includes the characteristics and categories of substances that will serve as guidance in the preparation of action plans, programmes and measures in which CO_2 streams could be included (e.g. the risk of undesirable changes in the marine ecosystem and irreversibility or durability of effects / Acid or alkaline compounds which may impair the quality of water).

1.13 In addition, the Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean, which coverage includes the seabed and its subsoil (Article 2), establishes in its General Obligations (Article 3.1(a)) to protect, preserve and manage in a sustainable and environmentally sound way areas of particular natural or cultural value, notably by the establishment of specially protected areas. Furthermore, in Article 5.2 specifies that if a Party intends to establish, in an area subject to its sovereignty or national jurisdiction, a specially protected area contiguous to the frontier and to the limits of a zone subject to the sovereignty or national jurisdiction of another Party, the competent authorities of the two Parties shall endeavour to cooperate, with a view to reaching agreement on the measures to be taken and shall, inter alia, examine the possibility of the other Party establishing a corresponding specially protected area or adopting any other appropriate measures. Among the Protection Measures established in Article 6 (b) and (e), there is the prohibition of the dumping or discharge of wastes and other substances likely directly or indirectly to impair the integrity of the specially protected area and the regulation or prohibition of any activity involving the exploration or modification of the soil or the exploitation of the subsoil of the land part, the seabed or its subsoil;

1.14 The Article 4 of the Protocol for the Protection of the Mediterranean Sea against Pollution Resulting from Exploration and Exploitation of the Continental Shelf and the Seabed and its Subsoil states that all activities in the Protocol Area, including erection on site of installations, shall be subject to the prior written authorization for exploration or exploitation from the competent authority. Such authority, before granting the authorization, shall be satisfied that the installation has been constructed according to international standards and practice and that the operator has the technical competence and the financial capacity to carry out the activities. Such authorization shall be granted in accordance with the appropriate procedure, as defined by the competent authority. Also in accordance with Article 8, the Parties shall impose a general obligation upon operators to use the best available, environmentally effective and economically appropriate techniques and to observe internationally accepted standards regarding wastes, as well as the use, storage and discharge of harmful or noxious substances and materials, with a view to minimizing the risk of pollution. Considerations should be taken to the Annexes of this protocol in relation to the disposal of carbon dioxide and associated substances in the subsoil.

1.15 The Protocol on the Prevention of Pollution of the Mediterranean Sea by Transboundary Movements of Hazardous Wastes and their Disposal specifies in its Article 5.1 that the Parties shall take all appropriate measures to prevent, abate and eliminate pollution of the Protocol area which can be caused by transboundary movements and disposal of hazardous wastes. Among the Categories of Wastes Subject to this Protocol listed in Annex I there is no CO_2 streams but some of the compounds contained in the streams are included. In Annex II classification of Hazardous Characteristics, CO_2 streams could be classified as H6.1 - Poisonous (acute) as it is a substances or waste liable either to cause death or serious injury or to harm human health if swallowed or inhaled or by skin contact and H12 - Ecotoxic as if released present or may present immediate or delayed adverse impacts on the environment by means of bioaccumulation and/or toxic effects upon biotic systems depending on the leakage rate, also the leakage could be included in code H13. The disposal classification of CCS in Annex III will be D12 - permanent storage.

1.16 The following Risk Assessment and Management Framework for the storage of CO_2 in geological formations in the Mediterranean basin is prepared to assist Contracting Parties in:

(a) Assess the suitability of a potential storage site for permanent containment of CO_2 streams and identification of the necessary measures for hazard reduction, remediation and mitigation;

(b) Characterize the risks to the marine environment from carbon dioxide capture and storage on a site-specific basis; and

(c) Collect the necessary information (monitoring) and develop a management strategy to address uncertainties and manage and minimize risks.

A.2. Scope

2.1 The ultimate objective of storage of CO_2 streams in geological formations is to ensure permanent containment of CO_2 streams as one of a portfolio of options to reduce future levels of atmospheric carbon dioxide and further ocean acidification

2.2 Although permanent containment is the ultimate objective, it is necessary to show that, if leakage does occur, it does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

2.3 This Framework for risk assessment and management of storage of CO_2 streams in Geological Formations in the Mediterranean Basin is developed to provide generic guidance to the Contracting Parties to the Barcelona Convention.

A.3. Definitions and Purpose

3.1 Carbon dioxide capture and storage (CCS) is a process consisting of the separation of a CO_2 stream from industrial and energy-related sources, transport to a storage location and long-term isolation from the biosphere, including the atmosphere.

3.2 Although the storage of CO_2 streams in geological formations under the seabed includes the capture of CO_2 (either onshore or offshore) and its transport (either by pipelines or ships) to the injection site, this Framework is limited to the process of injection and post-injection risks of leakage. Some issues related to transport are included, where relevant. However, the risks of the CO_2 streams transport should be adequately addressed in other regulations and standards at national and/or international level.

3.3 The CO_2 storage in the water column is not considered as an option and it is banned by the Convention.

3.4 For the purpose of this framework for risk assessment and management, the following categories of substances are distinguished:

1) CO_2 stream
    a) CO_2;
    b) Incidental associated substances derived from the source material and the capture, transport and storage processes used, consisting of:
        i) source and process derived substances; and
        ii) added substances (i.e. substances added to the CO_2 stream to enable or improve the capture, transport and storage processes); and
2) Substances mobilized as a result of the disposal of the CO_2 stream.

3.5 The depth of water above CO_2 storage sites is likely to be less than 500 meters (i.e. predominantly beneath continental shelves). This is sufficiently shallow such that most forms of CO_2 potentially escaping from the underlying sediments will have positive buoyancy. In case that CO_2 storage extend to geological formations beneath much greater depths than in continental shelf and upper continental slope environments, this Framework may need to be further developed to take account of other potential exposure and effects pathways.

3.6 The assessment of hazard and risk related to storage of CO_2 streams in geological formations includes a significant level of uncertainty, and specially since extremely long time horizons are involved. This should be accounted for by using uncertainty analysis and included in the results.

3.7 The storage in geological formations of carbon dioxide streams from carbon dioxide capture processes shall not be permitted by Contracting Parties without authorisation or regulation by their competent authorities. Any authorisation or regulation shall be in accordance with the Barcelona Convention Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations, as updated from time to time.

3.8 A decision to issue a license for the purpose of CCS should only be made if all impact evaluations are completed and the monitoring requirements are adequately determined. This includes an adequate site characterization, an assessment of the likelihood for migration and leakage and associated impacts and a suitable risk management plan.

3.9 The Contracting Parties should verify the technical competence and financial ability of the operator of the CCS site before issuing a license.

3.10 When a storage site belongs to a geological formation from several countries, or when there is potential for transboundary movement of CO_2 streams after injection, the license should be issued in agreement with all countries with jurisdiction over this sub-seabed geological formation, without prejudice to international law. The Contracting Party where the injection occurs is responsible for the implementation of this Framework. The responsible Contracting Party should cooperate with Contracting Parties, other States and other relevant entities, including by way of arrangement or agreement to ensure that the guidelines included in this Framework are implemented effectively.

3.11 Short, medium and long-term liability for potential physical leakage or seepage of stored carbon dioxide, potential induced seismicity or geological instability or any other potential damage to the environment, property or public health attributable to CCS project activity during and beyond the license period, including the clear identification of liable entities, shall be applied during and beyond the license period; and be consistent with the different protocols of the Barcelona convention.

3.12 In Appendix II there is a compilation of several issues that, at the time of issuing this Framework, required further research in order to improve the process of risk assessment and management for the storage of CO_2 streams in geological formations under the seabed.

PART B:

CO_2 STORAGE IN THE MEDITERRANEAN BASIN

B.1. Carbon dioxide capture and storage (CCS) as one of a portfolio of options to effectively reduce future levels of atmospheric CO_2

1.1 The current rates of emission of greenhouse gasses to the atmosphere need to be reduced to mitigate climate change. However, global warming and sea level rise will continue to increase for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were stabilized in the atmosphere.

1.2 Carbon dioxide is the most important anthropogenic greenhouse gas. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 parts per million (ppm) to 400 ppm by 2013. The main source of this carbon dioxide is from the use of fossil fuel and, according to the International Energy Agency (IEA), fossil fuels will be responsible for more than half of the estimated 36 per cent increase in worldwide energy consumption by 2035 (IEA 2010). In addition, it is expected that coal will continue to be the main fuel used for electricity generation due to the projected increases in its use in developing countries.

1.3 The Barcelona Convention is aware of the adverse effects of climate change on coastal and marine ecosystems and on the environment in general and the negative consequences for sustainable development, particularly for developing countries in the Mediterranean basin. There are many and interlocking challenges that must be addressed in order to effectively mitigate, reduce and combat environmental degradation and to promote sustainable development in the Mediterranean region.

1.4 In order to reduce the impacts of climate change, a portfolio of mitigation efforts is required to reduce the emissions of carbon dioxide (CO_2) to the atmosphere.

1.5 Among the mitigation measures considered internationally, carbon capture and geological storage (CCS) is one of the options economically and technologically viable. According to the IEA scenarios, CCS could account for 19 per cent of the emission reduction in the energy sector, and together with the use of renewable energy and other mitigation efforts if the total atmospheric concentration of greenhouse gases (equivalent carbon dioxide, CO_2e) are to be stabilized at 450 ppm by 2050 (IEA 2010).

1.6 CCS involves the use a range of technologies to first capture and concentrate the CO_2 produced in industrial and energy related point sources, transport it to a suitable geological formation and permanently store it away from the atmosphere. Recent technological developments have made possible to capture CO_2 from diffuse sources (air capture) and together with permanent storage could increase the contribution of emissions reduction of CCS.

1.7 Therefore, governments have increased research and demonstration efforts for CCS. At this point, governments have made the commitment to support around 25 large-scale CCS projects over the world. In the case of the European Commission there is the commitment to promote Member States and private sector investments to ensure the construction and operation of 12 full CCS demonstration projects by 2015, in order for

CCS to be commercially viable by 2020.

1.8 Moreover, CCS was included as a clean development mechanism (CDM) at COP17 of the United Nations Framework Convention on Climate Change (UNFCCC), including CMP7 of the Kyoto Protocol, in Durban South Africa in December 2010. Therefore, CCS projects in non Annex I Parties to the UNFCCC have the potential to earn certified emissions reduction units (CERs), which have a positive commercial value on the international carbon market. The agreement also requires that the countries accept long-term liability for the CCS projects to account for any leakage of stored CO_2, with 5% of the carbon credits being set aside during 20 years after it is buried. The combination of storage projects with enhanced oil or gas recovery (EOR/EGR) as a CDM is still under discussion.

1.9 CO_2 capture technologies have already been deployed commercially for some time in different industries but need to be further developed and tested when applied to the power generation, iron, steel or cement industries. The geological storage of CO_2 has been done for a long time in the oil and gas industry when CO_2 is been used to enhance hydrocarbons recovery (enhanced oil recovery, EOR and enhanced gas recovery, EGR). However, further research is needed in monitoring and verification of the CO_2 stored to prove the permanent and safe storage of the gas. Other storage formations as deep saline aquifers have been in use more recently in a few large-scale CCS projects.

1.10 According to the Global CCS institute, governments and industry are still in the early stages of implementing large-scale CCS projects and therefore speed up the commercial deployment of this emission reduction measure.

B.2.Technical requirements of CCS in sub-seabed geological formations

2.1 CCS consists in four main processes: CO_2 capture, transport, injection and geological storage.

CO_2 Capture

2.2 CO_2 gas has to be captured and concentrated to be suitable for transport and storage. Injection and storage of dilute gas streams is impractical and economically unviable due to a higher energy cost and other costs related to transport and injection of larger volumes of gas and also because a larger volume of gas will require more volume of the storage formation.

2.3 Separation of CO_2 in industrial processes is common, mainly for purifying other industrial gas streams, very rarely for CO_2 storage. There are three main types of capture of CO_2 depending on the type of industrial process or power plant. These are:

a. Post-combustion separation: CO_2 is removed from flue gases from fuel combustion with air. This system can be used in modern pulverized coal (PC) and natural gas combined cycle (NGCC) plants. About 85% of the CO_2 can be removed.

b. Pre-combustion separation: The primary fuel is processed before combustion in a reactor with steam and air or oxygen. This process produces hydrogen (H_2) and carbon monoxide (CO), which is then reacted with steam in a second reactor to produce H_2 again and CO_2. These gases are then separated. This system requires more energy than post-combustion separation but produce higher concentrations of CO_2 in the flue gas and at higher pressure.

c. Oxyfuel: Those systems combust primary fuel with oxygen (instead of air) to produce a flue gas comprising mainly of CO_2 (more than 80% by volume) and water vapor (H_2O). The water vapor is removed by cooling and compressing the flue gas and other processing may be required to remove other gaseous pollutants.

2.4 Current technology is able to capture 85-95% of carbon in pre-combustion and post-combustion systems. However, as capture and compression requires an extra 10-40% more energy compared to an equivalent plant without capture, the net amount of CO_2 captured (or net CO_2 avoided) is 80-90% (IPCC 2005).

CO₂ Transport

2.5 In CCS from energy related sources or industries, transport of CO_2 is necessary as they would probably be at some distance away from the storage location. There is a wide experience in transport of pressurized gaseous CO_2 with pipelines as it has been used for EOR or EGR. In the USA there are more than 2,500 km of pipelines that move more than 40 Mt CO_2 annually, so CO_2 pipeline transport is already considered mature market technology. Transport of CO_2 by ships, road or rail is also possible and might be more suitable if CO_2 has to be transported over large distances or overseas. There are different considerations for different modes of transport like cost, safety and feasibility (IPCC 2005).

CO₂ Injection and storage

2.6 Geological storage involves the injection of dense CO_2 into a geological formation below the earth's surface. The four types of geological formations that are being most used are storage in oil and gas reservoirs, deep saline formations, basalts and un-minable coal seams, due to the ability of these formations to receive and trap injected CO_2 permanently. Suitable storage sites can be located onshore or offshore. Also, the possibility of storing CO_2 in coal beds while enhancing methane production is being studied. The technology necessary for injection of CO_2 into geological formations is similar to those already in use in the oil and gas exploration and production industry, or natural gas storage, or liquid gas and acid gas disposal industries (IPCC 2005).

2.7 For deep saline formation and hydrocarbon reservoir storage, the CO_2 is likely to be injected at a depth of more than 800 m where the temperature and pressure will keep the CO_2 in a dense liquid or supercritical state suitable for storage. However, at these depths CO_2 will still be more buoyant than water (being 50-80% the density of water), and has a tendency to move upwards compared to water. Thus, a well-sealed cap rock is necessary to trap the CO_2. Upon injection, the CO_2 compresses and partially displaces the fluids that are already present in the pore space. In oil and gas reservoirs CO_2 displaces most of the pore fluids, but saline formations have a lower potential for storage as there is a smaller suitable porose space (around 30% of the total rock volume, IPCC 2005). However, estimates indicate larger amount of saline formations that might be available for CCS.

2.8 According to the IPCC 2005, the fraction of CO_2 retained in the long-term depends on the physical and geochemical trapping mechanisms in the storage formation. Estimates drawn from current CCS storage systems, analogous natural systems, engineering systems and models show that it is very likely to exceed 99% over 1000 years. This retained fraction is likely to increase over time as different trapping mechanisms affect the process over time. Initially, one of the most important trapping mechanisms is the physical trapping in the form of an impermeable cap rock that stops the upward movement of CO_2. Then, capillary forces work to keep the CO_2 in the pore space. Lateral movement of CO_2 beneath the cap rock due to breaks or absence of the cap rock is possible but geochemical trapping mechanisms work to retain the injected CO_2. Geochemical trapping occurs as CO_2 reacts and dissolves into the pore water over hundreds to thousands of years. The resulting mixture increases in density and sinks instead of being buoyant. Further chemical reactions with the rock minerals form solid carbonates that are stable over millions of years. CO_2 could also be adsorbed onto coal or organic-rich shales, displacing gases like methane, which can be harvested for combustion. Under this situation, the CO_2 will remain trapped unless pressures and temperatures are disrupted (IPCC 2005).

2.9 According to Bachu (2007), a suitable geological CO_2 storage site has to fulfill three requirements: ‘capacity’ to receive intended amount of CO_2, the ability to accommodate the rate of CO_2 supplied by the emitter (‘injectivity’) and the long-term ‘confinement’ of stored CO_2 in the storage site. Sedimentary basins are particularly suitable as they contain sandstone and carbonate rocks. These are porous thus enabling storage capacity, permeable to allow gas or liquid injection and possess an impermeable caprock layer that stops the movement of CO_2 out of the storage site. Coal beds are also being investigated for CO_2 storage due to their ability to adsorb CO_2. Currently, most of the estimated potential for safe long-term storage comes from oil and gas reservoirs or saline aquifers, and a large proportion of the identified storage capacity is found offshore (London Convention and Protocol 2006).

B.3. Environmental characteristics of the Mediterranean Sea

3.1 The Mediterranean Sea is the largest (2,969,000 km^2) and deepest (average 1,460 m, maximum 5,267 m) enclosed sea on Earth. It supports a high density of inhabitants, distributed in 21 modern states, and it is one of the top tourist destinations in the world, with 200 million tourists per year.

3.2 The Mediterranean is considered a ‘biodiversity hotspot’, having the longest history on continuous human civilization records of ecological and biodiversity studies, dating back from Egyptian Civilization.

3.3 Oceanography and biogeochemical cycles in the Mediterranean Sea are largely affected by flows through the straits, where the minimum contact with the rest of the oceans occurs, and river inflow, when continental and anthropogenic substances are incorporated into the biogeochemical cycles. Fluxes on the atmosphere – sea surface interface, such as evaporation or incorporation of desert dust, and vertical dynamics, such as upwelling/downwelling processes are also considered basic to understand both the general dynamics and regional particularities of the Mediterranean Sea.

3.4 The Mediterranean seabed is composed by a variety of terrestrial sediments over an oceanic crust. Several subsurface gas and oil reserves have been identified in the

Mediterranean seabed, as well as areas were natural leakage of CO_2 from those structures exist. The region is seismically active mainly due the northward convergence and complex plate boundary of the African plate with the Eurasian plate. The Hellenic subduction zone (Southern Greece), the North Anatolian Fault Zone (Western Turkey) and the Calabrian Subduction zone (Southern Italy) present the highest seismicity rates in the Mediterranean:

a. The Hellenic subduction zone presents local high rates of convergence associated with back-arc migration above the subducting oceanic crust (throughout Greece and western Turkey)

b. The North Anatolian Fault has a high seismicity due to the lateral horizontal motion between the Anatolian micro-plate and the Eurasian plate. The Anatolian micro-plate is pushed due to the collision of the African and Arabian plates in southeastern Turkey.

c. The Callabrian subduction zone causes a significant zone of seismicity around Sicily and in general southern Italy, with active volcanoes in the area.

3.5 Effects of the active seismicity in the Mediterranean region have been recorded for several centuries. Earthquakes have historically caused widespread damage across central and southern Greece, Cyprus, Sicily, Crete, the Nile Delta, Northern Libya, the Atlas Mountains of North Africa and the Iberian Peninsula. The largest instrumentally recorded Mediterranean earthquakes (the 1903 M8.2 Kythera earthquake and the 1926 M7.8 Rhodes earthquakes) are associated with subduction zone tectonics. Some of the most intense earthquakes recorded affected dense population areas, with high casualties. Large earthquakes in the Mediterranean region have also produced significant tsunamis.

3.6 In terms of oceanographic conditions, the Mediterranean Sea can be separated in an East - West axis, with the limit being in the strait of Sicily. Western Mediterranean shows some Atlantic influence, while the strait of Sicily acts as a barrier and minimizes the effect of Atlantic water in the Eastern Mediterranean. In turns this have an effect on the productivity of the different areas, with eastern areas generally showing a more oligotrophic status.

3.7 In terms of climatic and socioeconomical aspects of riparian countries, the Mediterranean Sea can also be separated in a North – South axis, with higher density and more industrial coastal settlements in the North and lower densities of lower industrial coastal settlements in the South. Water resources are also more abundant in the North riparian countries than in the South, due to climatic reasons.

3.8 Due to its oceanographic, biogeographic and socioeconomic characteristics, a number of threats to the Mediterranean Sea ecosystems (including human inhabitants) have been identified. A recent report has shown that the Mediterranean Sea shows a larger ecological deficit than other parts of the planet, with resources being spent 2.6 faster than they can be regenerated (1.5 for the planet, Plan Bleu nº 22 June 2012)

3.10 Threats due to human pressure are mainly related to urbanization of coastal areas, increasing pressure of competing marine and maritime activities in the Mediterranean Sea, management of human produced waste, and acidification of the marine environment due to increasing CO_2 concentrations in the atmosphere and in the sea.

3.11 Urbanization of littoral area in the northern area is considered to already have reached its climax, with regions where the balance between population density, available resources and current waste management procedures is not sustainable. In the south, population growth of specific human settlements is creating and unprecedented anthropogenic pressure on the system. The effects of this coastal urbanization pressure are the appearance of local pollution focus, scarcity of water in the coastal areas, degradation of coastal geography and coastal ecosystems and potential effects on local oceanography.

3.12 Threats directly attributable to climate change include increasing temperatures, reduction of pluviosity, rise of water level, increasing probability of strong events, and changes in ecosystems.

3.13 In general, slight increases of land average temperature have been already registered except for the eastern Mediterranean where average temperature has slightly decreased. In the same trend, deep western Mediterranean water temperature has increased. It is very likely that the temperature extremes will also increase and that droughts, drying of coastal wetlands, saline intrusion in underground water resources and the reduction of annual water availability will become more frequent around the Mediterranean region.

3.14 The potential effects of the rise of sea water level in the Mediterranean coast are also expected to lead to critical social and economic problems, due to high human density in coastal areas.

3.15 The combination of climate change and anthropogenic pressure in the Mediterranean Sea is expected to lead to drastic changes in species and ecosystems, some of which are starting to be apparent in the scientific literature.

B.4. Pilot and proposed storage sites in the Mediterranean basin

4.1 The Mediterranean Sea is an area in which concentrated sources of CO_2 can be found near potential submarine storage sites, therefore with a high potential for CO_2 capture and storage sites.

4.2 Temperature and pressure conditions on the potential storage site, together with physical and or chemical trapping mechanisms are crucial to ensure long-term storage and minimize the risk of CO_2 looses or leakages from the storage formations

4.3 Onshore deep saline aquifers, shallow offshore depleted oil and gas fields or un-mined coal seams have been the geological formations most used in pilot CO_2 storage studies, as the technological requirements are already at hand and the cost is comparative lower – and in the cases where enhanced oil recovery is implemented even economically profitable - than for deeper areas.

4.4 There are few pilot CSS studies in the world that include the capture process, the transportation and a storage site. Within the Mediterranean Sea, the first pilot project that included an analysis of storage performance and a risk assessment study was performed within the CASTOR project (Figure B1) starting in 2004, in a depleted oil reservoir off the Tarragona coast, northwest Spain. The study included both an in-situ experiment of the CO_2 behavior within the storage site and simulation studies to analyze different scenarios for CO_2 long-term storage within the site. The initial project finished in 2008 and it was inconclusive in relation to the long-term storage capacity of the site, due to several uncertainties in the analysis and the identification of potential problems such as escapes through existing faults in the geological formation or effects in the injection capacity due to deposition in the injection well.

4.5 In the last years, following both research and development initiatives from the European Union and self funded private initiatives, several CCS networks that include initiatives in the Mediterranean Sea have been created, such as “The European CCS Demonstration project network” (http://www.ccsnetwork.eu), the “Carbon Dioxide Knowledge Sharing Network” (http://www.co2net.eu) or the “European Network of Excellence on geological storage of CO_2“ (http://www.co2geonet.com). An updated map of existing and planned CCS studies in the Mediterranean Sea is kept on the Scottish Carbon Capture & Storage network (http://www.sccs.org.uk/map.html, Figure B2).

4.6 In 2011, the first CCS pilot project in Italy was started in Brindisi. The project includes a post-combustion capture site at Brindisi (operational since 2010), a liquefaction and cryogenic storage plant also at Brindisi (to be functional within 2012), a truck-based transportation system and several potential storage sites. Some of the potential storage sites are located in the Adriatic Sea sub-seabed, but studies are still preliminary and the start of the injection phase has been postponed as the project is still pending permits from Italian and European authorities.

4.7 In Porto Tolle, (Veneto, Italy) Since 2011, Enel is doing all the steps for converting the power plant from using heavy oil to coal. One of the 3 new 660MW coal fired units is to be fitted with post combustion CO_2 capture. About 1 million tonnes CO_2 per year will be captured, compressed and transported by pipe for offshore storage in a deep saline formation located about 100 km south-east of the power unit under the Northern Adriatic sea. Preliminary charaterisation of storage sites has taken place and are planed to store from multiple sources in the Veneto region in the long term.

4.8 In the carbon minning site of Carbosulcis (Sardinia, Italy) there is planned another CCS project integrated in a new thermal plant of 450 MWe, where about 67% of the CO_2 is planned to be captured and stored in underground formations.

4.9 In Delimara, Malta, a Norwegian company is proposing to start a power plant, which would include carbon capture and storage technology and aim to capture around 95% of its CO_2 emissions. The project is still pending initial assessments and permits, and the captured CO_2 is proposed to be transported by ship to Denmark, where it will be stored in depleted oil reservoirs.

4.10 In South East France there is the VASCO initiative that aims to decrease the CO_2 emissions on the Fos-Berre-Gardanne-Beaucaire area by shipping export of CO_2 for injection in oil fields (enhanced oil recovery – CO_2-EOR) with the creation of a CO_2 liquefaction terminal at Fos sur Mer Harbour, bio-remediation of CO_2 through micro-algae production, local industrial use of CO_2 such as water treatment, and pipeline transport and geological storage of CO_2 in nearby deep saline aquifers.

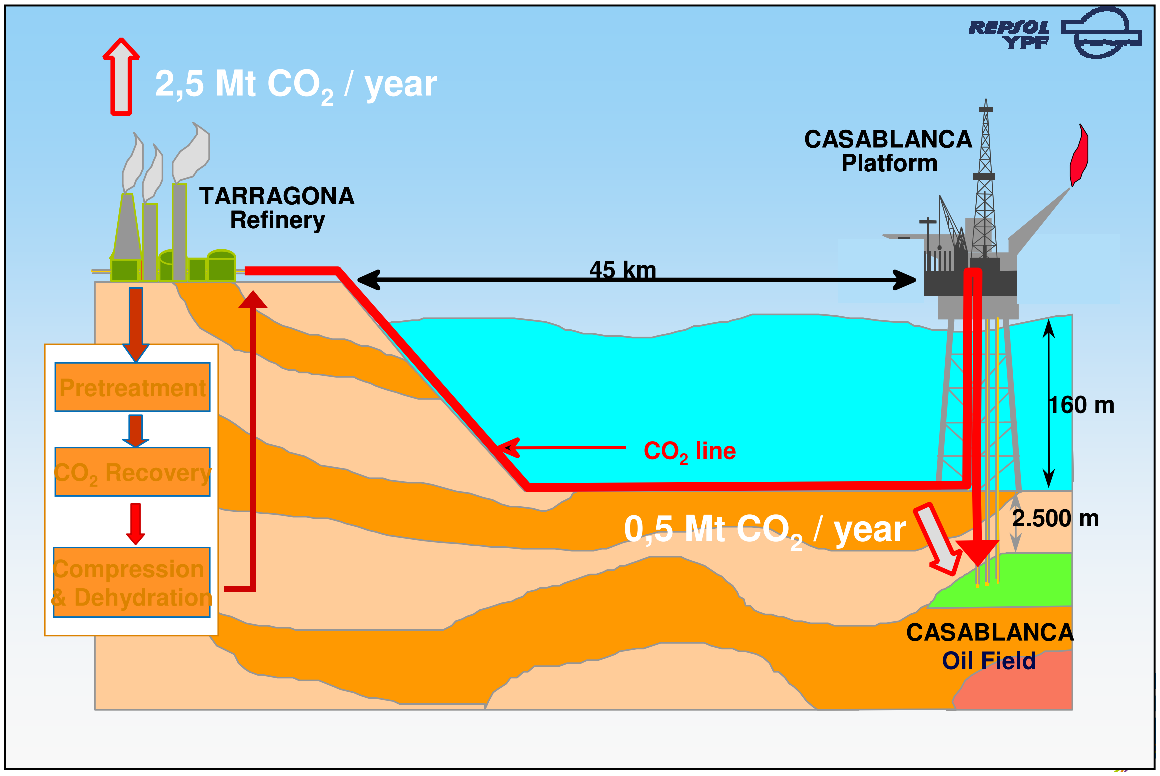


Figure B1: Schematic representation of the Casablanca oil field pilot CCS project within the project CASTOR.

Figure B2: Location of large scale CCS operating and planned projects (at least 500,000 tonnes of CO_2) and smaller scale but significant pilot projects. Operational (green), in Planning (yellow) and pilot (blue) sites in the Mediterranean Sea and riparian countries. Modified from SCCS 2013.

B.5. Specific risks and potential effects of CCS in the Mediterranean basin

5.1 In general, the risk associated with Carbon Capture and Storage can be separated into risks associated with surface and injection installations and risks associated with CO_2 sequestration in geological reservoirs. Risk associated with surface and injection installations are generally well known and technology to prevent, monitor and solve them is considered mature. This Framework document only consider in detail the risks associated with CO_2 sequestration in geological formations.

5.2 Risks associated with CO_2 sequestration in geological formations can be classified within the following classes:

- CO_2 and/or CH_4 leakage from the reservoir to the atmosphere
- Micro-seismicity in the geological structure due to pressure and stress changes in the reservoir, causing small earthquakes and faults
- Ground movement, subsidence or uplift due to pressure changes in the reservoir
- Displacement of brine from an open reservoir to other formations, possibly containing fresh water

5.3 CO_2 and CH_4 leakage from the formation to the atmosphere depends on thickness of overlying formations and trapping mechanisms and occurs when (see also Figure B3):

- Inability of cap rock to prevent upward migration, due to:
  - too high permeability (possibility for diffusion of CO_2)
  - dissolving of cap rock by reaction with CO_2
  - cap rock failure (fracturing and faulting due to over pressuring of the reservoir)
- Escape through (old) wells through:
  - Improper plugging
  - Diffusion through cement or steel casing
- Dissolving of CO_2 in fluid that flows laterally
- Fractures originated by natural or induced seismicity

5.4 When a leakage occurs, effects of the leakage will depend on the leakage volume and the nature of the stream (percentage of CO_2 and amount and nature of incidental substances), and can be classified in terms of their spatial scale. At local scale, human and animal health can be affected at elevated CO_2 concentration, especially if accumulation in confined areas happens. In terms of ecosystems, leakage effects may produce the following effects at the different spatial scales:

- Local scale: Decrease of pH of soils and water, causing:
  - Calcium dissolution

    - Increase in hardness of the water
    - Release of trace metals
- Global scale: leakage reduces the CO_2 mitigation option, effect depends on stabilization of greenhouse gas concentration
    - Stabilization targets
    - Extend and timing of CO_2 storage (simulation models)

5.5 The effect of CO_2 injection in regional seismicity is currently a controversial scientific issue. There are several scientific works showing the existence of microseismicity related to the injection of fluids, including CO_2 streams, in geological formations. A recent scientific article goes further and concludes that CCS is likely to cause earthquakes, which although too small to cause major damage, could release stored CO_2 into the atmosphere (Zoback and Gorelick, 2012). However, a more extensive study by the United States National Research Council shows that there are various human activities that cause an increase in seismicity (National Research Council, 2012) . Among them, the largest seismic event has been caused by an oil/gas extraction operation, while the more frequent sources are geothermal and waste water injection projects. No felt earthquakes are known to have been caused by enhanced oil recovery operations that inject CO_2. The most important concern raised in relation to CCS induced seismicity is the cap-rock integrity and the potential for leakage through faults (CO2GeoNet European Network of Excellence 2012 and Juanesa *et al.*, 2012). However, this issue is currently already included in the protocols for site selection, such as the recommendations included in this Framework and previously in other context such as the London Protocol or the OSPAR Convention.

5.6 For the specific case of the Mediterranean Sea, there are a number of characteristics that should be taken into account for risk management:

- The Mediterranean Sea is an enclosed sea, surrounded by coastal areas with high population density, and in which there is an important level of ocean connectivity between processes occurring in neighborhood areas.
- The Mediterranean Sea includes several fragile ecosystems as well as ecosystems of interest, and there are several protected areas of different ecosystem value and legal characteristics
- There is a high level of competition for the use of the Mediterranean Sea for different purposes, from tourism to transport, marine resources extraction – both mineral and live resources – or the protected areas cited above.
- The Mediterranean region is seismically active due to the convergence of the African plate with the Eurasian plate along a complex plate boundary. Also, its land-locked configuration creates extended basins and migrating tectonic arcs in the region.

Therefore, the risk management framework for the Mediterranean Sea should be designed to minimize the effects in areas of human interest, areas of potential human hazards, and areas of special ecosystem interest, as well as areas with a high seismicity. The enclosed condition and ocean connectivity between areas should also be taken into account in order to prevent these effects.

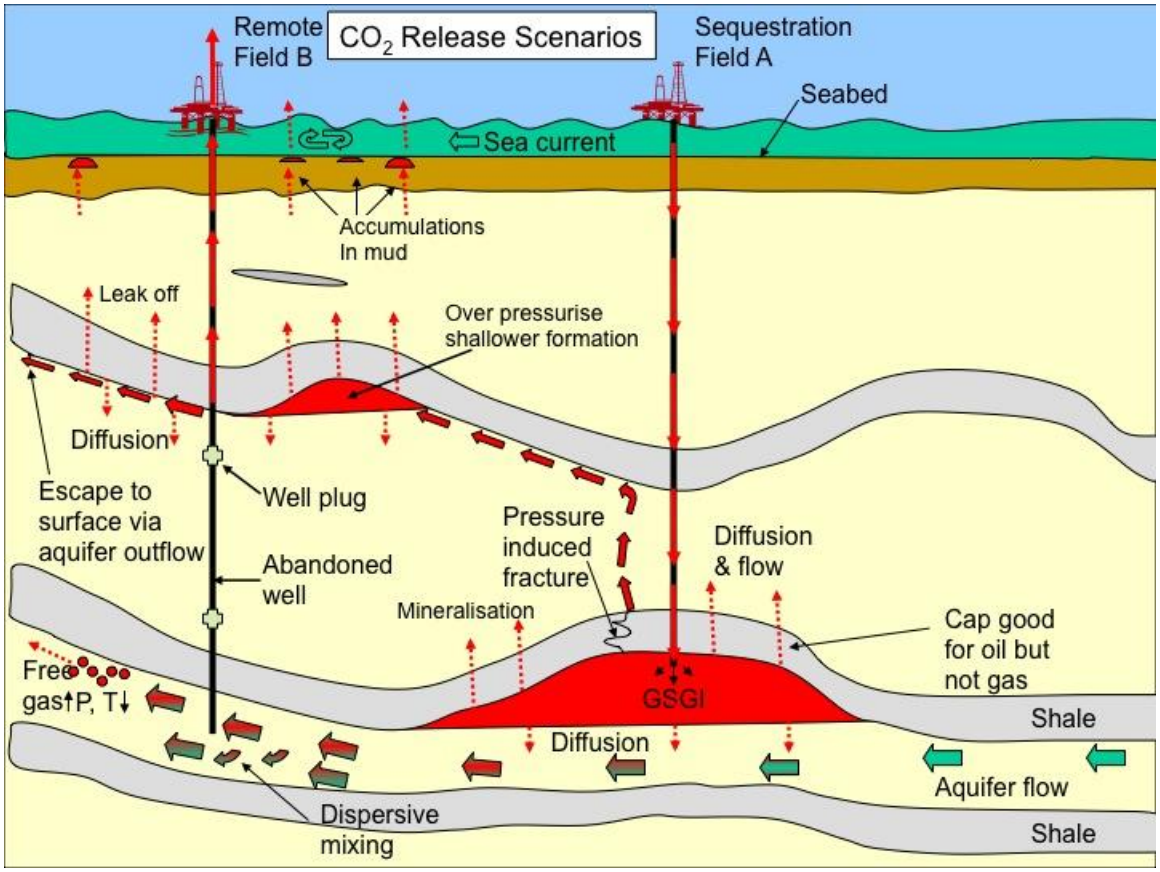


Figure B3: Schematic representation of risk associated with CO_2 release from storage sites (from www.co2net.com)

PART C

RISK ASSESSMENT AND MANAGEMENT OF CO_2 STORAGE IN SUB-SEABED GEOLOGICAL FORMATIONS OF THE MEDITERRANEAN BASIN

C.1. Introduction

1.1 This risk assessment and management of carbon dioxide storage in sub-seabed geological formations of the Mediterranean basin is developed to provide guidance to the Contracting Parties of the Barcelona Convention. The aim of CO_2 sequestration in sub-seabed geological formations is to reduce the emission of large amounts of this gas of anthropogenic origin into the biosphere. This CO_2 is expected to be stored permanently. This process is one option in a portfolio of mitigation efforts for stabilization of greenhouse gas concentrations in the atmosphere with the potential significant benefits at the local, regional and global levels over both the short and long terms.

1.2 The risks associated with CO_2 sequestration in sub-seabed geological formations include those associated with leakage of CO_2 and associated substances in or mobilized by the stream into the marine environment. There are different levels of adverse consequences regarding potential leakage that range from the local to the global over both the short- and long-terms.

1.3 The risk assessment and management framework is required to minimize any risk associated to the storage of CO_2 in sub-seabed geological formations, and ensure that, in the case of leakage, it does not lead to significant adverse consequences for the environment, human health and other uses of the sea.

1.4 Therefore, the CCS projects should:

(a) Assess the suitability of a potential storage site for permanent containment of CO_2 streams and identification of the necessary measures for hazard reduction, remediation and mitigation;
(b) Characterize the risks to the marine environment from carbon dioxide capture and storage on a site-specific basis; and
(c) Collect the necessary information (monitoring) and develop a management strategy to address uncertainties and manage and minimize risks.

1.5 The carbon capture and storage process includes the capture of the CO_2 and its transport to the injection and storage site; however, the focus of this framework is limited to the injection and post-injection risks of leakage.

1.6 This risk assessment and management framework includes the following stages:

a. *Problem Formulation* is a critical scoping step as it defines the boundaries of the assessment, including the scenarios and pathways to be considered. Important issues to include in this assessment are:

(i) The suitability of deep geological formations to permanently retain the CO_2 stream reliably, including the nature of the overburden;

(ii) The characteristics of the surrounding environment, including human settlements, human activities and marine environment in the surroundings of the site; and

(iii) The need for monitoring over a long period (also after site-closure). The latter is especially important with respect to the long-term safety of storage and any future handover of the responsibility for the storage site (liability for future risk);

b. *Site Selection and Characterization* concerns the collection of data necessary for describing the physical, geological, chemical, and biological conditions necessary for determining the suitability of a site proposed for storage (and its surrounding area) and to establish a baseline for management and monitoring;

c. *Exposure Assessment* is concerned with the characterization and movement of the CO_2 stream within geological formations and, potentially, the marine environment as a basis for an effects assessment. The processes and pathways of potential migration of CO_2 streams from geological storage formations and leakage to the marine environment, during and after injection of the CO_2 stream, should be assessed. This should include an assessment of additional substances, already present in or mobilized by the CO_2 stream and displaced saline formation water, based on an informed decision of the relevance of such substances. The processes involved in such migration behavior will be governed by site-specific factors. The uncertainties associated with such an assessment should be identified and, wherever possible, quantified;

d. *Effects Assessment* assembles the information necessary to describe the response of receptors within the marine environment resulting from potential exposure to the CO_2 stream if leakage were to occur. The main effects of concern to such an assessment include effects on human health, marine resources, relevant biological communities, habitats, ecological processes, and other legitimate uses of the maritime area. Effects of exposure to other contaminants in the CO_2 stream, as well as metals and other substances mobilized in a decreased pH environment, have to be included in the assessment;

e. *Risk Characterization* integrates the exposure and effects information to provide an estimate of the likelihood of adverse impacts. Risk characterization should be performed on the basis of site-specific information. Factors evaluated in a risk characterization may change over time given the operational status of the project and ongoing data collection used to update predictive models. The sources and levels of uncertainty associated with a risk estimate will be a function of the data and modelling assumptions used. Given the long time-scales involved for the intended storage of CO_2 streams in geological formations, it will be useful to distinguish between processes relevant to characterizing risks in the near-term during the period of active operations and injection at a site and long-term processes operating after site closure;

f. *Risk Management* (including Monitoring and Mitigation). In the planning phase, risk management is used to design preventive measures based on prediction (derived from the risk assessment process and in particular the outcome of the risk characterization stage). Risk management further includes the definition of the requirements for monitoring, during and after injection of CO_2 streams. When injection starts, the results of monitoring are valuable and, if necessary, can lead to the identification of additional preventive and/or mitigative measures. Although the process of monitoring continues after site closure, its intensity is expected to decrease and, eventually, monitoring may be discontinued when there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.

1.7 The life cycle of a CO_2 storage project consists of the following phases:

a. planning;
b. construction;
c. operation;
d. site-closure; and
e. post-closure.

The planning, including design, construction and operation should lead to an inherently safe storage site. Each phase of the project requires all, or a selection of, the stages of the framework (see 1.8) to be carried out. The following table indicates which stages are applicable to each phase of the project (OSPAR 2007):

	Problem formulation	**Site selection & characterization**	**Exposure assessment**	**Effects assessment**	**Risk characterization**	**Risk management**
Planning	▨	▨	▨	▨	▨	▨
Construction		▨	▨	▨	▨	▨
Operation		▨	▨	▨	▨	▨
Site-closure			▨	▨	▨	▨
Post-closure			▨	▨	▨	▨

1.8 The risk assessment and management process should be a lifecycle iterative process in order to assure the safety and continual improvement of the CCS project with time.

1.9 Stakeholder participation should be included as part of risk management and risk characterization to ensure completeness of the assessment. Stakeholder involvement is an important feature of CCS to ensure public acceptance of the project.

C.2. Definition of the composition of the CO_2 stream that can be stored

2.1 A CO_2 stream shall consist overwhelmingly of carbon dioxide. To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter. However, a CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration.

2.2 Concentrations of all incidental and added substances shall be below levels that would:

(a) adversely affect the integrity of the storage site or the relevant transport infrastructure;

(b) pose a significant risk to the environment or human health; or

(c) breach the requirements of applicable (national or international) legislation.

C.3. Risk assessment and management of CO_2 storage in sub-seabed geological formations of the Mediterranean basin

Step 1. Problem formulation:

3.1.1 It is the critical scoping step, describing the boundaries of the risk assessment and includes the collection of information that will be used to develop a site-specific conceptual model to direct a site-specific risk assessment. It is important to identify gaps and uncertainties at this stage.

3.1.2 The ultimate objective of storage of CO_2 in geological formations is to ensure permanent containment of CO_2 streams beyond the biosphere (including the atmosphere) as one of a portfolio of options to reduce future levels of atmospheric carbon dioxide and additional ocean acidification.

3.1.3 In sub-seabed storage, for the purposes of climate change mitigation and prevention of ocean acidification, CO_2 streams are injected into geological strata at least several hundred meters below the layer of unconsolidated sediments on the seabed. Therefore, it should be stressed that the locations of disposal will differ from most other operations currently permitted under the Barcelona Convention and consequently the site selection and assessment considerations will also require a geological assessment.

3.1.4 The sources of CO_2 considered here are those industrial activities releasing large quantities of CO_2 to the atmosphere. The objective of CO_2 capture and storage is to capture CO_2 from the emission streams of these sources for storage in geological formations. It is not to be considered as an alternative waste disposal mechanism for other substances. However, CO_2 streams may contain incidental associated substances from the source or capture process. Furthermore, it should be stressed that no substances may be deliberately added to the CO_2 stream for the purposes of waste disposal but may be added to enable or improve the efficiency of capture, transport, and storage. In all cases, acceptable concentrations of substances should be related to their potential impacts on the integrity of the storage site(s) and relevant transport infrastructure, the risk they pose to the marine environment, and to requirements of the applicable regulations.

3.1.5 Major issues to be addressed include:

a. the suitability of deep geological formations to retain the CO_2 streams permanently;

b. the nature of the overburden to act as a barrier to prevent or retard upward migration of CO_2 streams;

c. the potential mobilization of substances by CO_2 streams directly or indirectly (e.g., heavy metals released due to a pH reduction) in the formation and the overburden;

d. the characteristics of the marine environment, specially if it is a remarkable/protected area, above and around the site of storage of CO_2 in geological formations in relation to concerns regarding potential adverse effects of any CO_2 streams leaking from the formation that succeeds in reaching the unconsolidated sediments and/or the overlying water column; and

e. the need for records associated with the authorization and licensing process, together with monitoring data, to be maintained for much longer periods than those associated with other authorized practices and most other human activities. The longevity of monitoring activities and management response capabilities is also much longer than those required for other practices permitted under these instruments; and

f. depending upon the depth of the water column into which leakage of CO_2 from the underlying sediments could potentially occur, differing exposure and effects regimes will be relevant. A primary cause for this relates to the specific gravity of CO_2 as a function of hydrostatic pressure in the marine water column. At shallower water depths (approximately < 2500 meters), the forms of CO_2 potentially released are buoyant in seawater. At greater depths, the forms of CO_2 can include components that are denser than the surrounding seawater and will tend to sink. The latter situations will impose a need to take account of differing exposure and effects conditions than those applicable to releases involving buoyant forms of CO_2.

3.1.6 Generic conceptual models of potential environmental pathways and effects that are relevant to the consideration of the potential consequences of CO_2 release to the marine environment from CCS in geological formations under the seabed are shown in figures C1 and C2. It is important to point out that the problem formulation and, indeed, the Risk Assessment and Management Framework itself should be followed in an iterative manner rather than as a strictly sequential once-through process.

Figure C1. *Effects in a risk assessment framework (from the risk assessment and management framework for CO_2 sequestration in sub-seabed geological structures of the London Convention and Protocol)*

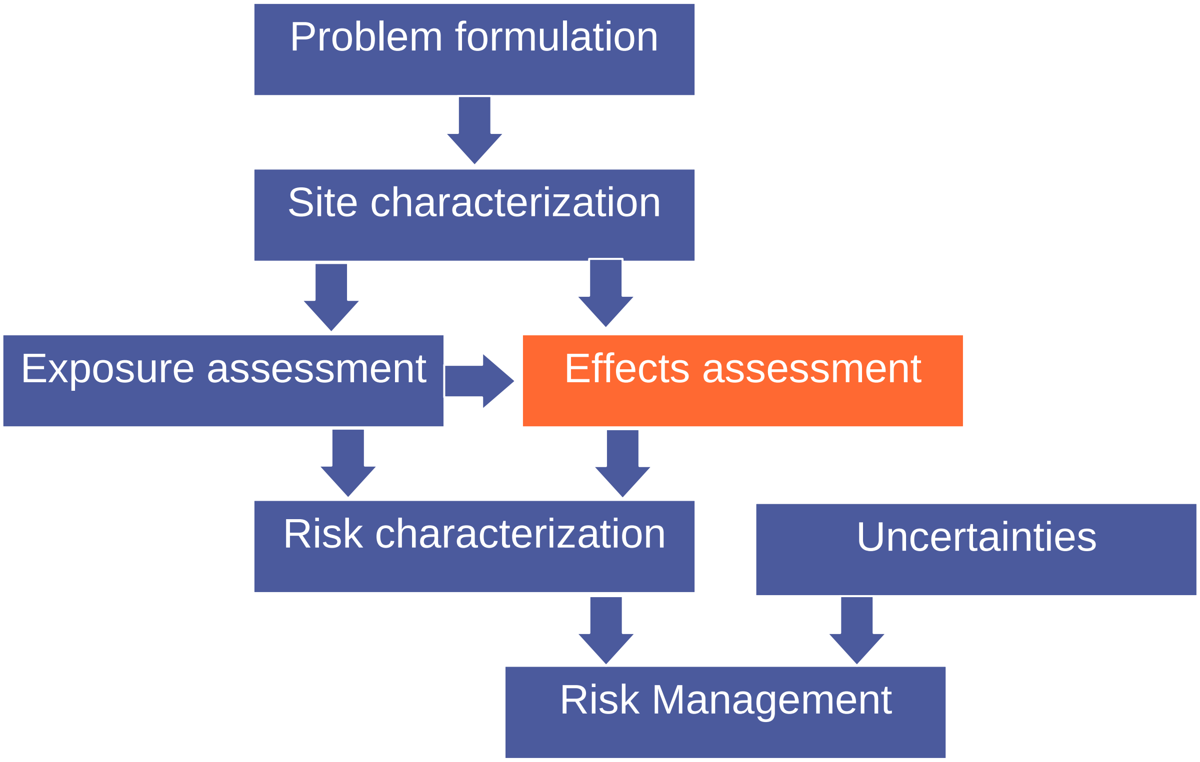
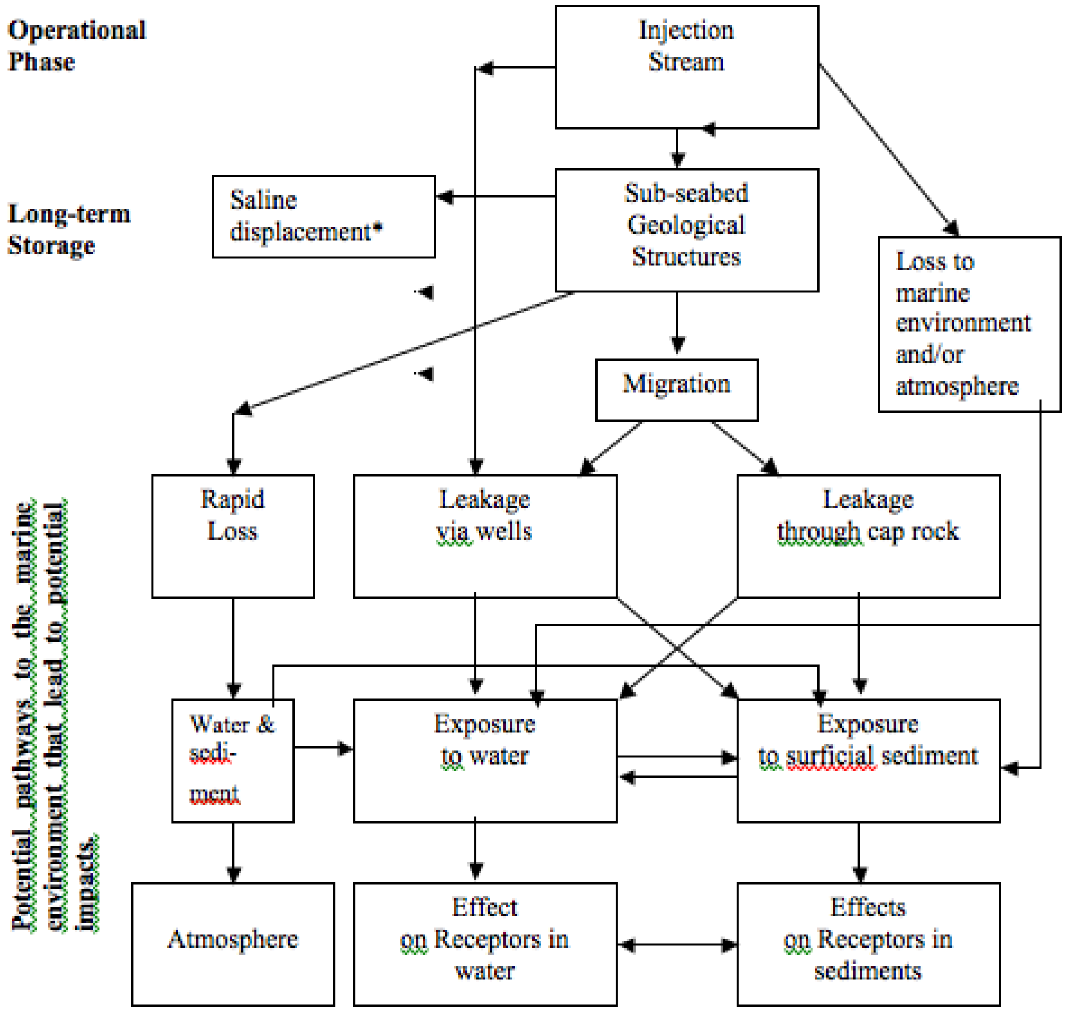


Figure C2 - Conceptual model of potential environmental pathways and effects[3] (from the risk assessment and management framework for CO_2 sequestration in sub-seabed geological structures of the London Convention and Protocol)



* Exposure and effects assessments of the displacement of saline water by injection streams may be required. The sites of these displacements into the marine environment can be at great distances from the injection site, depending on the geological circumstances.

---

[3] It is important to point out that the problem formulation and, indeed, the Risk Assessment and Management Framework itself should be followed in an iterative manner rather than as a strictly sequential once-through process.

Potential migration or leakage of CO_2 streams into the marine environment

3.1.7 This comprises two distinct considerations:

a. Potential leakage during the operational phase of storage of CO_2 streams in geological formations; and

b. Migration and leakage of CO_2 streams from the geological formation following the injection process.

Potential leakage during injection

3.1.8 These would most likely result from major seal failure or disruption of the means of emplacement of the CO_2 streams in the geological formation (i.e. the pipeline or means of insertion from a vessel and the injection well). Capped well locations are also potential sources of leakage and their potential is dependent upon well integrity and age. The probability of leakage through cap rock is unlikely with proper site characterisation and selection, barring an unpredictable seismic event. However, if leakage does occur during this phase, then remediation and/or mitigation is likely to be possible e.g., by relieving formation pressure.

3.1.9 The physical effects associated with major, sudden leaks of gaseous CO_2 are primarily the disturbance of unconsolidated bottom sediment caused by the flow and expansion of CO_2 as it passes through the upper sediment column and into the overlying water column. Associated with such events would also be turbulence and therefore increased vertical mixing in the water column. At the extreme, a large and rapid gas leak at the seafloor could cause damage to the marine environment, interference with other legitimate uses of the maritime area, including fishing and maritime transport, with the potential for associated risks to human health.

3.1.10 In the event of slower, more diffusive CO_2 leak, the CO_2 enriched stream, including any associated substance, could potentially contact the marine sediments and/or the water column. This contact could potentially alter the physiochemical nature of marine sediments, the surrounding boundary layer of marine waters, and/or the water column, e.g., depression of pH. The spatial and temporal nature of such a leak, and the underlying nature of the surrounding hydrodynamics will determine the degree of any exposure in the water column. Short and long-term effects as well as population level effects and species-specific impacts need to be considered. Impact Hypotheses derived from these potential impacts should be used to define monitoring and mitigation plans.

Potential post-injection leaks

3.1.11 Those will be similar to the potential operational leaks in the case of leakages via a capped well and the cap rock or by unpredictable geological events (such as earthquakes) but with the significant difference that they will probably occur over longer timeframes. In addition, the capacity to mitigate is likely to be reduced as the infrastructure and associated resources may not be immediately available and much more costly. Any necessary cautionary (precautionary) measures should be taken, to the extent possible, prior to closure of the injection site.

Step 2. Site selection and characterisation

Introduction

3.2.1 Key objectives for geological CO_2 storage site selection and characterisation are to:

a. assess how much CO_2 can be stored at a prospective storage site. Formation parameters like volume, porosity, permeability need to be characterised in order to calculate the storage capacity;

b. demonstrate that the site characteristics are consistent with expectations of long- term storage and protection of the marine environment and future uses of the maritime area;

c. establish a baseline for the management and monitoring of the injection and storage of CO_2 streams.

3.2.2 Site characterisation requires the collection of a wide variety of geological and environmental data that are needed to achieve these objectives. Much of the data will necessarily be site-specific. Most data will be integrated into geological models that will be used to simulate and predict the performance of the site. These and related issues are considered below. Characterisation should explicitly take into account uncertainties (see Appendix II). Results of site characterisation feed into the next stages of risk assessment and management in the lifecycle of a CO_2 storage facility.

Different types of storage formations and trapping mechanisms

3.2.3 Oil or gas reservoirs and saline aquifers have the largest potential for safe and long-term CO_2 storage. A large part of the identified storage capacity is located offshore.

Oil and gas reservoirs

3.2.4 CO_2 streams can be injected in oil and gas reservoirs, either for storage or for enhanced oil recovery. The latter falls outside the scope of this framework. The existence of abandoned oil and gas wells within the relevant geological domain of the storage site provides potential avenues for leakage pathways. Because the capillary seal for oil and gas reservoirs has already proven its sealing integrity, the potential for leakage through these types of seals is considered most unlikely, provided that the seal has not been damaged during exploitation of gas or oil. There is a wealth of knowledge on the geology and sealing potential of these formations and structures to facilitate the site selection and characterisation. Additional information may be needed, once a reservoir is selected for the storage of CO_2 streams in geological formations, as the behaviour of a CO_2 stream may differ from the original formation content.

Deep saline formations

3.2.5 Deep saline formations are geological formations or structures containing saline water. For such formations that have not been storing oil or gas, the verification of the integrity of the sealing rock is generally more challenging than for oil or gas fields, due to the more limited information and experience. In some areas, the geology of such formations is well documented, e.g., where oil and gas exploration has take place, while in other areas such data will need to be collected and modelled in order to verify the formation’s capability of storing CO_2 streams.

Other possible geological formations for CO$_2$ storage

3.2.6 Unminable coal beds, basalts, oil and gas shales, salt caverns and other geological formations and structures may also be considered for storage of CO$_2$ streams. However, these formations have not been explicitly considered during the development of this Framework for Risk Assessment and Management.

Trapping mechanisms

3.2.7 In the selection of appropriate sites, the different mechanisms retaining CO$_2$ streams underground are relevant. Driving forces that could promote the migration of CO$_2$ streams out of the formation are the pressure increase caused by the injection of CO$_2$ streams and the buoyancy due to the density of CO$_2$, which is lighter than brine. This density difference is about the same as the density difference between oil and brine. There are several mechanisms that are effective in preventing injected CO$_2$ from escaping from a formation. The most important is the presence of a cap rock acting as an upper seal to prevent CO$_2$ streams flowing out of the formation. Nevertheless, attention has to be given to the possibility of faults in existing seals. This is relevant for both storage in oil and gas reservoirs and for deep saline aquifers. The types of trapping mechanisms (Figure C3) are strongly related to the characteristics of the site. Structural and stratigraphic trapping is an important trapping mechanism for conventional oil and gas reservoirs and traps in saline formations. Residual and solubility trapping become important in storage formations where CO$_2$ is able to migrate and disperse. If reactive minerals are present in these storage formations, mineral trapping becomes an additional trapping mechanism.

3.2.8 Other trapping mechanisms include pore trapping of CO$_2$ (residual gas trapping), dissolution of CO$_2$ in brine and mineral trapping of CO$_2$.[i] For well-selected, designed and managed geological storage sites, the vast majority of the CO$_2$ will gradually be immobilised by these trapping mechanisms. These mechanisms should enhance the security of CO$_2$ storage (IPCC 2005).

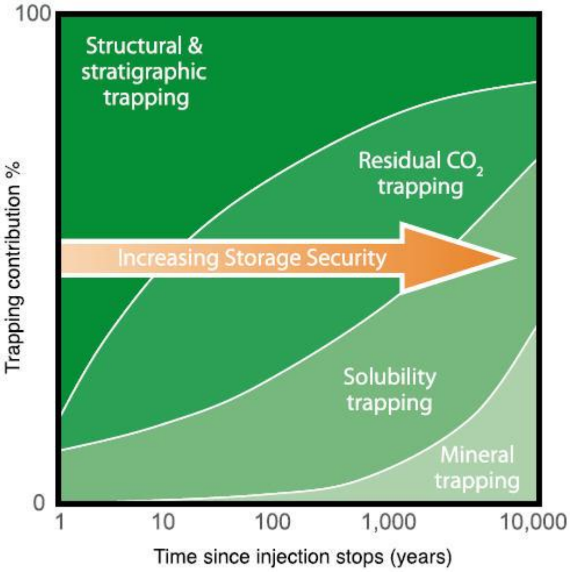


Figure C3 Storage security depends on a combination of physical and chemical trapping. Over time, the physical processes of residual CO$_2$ trapping, geochemical processes of solubility trapping and mineral trapping increase (from IPCC, 2005).

Site selection process and site characterisation

3.2.9 Important issues during the site screening and selection process for the storage of CO_2 streams include:

- a. the storage capacity and injectivity of the formation;
- b. the long-term storage integrity;
- c. the technical and environmental suitability of the vicinity and surrounding area;
- d. potential migration and leakage pathways over time and potential effects of leakage of CO_2 streams; and
- e. possibilities for monitoring, remediation and/or mitigation.

3.2.10 Appendix I to this Framework outlines the information that facilitates the selection and characterisation of sites for storage of CO_2 streams in geological formations. The appendix shows elements that should be considered rather than constituting formal requirements. A storage site and its surroundings, including the overlaying sediment and water column, need to be characterised in terms of geology, hydrogeology, geochemistry, geomechanics and biology. A significant amount of data may be needed to establish both the feasibility of injection of a CO_2 stream and also to provide evidence of the integrity of the site over the time-scale relevant for the sequestration issue. The site selection will typically include a reservoir simulation to assess a potential storage site, e.g., by a three-dimensional geological model. Relevant factors for the assessment of the suitability of geological formations for storage of CO_2 streams in respect of both the protection of the marine environment and climate-change include characterisation of the formation, the cap rock, geological stability, possible leakage-pathways, trapping mechanisms and modelling of the behaviour of the CO_2 stream.

3.2.11 Considering the potential consequences to the environment in the event that a CO_2 stream leaks to the sea floor, the characterisation and selection of sites should take into account the proximity of the site to sensitive or endangered habitats and species, including natural resources such as fish. Other uses of the area such as oil and gas exploration and exploitation and fisheries should also be taken into consideration. Finally, possible lateral migration through porous and permeable layers to onshore surface locations should also be considered.

3.2.12 The sources of information will vary, but analysis will mainly rely on the sampling of well cores (both in the formation and the overlying structures), the acquisition of well logs, seismic and biological surveys, and also data available from existing wells or fields in neighbouring locations.

3.2.13 This information is useful for the site selection and characterisation, and thus establishes a geological and marine environmental baseline before the site is used for storage of CO_2 streams (i.e. at the pre-injection stage). It should also be noted that, as the project moves into the injection and the post injection stages, this baseline information should be used for the development of a monitoring strategy. Evaluation of the results of the monitoring may be used to update the monitoring strategy and other operational practices.

Conclusions on site selection and characterization

3.2.14 Important issues during the site screening and selection process for carbon storage in geological formations under the seabed may include:

a. the storage capacity and injectivity of the formation;
b. the long-term storage integrity;
c. the technical and environmental suitability of the vicinity and surrounding area;
d. potential migration and leakage pathways over time and potential effects of leakage of CO_2 streams; and
e. possibilities for monitoring, remediation and/or mitigation

3.2.15 There is significant potential for geological storage in structures beneath the oceans. Oil and gas reservoirs and saline formations are expected to have the largest potential to accommodate safe, long-term storage. The aim is to retain CO_2 permanently. Because of the various trapping mechanisms, storage may, in some cases, become more secure over time.

3.2.16 Criteria for site selection, management procedures and contingency planning could be seen as one means of guaranteeing the high environmental integrity of CCS in geological formations under the seabed.

Step 3 Exposure assessment

3.3.1 Exposure assessment provides the characterisation of potential effects and provides an input into the wider risk characterisation and risk mitigation processes. Information gathered at this stage should be appropriately recorded and documented. Although permanent containment is the ultimate objective, it is advisable to show how any leakage will be managed in such a way that that it does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

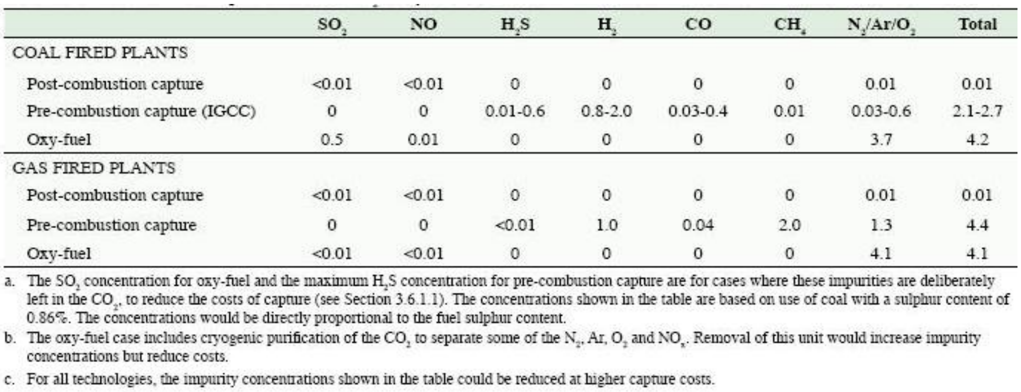
Chemical and physical characterisation of the CO_2 stream, including incidental associated substances

3.3.2 Characterisation of the injection stream is essential. While no substances will deliberately be added to the CO_2 stream for the purposes of waste disposal, the composition of the injection stream should be consistent with the primary purpose of mitigating CO_2 emissions to the atmosphere. Incidental associated substances may be present in the CO_2 stream, which is defined in section C.2.

3.3.3 CO_2 and incidental associated substances may react in the storage formation to form new substances and they may mobilise substances in the formation. These new and mobilised substances could have practical impacts on CO_2 storage systems and also have potential impacts on health, safety and environment. Such substances can be identified and quantified and uncertainties can be characterised, for the purposes of gathering information required for the effects assessment (see Step 4) and the wider process of risk assessment and management (Step 5 and 6). Particular attention should be given to those substances that may reduce the integrity of storage and/or are known to have significant effects on the marine environment.

3.3.4 The types and concentrations of such other substances vary, depending mainly on the basic source process (e.g., gasification, combustion, natural gas cleanup), the source material, and the type of capture process. As an example, the following table from the IPCC SRCCS[ii] demonstrates the types and magnitudes of other substances that may be found in CO_2 streams from fossil-fuelled power plants. Note that these substances may be different for CO_2 streams from other sources, such as refineries, steel plants, etc.

Table C1 Concentrations of impurities in dried CO_2, % by volume



	SO_2	NO	H_2S	H_2	CO	CH_4	$N_2/Ar/O_2$	Total
COAL FIRED PLANTS								
Post-combustion capture	<0.01	<0.01	0	0	0	0	0.01	0.01
Pre-combustion capture (IGCC)	0	0	0.01-0.6	0.8-2.0	0.03-0.4	0.01	0.03-0.6	2.1-2.7
Oxy-fuel	0.5	0.01	0	0	0	0	3.7	4.2
GAS FIRED PLANTS								
Post-combustion capture	<0.01	<0.01	0	0	0	0	0.01	0.01
Pre-combustion capture	0	0	<0.01	1.0	0.04	2.0	1.3	4.4
Oxy-fuel	<0.01	<0.01	0	0	0	0	4.1	4.1

a. The SO_2 concentration for oxy-fuel and the maximum H_2S concentration for pre-combustion capture are for cases where these impurities are deliberately left in the CO_2, to reduce the costs of capture (see Section 3.6.1.1). The concentrations shown in the table are based on use of coal with a sulphur content of 0.86%. The concentrations would be directly proportional to the fuel sulphur content.

b. The oxy-fuel case includes cryogenic purification of the CO_2 to separate some of the N_2, Ar, O_2 and NO_x. Removal of this unit would increase impurity concentrations but reduce costs.

c. For all technologies, the impurity concentrations shown in the table could be reduced at higher capture costs.

3.3.5 The IPCC SRCCS states that the fate in the capture plant of other substances that may occur in the feed gas (such as heavy metals) is not well known, and therefore attention should be paid to identifying these substances in the injection stream.

Exposure processes and pathways from injection equipment

3.3.6 Processes and pathways for the leakage of CO_2 and any incidental associated substances to the marine environment and the atmosphere during transport and injection equipment should be addressed, and uncertainties should be identified. There is potential for leakage along the chain of storage of CO_2 streams in geological formations, i.e. from the capture site, during compression, pipeline transportation and injection phases, to the final storage formation. These will be site-specific. Potential pathways to the water column from equipment during the injection phase can occur from:

a. the connecting pipeline from the CO_2 recovery plant to the storage site;

b. the sub-sea template and injection well(s) (if no surface installation); and

c. the platform injection well or CO_2 riser, pipeline and injection well.

3.3.7 The IPCC SRCCS noted that, at the storage site, adequate plans need to be in place for dealing with excess CO_2 if the injection well(s) need to be shut in. Options include having a backup injection well or, in the most extreme cases, methods to safely vent the CO_2 stream to the atmosphere. Proper maintenance of site facilities and injection wells is necessary to avoid leakage and well failures. For injection through old wells, key factors include the mechanical condition of the well, the quality of cement and the degree of maintenance. All materials used in injection wells should be designed to anticipate peak volume, pressure and temperature. In the case of gas containing free water, use of corrosion-resistant materials is essential. There are several analogues from offshore transport and injection of hydrocarbon gas and onshore CO_2 injection projects that can provide data for risk assessment and management.

Exposure processes and pathways from geological storage formations

3.3.8 A proper risk assessment should address, amongst others, any risk of leakage to the marine environment. Processes and pathways for migration of CO_2 and incidental associated substances from geological storage formations and leakage to the marine environment, during and after injection of CO_2 streams, should be assessed. This assessment needs to include the consideration of substances, mobilised by the CO_2 stream and also displaced saline formation water, based on an informed decision on the relevance of these issues. Such assessments should be site-specific. Attention should be paid to both long-term and short-term processes.

3.3.9 Processes to be considered should take account of the fact that free gaseous CO_2 and supercritical CO_2 are less dense than either water or brine under typical geological conditions, so that they tend to rise towards the seabed. For example, if the formation pressure is high and leakage pathways exist, migration of free and dissolved CO_2 and incidental associated substances out of the storage formation may result. Low-pH formation water resulting from the dissolution of CO_2 may promote corrosion of well-construction and plugging materials.

3.3.10 The IPCC SRCCS[iii] indicates that potential migration and leakage pathways from geological formations include:

a. migration through the pore system in low-permeability cap rocks if the capillary entry pressure at which CO_2 may enter the cap rock is exceeded;

b. migration, because the cap rock is locally absent, in combination with lateral migration of free or dissolved CO_2 and incidental associated substances (spilling);

c. migration through faults or other fractures in the cap rock;

d. migration through inadequately completed and/or abandoned wells; and

e. migration due to degradation of the cap rock or wells by reaction with acidic formation waters.

3.3.11 Site characteristics and numerical simulation of the injection of the CO_2 stream and the long-term fate of the stored CO_2 (and any incidental associated substances) are appropriate to help identify potential migration pathways, leakage pathways and fluxes.

Water/biosphere – exposure processes and pathways

3.3.12 An assessment should be made of the fate of CO_2 and incidental associated substances, including any migration from the geological formation and the potential for leakage of CO_2 to the seabed sediments and water column. Leakage of free and dissolved CO_2, incidental associated substances and other substances mobilised by the CO_2 stream, for example saline formation water (as per “saline displacement” identified in Figure C2 in Step 1 of this Framework), should be considered.

Likelihood of exposure

3.3.13 The probabilities of the exposure processes may be assessed using appropriate techniques, including numerical modelling and simulation tools. Uncertainties should be identified, as well as sensitivity for the choice of models by comparing different simulation techniques.

3.3.14 Data from existing CO_2 storage projects contributes to improving the quality of long-term performance predictions and the knowledge base is growing. The IPCC SRCCS[iv] concluded that, assuming that sites are well selected, designed, operated and appropriately monitored, the balance of available evidence indicates that it is likely that the fraction of stored CO_2 retained in a geological formation is more than 99% over the first 1,000 years.

Scale of exposure

3.3.15 An assessment of the fluxes of CO_2 and incidental associated substances and their scale of spatial and temporal variability should be undertaken using appropriate numerical modelling and simulation techniques. Uncertainties should be identified and quantified (see the previous sections).

3.16 Because each site is different, the possible quantities of CO_2 (and incidental associated substances) and the scale of spatial and temporal fluxes, e.g., CO_2 concentration in the water column, should be assessed on a site-specific basis, for the purposes of the Effects Assessment.

Conclusions on exposure assessment

3.3.17 An exposure assessment should be undertaken to inform the effects characterization and form part of the wider risk characterization and risk mitigation. The information gathered should be appropriately recorded and documented.

3.3.18 Characterization of the injection stream is essential. The types and concentrations of other substances vary depending mainly on the basic process (e.g., gasification, combustion, natural gas cleanup), source material, and type of capture process.

3.3.19 Processes and pathways for migration of CO_2 from geological storage reservoirs and leakage to the marine environment and the atmosphere, during and after CO_2 injection, should be assessed. This should include additional substances mobilized by the CO_2 and displaced saline formation water. These should be site-specific. The uncertainties should be identified.

3.3.20 The transport, mixing processes and rates of leakage of any CO_2 (and other substances mobilized by CO_2) to the seabed sediments and water column should be assessed.

3.3.21 The probabilities of the exposure processes may be assessed using appropriate numerical modelling and simulation tools. Assessment of the amount of CO_2 and the scale of spatial and temporal fluxes should be undertaken using an appropriate numerical modelling and simulation tool.

Step 4. Effects Assessment

Introduction

3.4.1 Assessment of potential effects should lead to a concise statement of the expected consequences of storage of a CO_2 stream in geological formations. It provides input for deciding whether to approve or reject a CO_2 storage proposal, site selection, and monitoring both to verify the Impact Hypothesis and to determine what additional preventive and/or mitigating measures are required. It therefore provides a basis for management measures and for defining environmental monitoring requirements.

3.4.2 Although permanent containment of CO_2 streams is the ultimate objective of storage of CO_2 in geological formations, effects and risk assessment is carried out to demonstrate that, in the event of leakage, storage does not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

3.4.3 Potential risks to humans and ecosystems from geological storage may arise from leakage during injection and leakage across faults or ineffective seals. Leakage from offshore geological storage sites may pose a hazard to benthic and pelagic ecosystems as well as other legitimate uses of the maritime area, in the event the CO_2, any incidental associated substances or substances mobilised as a result of the storage of the CO_2 stream move from deep geological formations through benthic sediments into the sea[v] (see exposure assessment).

Sensitivity of species, communities, habitats and processes

3.4.4 This section highlights the sensitivity of species, communities, human health and other legitimate uses of the maritime area to exposures to CO_2 and incidental associated substances and data requirements including those addressing issues of temporal and spatial scales and variability.

3.4.5 The main effects to consider in relation to the leakage of CO_2 streams are those that result from increased CO_2 concentrations in ambient marine sediments and waters and biological sensitivity to such increases. The effects of CO_2 leaking to water bodies depend upon the magnitude and/or rate of leakage[vi], the chemical buffering capacity of the sedimentary or water body and transport and dispersion processes. Changes in pH are directly related to the partial pressure of CO_2 and the chemical buffering capacity of the aqueous phase. High CO_2 levels in the aqueous phase may impair respiration in organisms and cause lowering of pH in animal body fluids (*acidosis)*, increased concentrations of CO_2 in body fluids (*hypercapnia*) and impairment of oxygen transport in animals (*asphyxiation*). The changes in ocean chemistry caused by CO_2 leakage may have profound effects on calcareous organisms such as corals, shellfish, and specific groups of phytoplankton. Effects of *disturbed calcification rates* may include reduced levels of growth and reproduction, as well as increased mortality rates. The OSPAR report[vii] distributed as *"Effects on the marine environment of ocean acidification resulting from elevated levels of* CO_2 *in the atmosphere"* contains an overview of ecosystem sensitivity to CO_2 exposure

3.4.6 Effects of exposure to other contaminants in the CO_2 stream should be assessed as well. Also, changes of pH in sediments due to CO_2 might have effects on metal speciation (e.g., mobilising trace metals and other compounds to a higher extent of bioavailability[viii]).

This may lead to direct toxic effects and/or accumulation in the food chain. The effects of displacement of saline water should be included in the effects assessment as well.

Temporal and spatial issues

3.4.7 Stored CO_2 and any incidental associated substances may affect the overlying marine environment with which it comes into contact through different exposure scenarios. Leaks may occur on a variety of temporal and spatial scales, ranging from local sudden, major leaks (e.g., blow-out during injection or well integrity failure) up to slow leakage over a wide area. The impacts will likely differ accordingly.

3.4.8 The worst-case scenario is not only defined by the rate of CO_2 leakage but also by the total amount of CO_2 and incidental associated substances with which the ecosystem comes into contact and the sensitivity of the receiving environment. The spatial extent of the waters and sediment with increased CO_2 content and decreased pH will depend on the amount of CO_2 and incidental associated substances and also on the prevailing environmental conditions at the sea bottom as these can significantly influence the behaviour and fate of the leaking CO_2. For example, stratification may trap CO_2-enriched water at the bottom of the sea.

3.4.9 The resilience of marine ecosystems remains largely unknown. Disturbance, re-colonisation and community recovery differs in the shallow and deep sea. It is generally assumed that recovery is faster in shallow areas (weeks/months) than in the deep sea (several years), although this should be assessed on a site-by-site basis. Prediction of future changes in ecosystem dynamics, structure and functioning benefits from data on sub-lethal effects over the entire life history of organisms.

Human health and other legitimate uses of the maritime area

3.4.10 In addition to effects on the environment, the effects assessment evaluates the potential effects on human health (including those associated with food chain transfer of contaminants), marine resources, amenities and other legitimate uses of the maritime area. This might especially be relevant if large amounts of CO_2 (potentially including incidental associated substances) may reach the sea surface, which consequently may endanger human life and other legitimate uses of the maritime area.

Conclusions on effects assessment

3.4.11 Although the intention of the process of CO_2 storage in sub-seabed geological formations is no leakage, effects assessment contributes to informing site selection, monitoring to verify the impact hypothesis, and management measures.

3.4.12 While the effect mechanisms of release of CO_2 from CCS in sub-seabed geological formations may differ from the disposal of other controlled materials, the possible impacts can be identified and assessed

3.4.13 The main considerations in relation to the leakage of CO_2 should be the effects of CO_2 concentrations on human health, marine resources, sensitivity of species, communities, habitats and processes, and other legitimate uses of the sea.

3.4.14 Effects of exposure to other contaminants in the CO_2 stream should be included in the assessment.

3.4.15 Metals and other substances mobilized in a decreased pH environment should be included in the assessment.

3.4.16 A qualitative assessment of environmental effects is possible, based on available data, but further research would inform quantitative assessments.

Step 5. Risk characterisation

Introduction

3.5.1 Risk characterisation is used to provide an overall assessment of the potential hazards associated with an activity and establish relationships between exposures and sensitivity of ecological entities. Though permanent containment of CO_2 streams is the ultimate objective of storage of CO_2 in geological formations, it is advisable to show that the residual risk of leakage is well characterised. The following basic steps are associated with risk characterisation:

a. identifying potential hazards related to an activity (see site selection);

b. estimating the probability of these hazards occurring and the severity of effects posed to exposed species and ecosystems and the risks to human health and other legitimate uses of the maritime area;

c. describing the risk estimate in the context of the significance of any adverse effects and the lines of evidence supporting their likelihood;

d. identifying and summarizing the uncertainties, assumptions and qualifiers in the risk assessment; and

e. reporting and communicating the conclusions.

Risk Characterisation for storage of CO_2 streams in geological formations

Overview

3.5.2 Risk characterisation for the storage of CO_2 streams in geological formations should be based on site-specific considerations of the potential exposure pathways, the probabilities of leakage, and potential effects on the marine environment, human health, and other legitimate uses of the maritime area, as described in the previous steps. A thorough site characterisation is therefore critical for defining the nature and temporal and spatial scales of potential impacts.

3.5.3 Given the time-scales associated with storage of CO_2 streams in geological formations, it would be useful to characterise the risks at different stages of a project. The risks during injection and in the near-term (e.g., decades) may be different than the longer-term risks (e.g., over centuries to millennia) depending on site-specific considerations. In the injection phase, consideration should be given to risks such as the buoyant behaviour of CO_2, the pressure build-up in the formation, the quality of the seal and the well completion. Particular attention should be paid to the integrity of the wells. Over the longer term, the risk assessment should also address any change in the integrity of the seal and of the plugs in the abandoned wells and might include the effects of CO_2 dissolution and mineralization. It is important to update the risk characterisation periodically, as part of the risk management process, based on new field data and/or performance assessment data and/or new/improved scientific knowledge.

3.5.4 When evaluating the spatial aspects of risk characterisation, various factors are relevant to the potential area impacted, including the injection volumes and geological characteristics of the storage formation. A thorough site characterisation (see above) is therefore critical to the risk characterisation. In order to conduct an appropriate risk characterisation, the potential spatial extent of potential impacts should be estimated using models or other analytical tools.

3.5.5 A thorough site characterization (as discussed above) will be critical for the risk characterization which will also be closely linked to the development of a sound monitoring plan.

3.5.6 It would also be useful to update the risk characterization based on collection of new field data and/or performance assessment data.

Methods

3.5.7 Well-established methods exist for characterizing the risks of industrial injection operations. Various methods for assessing the long-term passive storage phase are being developed, building partly on the experience from hazardous and nuclear waste management. These models can vary from relatively simple to very detailed models. Where significant uncertainties in model input variables are projected to exist, it is recommended that uncertainty ranges around the most likely values be applied in the assessment. Similarly, if discrete events are not certain to occur, probability values should be assigned to such events. The assessments can be executed in a deterministic way following a conservative approach or in a probabilistic manner that quantifies the uncertainties connected with storage of CO_2 streams. Several techniques are applied to address and/or quantify the uncertainties such as Monte Carlo simulation[4], fault tree analysis and expert judgement. Natural and industrial analogues present suitable opportunities for testing the risk assessment models. These (mostly exposure-) models are integrated with effects assessment models to provide a comprehensive risk characterisation.

Impact hypothesis

3.5.8 The risk characterisation should lead to the development of an “Impact Hypothesis”. This is a concise statement of the expected consequences of disposal. It provides the basis for deciding whether to approve or reject the proposed disposal option and for defining environmental monitoring requirements. Key elements in the development and testing of the impact hypothesis are:

a. characterization of the CO_2 stream;

b. conditions at the proposed storage-site(s);

c. preventive and/or mitigating measures (with appropriate performance standards);

d. injection rates and techniques;

---

[4] See the Glossary in Appendix 3 to this report for an explanation.

e. potential leakage rates and exposure pathways;

f. the potential impacts on amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the maritime area, including fishing, navigation, engineering uses, areas of special concern and value, and traditional uses of the maritime area;

g. potential impacts on human health;

h. the nature, temporal and spatial scales and duration of expected impacts.

3.5.9 The ultimate objective of storage of CO_2 streams is to ensure permanent containment of CO_2 streams in geological formations, in a manner that avoids significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area, thereby contributing to reduce atmospheric levels of CO_2. Qualitative or quantitative performance criteria should be set for elements of the impact hypothesis, such that - as a whole – these are consistent with the ultimate objective.

3.5.10 Results from the risk assessment and monitoring procedures should be compared with the various performance criteria in order to determine whether the system deviates from the initially anticipated behaviour in a way that gives rise to concern about achievement of the overall objective. If such situation arises, mitigative measures should be implemented with the intention of meeting this overall objective and minimizing any adverse consequences.

3.5.11 Several general, relevant principles regarding development and application of an Impact Hypothesis are:

a. the evaluation of whether the performance criteria are met, should be as comprehensive as possible, but it must be recognised that even the most comprehensive impact hypotheses may not address all possible scenarios such as unanticipated impacts;

b. it is essential to determine "where" and "when" any impacts are likely to be expected;

c. the expected consequences should be described in terms of any effects on human health, amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the maritime area, including fishing, navigation, engineering uses, areas of special concern and value, and traditional uses of the maritime area;

d. the monitoring programme should be linked to the hypotheses through the performance criteria and to serve as a feedback mechanism to verify the predictions and review the adequacy of management measures applied;

e. it is important to identify the sources and consequences of uncertainty;

f. it is essential to include one or more steps of stakeholder involvement in the process of the development of an impact assessment in order to include all relevant endpoints and to reach the required level of community acceptance.

Conclusions on risk characterization

3.5.12 Risk characterization should be considered using site-specific information, but common guidelines would provide a useful framework.

3.5.13 Factors evaluated in a risk characterization may change over time given the operational status of the project and ongoing data collection used to update predictive models.

3.5.14 Sources and magnitude of uncertainty will be a function of the data and modelling assumptions used.

Step 6. Risk management

3.6.1 While storage of CO_2 streams in geological formations aims to isolate CO_2 from the biosphere (including the atmosphere) permanently, risk management procedures are necessary to maximise the intended isolation and to minimise the effects of possible leaks of $CO_{2,}$ incidental associated substances and substances mobilised by the CO_2 stream. Permanent containment of CO_2 streams is the ultimate objective of risk management. It should, however, demonstrate how an event of leakage would be managed in order to prevent it leading to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area.

3.6.2 The general and specific information that is needed for risk management of CO_2 storage sites, including options for remediation and mitigation, are outlined in Appendix I to this Framework.

3.6.3 Risk management is a structured process that begins with identifying and quantifying the risks associated with a given process, modifies the process to minimize risk and implements appropriate monitoring and intervention strategies to manage remaining risk. In the context of CCS under the seabed, risk management consists of careful site selection, monitoring to provide assurance that storage is proceeding as expected and to provide early warning of CO_2 migration out of storage, effective regulatory oversight, and implementation of remedial measures to eliminate or limit the impacts of leakage.

Prevention of CO_2 escape from the formation

Injection management

3.6.4 Because the physical state of injected CO_2 will be either supercritical or liquid and thus similar to the physical state of water, the OGP Guidelines for injection of produced water[ix] and those published by OSPAR[x] are applicable to injecting CO_2 streams in an environmentally safe manner. If these guidelines are applied to the injection of CO_2 streams, the probability of cap rock fracture is as low as that from injection of fluids in the oil and gas industry. For injection into exhausted oil or gas reservoirs, the required geological data is largely available. For injection into saline aquifers or for other types of geological storage, the information should be obtained if unavailable. Key items are the characteristics of the seal and dominant (short-term and long-term) trapping mechanisms.

3.6.5 The planning, design and construction should lead to an inherently safe storage site, which means that the risk of CO_2 (and incidental associated substances) escaping from the formation is reduced to an insignificant level.

3.6.6 The maximum estimated extent to which CO_2, incidental associated substances and mobilised substances could migrate in the formation defines the zone to be characterised for risk management purposes. To determine the confinement zone, the following factors, among others, will assist in the definition of the geographic volume to be reviewed (see also Appendix I):

a. regional and local geology;
b. regional stratigraphy;
c. regional structure;
d. regional hydrogeology;
e. seismic history;
f. injection, static and dynamic properties of containment and confinement zone; and
g. vertical hydraulic gradient.

3.6.7 Collection of such information in areas where there has been no previous hydrocarbon exploration or production is even more critical.

Well integrity

3.6.8 The design, construction and operation of a well within the storage site are key factors in achieving the CO_2 storage objective. The well design and construction should account for operating conditions (pressure, fluid composition and acidity, duration, etc.) and address identified potential well failure scenarios. The OGP Guidelines for injection of produced water list many of the elements that need to be considered.

3.6.9 Well integrity additionally depends on:

a. the quality of materials used - the probability of CO_2 (including incidental associated substances) escaping through failure of the integrity of the injection well is low if the well is lined with materials known to withstand the corrosion by carbonic acid, which may be formed at the point of injection;
b. the management of the operation;
c. proper site-closure procedures so that long-term isolation has been accounted for.

Formation flow and fracture propagation prediction

3.6.10 Predictive modelling of injection of CO_2 streams should include both flow (reservoir) simulation, prediction of fracturing and fracture propagation, e.g., induced by CO_2 injection, and modelling of geochemical rock-fluid interaction. These will establish the transport and fate of the injected CO_2 stream and provide the operator with an integrated knowledge sufficient to manage the injection process in an environmentally protective manner. The modelling should provide predictions during the operational injection period and an assessment of the residual pressure fields during the period after shut-in of the injection well and prior to decommissioning.

3.6.11 Modelling should be updated in the light of monitoring results.

Preventive maintenance and contingency planning

3.6.12 Preventive maintenance and contingency planning are an integral part of a CO_2 injection operation. Potential failure modes should be evaluated at the planning stage along with the necessary remedial actions that might be taken. Examples of potential failures include:

a. pressure build-up exceeding security levels;

b. confinement problems (fracturing of the cap rock, breach to casing or cement around the casing); and

c. mechanical complications (e.g., corrosion, erosion, failures of wellhead, etc).

3.6.13 It is anticipated that precautions taken after injection operations have ceased will be similar to those used for oil and gas wells and by acid-gas disposal wells under which the wells are plugged to prevent hydraulic communication to the surface. Attention should be given to the procedures and materials used for sealing and cementing the wells to ensure the long-term integrity of storage of CO_2 streams, and the probability of cap rock and formation fracture.

3.6.14 Because the ultimate objective of storage of CO_2 streams in geological formations is to ensure permanent containment of these CO_2 streams, it will be necessary to archive documentation so that future generations are informed of the existence of the CO_2 storage site and its history. This includes keeping records of the authorisation and licensing process, site-closure and decommissioning procedures, together with data of long-term monitoring and management response capabilities.

Monitoring migration of CO_2 streams and mobilised substances within and above the formation during the injection phase

3.6.15 Monitoring would be done for at least two different purposes:

a. detection of potential leakages from sub-seabed geologic storage; and

b. verification that such leakage does not occur.

3.6.16 A monitoring programme should attempt to quantify the mass and distribution of CO_2 in each storage site and should record related biological and geochemical parameters. The monitoring programme should include:

a. monitoring for performance confirmation;

b. monitoring to detect possible leakages;

c. monitoring of local environmental impacts on ecosystems; and

d. monitoring of the effectiveness of CO_2 storage as a greenhouse gas mitigation technology.

Process monitoring and control

3.6.17 Essential elements of process monitoring and control include:

a. the injection rate;

b. continuous pressure monitoring;

c. injectivity and fall-off testing;

d. the properties of the injected fluid (including temperature and solid content, the presence of incidental associated substances and the phase of the CO_2 stream);

e. mechanical integrity of seals and (abandoned) wells;

f. containment of the CO_2 stream; and

g. control measures, overpressure, emergency shut down system.

While not essential, if observation wells are available they can provide useful information.

3.6.18 Techniques for monitoring stored CO_2 have been described in two IPCC documents: the IPCC SRCCS (IPCC, 2005) and the "Guidelines for National Gas Inventories"[xi] (IPCC, 2006). Baseline information is required on the geological structures within and above the formation so that the signal produced by stored CO_2 can be distinguished from that associated with the natural system. Seismic methods have already been shown to work for monitoring oil and gas reservoirs but such methods may not be applicable to storage of CO_2 streams in all settings. Modelling may be applied to convert monitoring signals to distribution or fluxes of CO_2. If seismic methods are used, careful consideration should be given to the effects on marine organisms of propagating seismic signals through the water column and seafloor.

3.6.19 Monitoring of CO_2 containment and migration may include the following elements:

a. performance monitoring (sometimes referred to as testing the Impact Hypothesis) which measures how well injected CO_2 stream is retained within the intended geologic formation; and

b. monitoring the geological layers above the formation to detect and measure possible migration of the CO_2 stream out of the intended formation;

3.6.20 The following items may be included, especially if it is suspected that migration of CO_2 above the formation could extend to the seafloor and in case that the storage site is in proximity to sensitive or endangered habitats and species:

a. monitoring the seafloor and overlaying water to detect and measure possible leakage of CO_2 (and incidental associated substances) into the marine environment. In this context special attention should be given to wells that intersect the storage formation; and

b. monitoring biological communities to detect and measure the effects of leakages on marine organisms.

Long term, post injection, monitoring of migration of CO_2 streams and mobilised substances

3.6.21 Long-term monitoring can generally be accomplished with a sub-set of the technologies used during the injection phase. Moreover, new and more efficient monitoring technologies are likely to evolve. Methods chosen for monitoring should not compromise the integrity of a sealed formation, or the marine environment. In addition, records should be kept of the authorisation, licensing and site-closure processes, together with data on long-term monitoring and management response capabilities.

3.6.22 After a storage site has been closed, the operator should remain responsible for maintenance, monitoring and control, reporting, and corrective measures pursuant to the requirements of this Framework on the basis of a post-closure plan submitted to and approved by the competent authority as well as for all ensuing obligations under other relevant legislation until the responsibility for the storage site is transferred to the competent authority.

3.6.23 A storage site can be transferred to the competent authority on its own initiative or upon request from the operator, if the following conditions are met:

(a) all available evidence indicates that the stored CO2 will becompletely and permanently contained;

(b) a minimum period, to be determined by the competentauthority has elapsed. This minimum period shall be noshorter than 20 years, unless the competent authority is convinced that the criterion referred to in point (a) is compliedwith before the end of that period;

(c) the financial obligations referred to in 3.6.25 have beenfulfilled;

(d) the site has been sealed and the injection facilities have beenremoved.

3.6.24 After the transfer of responsibility, monitoring should be reduced to a level which still allows for identification of leakages or significant irregularities, but should again be intensified if leakages or significant irregularities are identified. There should be no recovery of costs incurred by the competent authority from the former operator after the transfer of responsibility except in the case of fault on the part of the operator prior to the transfer of responsibility for the storage site.

3.6.25 National authorities may, after transfer of responsibility, have to bear costs, such as monitoring costs, associated with CO_2 storage. A financial contribution should therefore be made available by the operator to the competent authority, before the transfer of responsibility takes place and on the basis of arrangements to be decided by Contracting Parties. This financial contribution should at least cover the anticipated cost of monitoring for a period of 30 years (DIRECTIVE 2009/31/EC).

Mitigation or remediation of CO_2 escape from the storage site or formation

3.6.26 National authorities should make sure prior giving an authorisation for a CCS project, that remediation, in case of leakage, would be possible (technically and financially) within a good/agreed period. The need for mitigation or remediation is determined by national authorities on the basis, among others, of the likelihood that CO_2 (and incidental associated substances) will reach living marine or water resources and the extent of significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area. Mitigation or remediation may begin as soon as CO_2 is known, or suspected, to have migrated from the formation. Leakage of a CO_2 stream from an injection site can occur during or after the injection phase. The most likely avenues for leaks include (see also Figure 4):

a. the injection well, possibly due to overpressure;

b. other abandoned or active wells;

c. areas where permeable rock reaches the surface of the seabed; and

d. fractures of, or high permeability zones, within the cap rock.

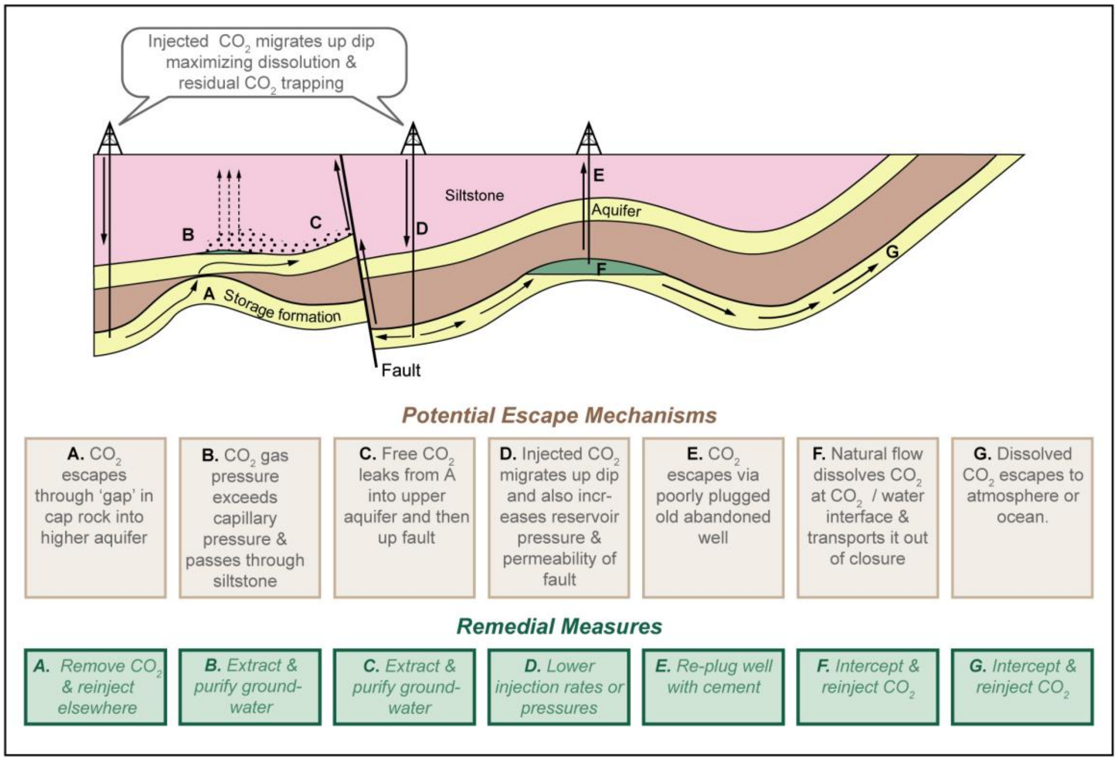


Figure 4 Escape mechanisms and remedial measures (IPCC, 2005).

3.6.27 Methods for remediation of these leaks are analogous to techniques used in the oil and gas industry. Strategies such as transporting CO_2 streams to other parts of the same formation or to different storage sites should be available. These are described in Table 5.7 of IPCC SRCCS.

3.6.28 If leakage occurs through an active or abandoned well, remediation methods may include:

a. recapping wells or repairing faults in cement between rock and casings; and

b. drilling intersecting wells followed by controlling the leak with heavy mud followed by recapping.

3.6.29 If leakage occurs through faults or fractures, remediation methods may include:

a. lowering the injection pressure or the formation pressure by removing water or other fluids;

b. halting the injection until the project is stabilised;

c. transferring CO_2 streams to a more suitable formation; and

d. plugging the pathway by injecting sealing material.

C.4. Establishment of an authorization and licensing process

4.1 The storage in geological formations of carbon dioxide streams from carbon dioxide capture processes shall not be permitted by Contracting Parties without authorisation or regulation by their competent authorities. Any authorisation or regulation shall be in accordance with the Barcelona Convention Framework for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations, as updated from time to time.

4.2 A decision to issue a license for the purpose of CCS should only be made if all impact evaluations are completed and the monitoring requirements are determined. This includes an adequate site characterization, an assessment of the likelihood for migration and leakage and associated impacts and a suitable risk management plan. It is recommended that opportunities are provided for public review and participation in the licensing process. The provisions of the license shall ensure, as far as practicable, that:

a- there are no significant risks for human beings and potential disturbance and detriment for any other legal human activities are minimized and the benefits maximized

b- marine environmental disturbance and detriment are minimized and the benefits maximized.

4.3 The licensing process requires the completion of a series of reports and documents on the characteristics of the sequestration site and injection and closure operations after injection ceases. Any license issued shall contain data and information specifying:

a- purpose of the license;

b- the types, amounts and sources of materials in the carbon dioxide stream, including incidental associated substances, to be disposed into the sub-seabed geological formation;

c- the location of the injection facility and sub-seabed geological formation;

d- the method of carbon dioxide stream transport; and

e- a risk management plan that includes:

e.1 monitoring (both operational and long term) and reporting requirements;

e.2 a mitigation or remediation plan as discussed under paragraph 8.11 above; and

e.3 a site closure plan including a description of post-closure monitoring and mitigation or remediation options.

4.4 Licenses will also include a letter of approval from the Contracting party, which should establish the conditions and duration under which the license applies.

4.5 Licenses should be reviewed at regular intervals, taking into account any changes to the composition of the CO_2 stream, results of monitoring, and the objectives of monitoring programmes. Review of monitoring results and updated risk assessments will indicate whether field programmes need to be continued, revised or terminated, and will contribute to informed decisions regarding the continuance, modification or revocation of licenses. This provides an important feedback mechanism for the protection of human health, the marine environment, and other uses of the sea.

4.6 When a storage site belongs to a geological formation from several countries, or when there is potential for transboundary movement of CO_2 streams after injection, the license should be issued in agreement with all countries with jurisdiction over this sub-seabed geological formation, without prejudice to international law. The Contracting Party where the injection occurs is responsible for the implementation of this Framework. The responsible Contracting Party should cooperate with Contracting Parties, other States and other relevant entities, including by way of arrangement or agreement to ensure that the guidelines included in this Framework are implemented effectively.

4.7 After the withdrawal of a license, either because expiration or because of a negative review, the competent authority should either issue a new license or close the storage site. In the mean time, the competent authority should take over the responsibility for the storage site, including specific legal obligations. Costs incurred should be covered by the former operator until a new license is issued.

4.8 The responsibility for the storage site, including specific legal obligations, should be transferred to the competent authority, if and when all available evidence indicates that the stored CO_2 will be completely and permanently contained. After the transfer of responsibility, monitoring should be reduced to a level that still allows for identification of leakages or significant irregularities, but should again be intensified if leakages or significant irregularities are identified.

4.9 Because the aim of disposal of carbon dioxide streams into sub-seabed geological formations is to store CO_2 permanently, licenses and other supporting documentation, including site location, monitoring results and mitigation or remediation plans should be archived and retained for long periods of time.

C.5. Liability of CCS in the Mediterranean Sea.

5.1 “Liability” means the legal responsibility arising from the CCS project activity or the relevant geological storage site, including all obligations related to the operation of the storage site (e.g. monitoring, remedial measures, etc.), to compensate for or remedy any significant damages, including damage to the environment, such as ecosystem damage, other material damages or personal injury;

5.2 Short, medium and long-term liability for potential physical leakage or seepage of stored carbon dioxide, potential induced seismicity or geological instability or any other potential damage to the environment, property or public health attributable to CCS project activity during and beyond the license period, including the clear identification of liable entities, shall:

(b) Be applied during and beyond the license period;

(c) Be consistent with the different protocols of the Barcelona convention;

5.3 The operator of a CCS proposal shall clearly document in the project design document how the liability obligations arising from the proposed CCS project activity or its geological storage site are allocated during the operational phase, closure phase and post-closure phase in accordance with this decision.

5.4 When determining the liability provisions referred to in paragraphs 5.2 and within the different phases defined in paragraph 5.3 above, the following issues shall be considered:

(a) A means of redress for Parties, communities, private-sector entities and individuals affected by the release of stored carbon dioxide from carbon dioxide capture and storage project activities;

(b) Provisions to allocate liability among entities that share the same reservoir, including if disagreements arise;

(c) Possible transfer of liability at the end of the license period or at any other time;

(d) State liability, recognizing the need to afford redress taking into account the longevity of liabilities surrounding potential physical leakage or seepage of stored carbon dioxide, potential induced seismicity or geological instability or any other potential damage to the environment, property or public health attributable to the clean development mechanism project activity during and beyond the crediting period;

5.5 During the operational phase and any time thereafter until a transfer of liability to the Countries has been effected in accordance with paragraph 5.5 below, liability, as defined in paragraph 5.1 above, shall reside with the CCS license operator.

5.6 A transfer of liability from the license operator to the host Country shall be effected after:

(a) The monitoring of the geological storage site has been terminated in accordance with the conditions for the termination of monitoring, as set out in the license issued following section C4 above.

(b) The host Country has established that the conditions set out by the designated national authority in its letter of approval, defined in paragraph 4.4 of section C4 above, and those set out in the relevant laws and regulations applicable to the geological storage site have been complied with.

5.7 Adequate provision for restoration of damaged ecosystems and full compensation for affected communities in the event of a release of carbon dioxide from the deployment of carbon dioxide capture and storage in geological formations must be established prior to any deployment of related activities;

5.8 Liabilities other than those covered by this Framework, in particular those concerning the capture and the injection phase should be evaluated in relation to the different protocols of the Barcelona convention.

C.6. Overall conclusions and implications

6.1 Carbon dioxide is the most important anthropogenic gas within the so-called greenhouse gases, which are in turn responsible ocean acidification and other global effects on the marine environment. The capture and storage of CO_2 in geological formations under the seabed is one of the actions that should be carried out together to reduce the concentration of greenhouse gases in the atmosphere and mitigate current climate change. As one such option, CCS is considered to be technically feasible, using established technologies.

6.2 The benefits of CO_2 storage in geological formations under the seabed have the potential to make a substantial contribution to reducing CO_2 emissions to the atmosphere, thus preventing these emissions from being absorbed into the oceans and providing mitigation of ocean CO_2, carbonate and pH change, effects on sensitive biological systems and nutrient availability and cycles. .

6.3 CCS in geological formations under the seabed is a waste management option to be considered within the context of Contracting Parties' approaches to mitigating greenhouse gas emissions5.

6.4 CO_2 injection streams may contain other substances derived from the source material. The actual composition of the injection streams intended for sequestration in the sub-seabed will therefore vary in their content of CO_2 and other substances depending on the nature of the source material and the methods used for CO_2 capture and liquefaction to super-critical temperatures and pressures. However, it must be stressed that none of these other substances will have been deliberately added to the CO_2 stream for the purposes of waste disposal.

6.5 Long-term monitoring and mitigation of any leakage of CO_2 will be important activities in the context of the Barcelona Convention and Protocol, due to the long time-scales of the storage, the potential for much larger sites than those used for conventional dumping operations and the nature of CO_2.

6.6 There is significant potential for geological storage in structures beneath the sea. Oil and gas reservoirs and saline formations are expected to have the largest potential to accommodate safe, long-term storage. The aim is to retain CO_2 permanently. Because of the various trapping mechanisms, storage may, in some cases, become more secure over time.

6.7 Because every site is expected to differ in regard to the properties affecting its suitability as a storage site, several important issues should be considered during the site screening and selection process for CCS in sub-seabed geological formations, including: the storage capacity and injectivity of the geological formation; the storage integrity; the suitability of the surrounding geological formations; potential migration and leakage pathways over time; and the potential effects on marine life and human health of leakage of CO_2.

6.8 Monitoring techniques for the detection of migration and potential leakage of CO_2 from the intended storage formations are available. The relevant time frames pose challenges with respect to management of the response capacity.

6.9 Although the intention of the process of CCS in sub-seabed geological formations is 'no leakage', the need for implementing mitigation measures in response to potential leakages should be based on the likelihood that CO_2 will reach the marine environment and the types and magnitudes of consequent effects.

6.10 The Risk Assessment and Management Framework for carbon dioxide capture and storage in sub-seabed geological formations can provide useful and important information

---

[5] This option includes CO_2 sequestration in depleted oil and gas fields, but excludes normal oil and gas exploitation operations, such as enhanced oil recovery (EOR).

regarding site-specific risks to the marine environment posed by this activity, for developing management strategies to address uncertainties and to reduce residual risks to acceptable levels.

6.11 Some of the risks of storage of CO_2 in sub-seabed geological formations are associated with leakage into the marine environment of the CO_2 and any other substances in or mobilized by the CO_2 stream. Those potential risks are focused primarily at the local scale and include the potential for impacts on the marine environment in proximity to the receiving reservoir. These risks should be minimized by a series of actions, which should be summarized in this Risk Assessment Framework that ensure that the storage is done in a safe way.

6.12 The assessment of risk for a given storage process should be done in a case-by-case basis. The Mediterranean Sea and the ecosystems and human settlements and activities within it show a set of specific characteristics. The Barcelona Convention includes a series of mechanisms and protocols to safeguard the conditions of the Mediterranean Sea, its ecosystems, human settlements and activities. However, the Storage of CO_2 has not been specifically regulated within the Convention.

6.13 This Framework for Risk Assessment and Management of Storage of CO_2 Streams in Sub-seabed Geological Formations aims to provide generic guidance to the Contracting Parties to the Barcelona Convention for developing management strategies to address uncertainties and to reduce residual risks to acceptable levels.

6.14 This framework is a reasonable starting point for developing specific guidelines for Storage of CO_2 Streams in Sub-seabed Geological Formations by an Intersessional Working Group on Carbon Storage. The development of specific technical guidance related to CO_2 storage in geological formations under the seabed would be useful.

APPENDIX I – Information needs for Risk Assessment and Management

A1.1 The following table has been modified from the Risk assessment framework on carbon dioxide capture and storage of the London Convention and Protocol. It is intended as a guideline of information needs to facilitate the different steps of the Risk Assessment and management of stored CO_2 and to describe the knowledge required to ensure that a storage site will be safe on the long term.

Variables to be included in the Risk Assessment	**Parameters to identify, qualify and –where possible- quantify the status of the variable in relation to reference points used in the Risk Assessment**
Characterisation of the injected CO_2 stream	Concentration, type and properties of substances other than CO_2 in the stream
Location and geographical factors	Basic information: Water depth, formation depth Relative distance in relation to, with special mention to potential competition between uses of the area of interest: - Human nucleus - Potable or irrigation water resources - Areas of economical relevance, such as: o Touristic areas o Fishing areas - Areas of special ecological, or scientific importance, including but not restricted to: o Protected areas: SPAMIS[1], FRAs[2], etc. o Areas with fragile ecosystems or ecosystems of special interest o Breeding areas - Areas of historical relevance
Local and regional geological setting	Regional geology, hydrogeology, hydrology, stratigraphy and structure Regional tectonics and seismicity – Faults and fractures
Previous uses of the area	Man-made structures, including: – Integrity of active and abandoned wells with respect to CO_2 that are likely to be affected by the injection process o Proximity to other wells (hydrocarbon producers, former or present) or fields o Proximity to potable, irrigation or industrial water producing wells o Proximity to other injection wells o Age, depth and condition of the wells o Geometry of plugs and casing and composition of plugs of abandoned wells Conversion of existing well for injection: information is needed on well age, its construction details, and its history

Reservoir/seal evaluation	Geological interpretation – Stratigraphic interpretations and well-log cross sections of the reservoir intervals – Reservoir/seal heterogeneity – Temperature, pressure, fluid characteristics (salinity) Geophysical mapping – 3-D maps of potential migration pathways (faults) – Structure and thickness of formations and cap rocks Petrophysics – Permeability, relative permeability (injectivity) – Porosity – Capillary pressure – Mineralogy Hydrodynamics – Displacement of formation water – Vertical hydraulic gradient Sealing capacity of cap rocks – Seal thickness – Capillary entry pressure Faults – Location, orientation and properties of faults or fractures that are likely to intersect the formation Geomechanics and geochemistry – CO_2 stream – water – rock interaction – Stress, stiffness and strength – Potential of the injected fluid to cause plugging of the formation – Compatibility with injected formation chemistry – In-situ stress profile in the various layers Other components in the input-stream Reservoir simulations – Short-term behaviour: formation response (pressure changes for a given injection rate) – Long-term behaviour: formation containment – Sufficient capacity of the formation for planned CO_2 storage Data quality History, current status and age of information available on the geological formation

APPENDIX II – Issues subject to further research to improve the Risk Assessment and Management

AII.1 This appendix includes a list of issues that require further research at the time of preparing this framework in order to improve the risk assessment process. The appendix focuses on the storage phase; for the capture phase, main research lines include

a) the amelioration of the existing chemical and physical sorbents;

b) enhancement of the ion-transport and other membranes and integration in the power technologies; and

c) reduce the scale-up gaps from laboratory to pilot or large scales (CSLF, 2010).

For the transport phase, the main focus of research is related to the effects of impurities in the gas flow and the response procedures in case of a pipeline accident.

AII.2 There are still high levels of uncertainty in several aspects of the CCS, some of which are listed below:

- There is an inherent uncertainty due to the long-term requirements of CCS, which is difficult to overcome due to our limitations for long-term predictions of earth dynamics and most of the processes involved.

- In addition to the above, the different processes and the different methods used in each of the stages involved in the CCS technology show different levels of maturity, which creates uncertainty when evaluating the general characteristics and potential of CCS. Also, the different methods have a different associated cost, which have also a high case-specific component, creating a large uncertainty in the evaluation of the cost-benefit assessment of a given site.

- The complexity and large spatio-temporal scale of physical and chemical processes in a storage site and within the injected CO_2 streams makes it difficult to obtain observations at the required level of spatio-temporal and numerical precision.

- Furthermore, and in relation to the difficulties on obtained the required observations, the evaluation of the capabilities of CCS in a specific case study is often at least partially based on numerical models, which themselves have a high uncertainty due to lack of basic data or validation for each specific case study.

AII.3 Research lines for the capture phase of CCS focus on increasing the efficiency of site selection, reducing of some of the sources of uncertainty listed above, improving the cost-efficiency of the injection and monitoring processes and providing remediation if a leakage occurs. Specific research lines that should be further explored to achieve these goals include:

- Comparative physical and chemical behavior of oil and gas during the injection process and inside the geological structure, both on general terms and under case specific conditions

- Instrumental efficiency for monitoring purposes, as well as minimum spatial and temporal coverage required to detect and quantify leakages, including those with small volume, due to the large temporal scale needed to evaluate CCS.

- Creation of databases of relevant observations on CCS sites and natural analogues and development and validation of improved (in terms of accuracy and precision) simulation models to describe main processes involved in CCS.

- Assessment of effects of CO_2 exposure on species and ecosystems as a result of a leakage, including effects at different temporal and concentration levels, and the effects of prolonged exposure.

AII.4 In addition to the research lines exposed above, several structural and inherent uncertainties are expected to remain when predicting at the large temporal scales required to evaluate CCS. Therefore, another important research line is the quantification and incorporation of uncertainty specific of CCS projects in the risk assessment framework, in order to be able to provide with efficient management of CCS.

Risk Management - Improving options for remediation, mitigation and monitoring

AII.5 Although a well-developed body of knowledge exists in the oil and gas industry for leak/release remediation, more experience will improve decisions on remediation and mitigation strategies to manage CO_2 leaking from geologic formations. This experience may be necessary either to:

a. confirm the similarities of behaviour between oil and gas operations and CO_2 injection sites; or
b. identify and describe possible differences in behaviour between oil and gas operation and CO_2 injection sites;
c. determine special procedures that are required for handling CO_2 streams in these situations;
d. determine the frequency and precision of monitoring during remediation and/or mitigating activities.

AII.6 It may be necessary to develop research programs at existing CO_2 injection sites to develop general guidelines for leak remediation and mitigation activities. These research activities may also explore new remediation and mitigation techniques that have not previously been examined in the oil and gas industry.

AII.7 Currently, there are no possibilities to determine leakage rates (in terms of volumes per time unit), once a leak would have been detected. Further, small leaks of CO_2 and incidental associated substances from the storage formation may remain undetected, when the resolution of the available monitoring techniques is less than necessary to observe such small leaks. It would be desirable to be able to detect small leaks, in view of the long time-frames involved in storage of CO_2 streams, in order to fulfil the objective of permanent containment and in order to improve possibilities of early intervention in the event CO_2 streams leaking from the storage site. Further research into refined monitoring techniques would therefore be desirable. The same applies for monitoring techniques, which may be applied in the water column or on the sea bottom.

Exposure assessment – Improving the predictions of exposure to CO_2 and incidental associated substances

AII.8 Although the CO_2 stream should be characterised on a case-by-case basis, it would be beneficial to have a basic understanding of expected composition of injection streams from CO_2-generation processes. This may also help understanding the behaviour (e.g., mobilisation in low pH environments) and interaction of other substances that may be in the injection stream once in the geological and marine environment.

AII.9 It appears that the availability of suitable models is limited. Development and application of simulation models is necessary to create understanding of, amongst others, abandoned well integrity and leakage processes, behaviour of CO_2 in seabed sediments and probability of exposure.

Effects Assessment – Improve the impact prediction by gaining knowledge on the effects on species and ecosystems as a result of leakage of CO_2 streams

AII.10 A qualitative assessment of environmental effects is currently possible, based on available data, but further research is needed for quantitative assessments. Nowadays, effects data from exposures to increased CO_2 concentrations is available, but is mostly scarce, scattered and limited in detail[xii]. Existing field data are mainly limited to deep-sea situations (for ocean storage of CO_2) although currently also research is carried out in shallow waters. Specific data are available on the effects of ocean acidification due to increased atmospheric CO_2 concentrations (e.g., OSPAR 2006)[vii]. With regard to the available effects data, considerations include:

a. the need for studies of the response of representative species to various doses of added CO_2 and incidental associated substances for determination of a quantitative relation between exposure concentrations and the related effects. This is essential for a quantitative assessment of effects;

b. effects data should be available at the level of physiological and ecological processes (including abundance and biodiversity as well as biological/geological/chemical cycles), individual species (including vulnerable life stages) and the ecosystem (ensuring representation of ecosystem structure and function);

c. effects data should include studies that are longer in duration (intervals greater than the duration of a reproduction cycle or the lifespan of an individual) and larger in scale than currently performed[xiii];

d. effects data should be generated using the realistic mechanisms of increasing CO_2 concentrations under marine conditions (not mimicking pH effects using acids) since CO_2 effects are generally broader than pH effects only;

e. performance of experimental field studies of ecosystem consequences and monitoring studies, including endpoints/receptors that are not quantifiable;

f. application of ecosystem models (where available and validated) to consider the effects on species, communities, habitats and processes in the context of these models;

g. performance of field studies of ecosystemic consequences;

h. preferably, data acquisition should be carried out to include the effects on vulnerable life stages for a range of representative species (including microbial communities) found at the site, ensuring that ecosystems structure and functioning is represented; and
i. the inclusion of receptors - for which sensitivity is not quantifiable - in a monitoring programme in the event of leakage.

In the case of the specifics effects of leakage on the Mediterranean Sea, it is nowadays one of the case studies of the European project ECO2 (www.eco2-project.eu) on the likelihood of leakage events from CCS projects and their effects on the marine ecosystems. Any recommendations arisen from the results obtained in this project should be taken into consideration.

APPENDIX III – Glossary, acronyms and abbreviations

III.1 This Appendix contains a glossary, acronyms and abbreviations from the Risk Assessment Framework on carbon dioxide capture and storage of the London Convention and Protocol, which have been selected and where appropriate modified from the glossary in Annex II to IPCC SRCCS 2005.

Acid gas	Any gas mixture that turns to an acid when dissolved in water (normally refers to H2S + CO2 from sour gas (q.v.)).
Anthropogenic source	Source that is man-made as opposed to natural.
Aquifer	Geological structure containing water and with significant permeability to allow flow.
Baseline	The datum against which change is measured.
Blow-out	Refers to catastrophic failure of a well when the petroleum fluids or water flow unrestricted to the surface.
Brine	Water with a high concentration of dissolved salts.
Buoyancy	Tendency of a fluid or solid to rise through a fluid of higher density.
Cap rock	Rock of very low permeability that acts as an upper seal to prevent fluid flow out of a formation.
Capillary entry pressure	Additional pressure needed for a liquid or gas to enter a pore and overcome surface tension.
CO_2 stream	Carbon dioxide streams from carbon dioxide capture processes for storage in geological formations, which consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used, i.e.: - source and process derived substances; and - added substances (i.e. substances added to the CO_2 stream to enable or improve the capture, transport and storage processes).
Casing	A pipe, which is inserted to stabilise the borehole of a well, after it is drilled.
CO_2 capture and storage	This is a process consisting of the separation of a CO_2 stream from industrial and energy-related sources, transport to a storage location and long-term isolation from the biosphere, including the atmosphere.
Closure of a geological storage site	It is the completion of the sealing of the geological storage site, including the appropriate plugging of wells relating to the geological storage site.
Closure phase	It is the phase that follows the operational phase and is the period that begins when carbon dioxide injection permanently ceases and ends when the geological storage site has been closed.
Completion of a well	Refers to the cementing and perforating of casing and

	stimulation to connect a well bore to a formation.
Confinement	The process by which a CO_2 stream is kept within a specified geological space.
Containment	Restriction of movement of a fluid to a designated volume (e.g., a reservoir).
D, Darcy	A non-SI unit of permeability, abbreviated D, and approximately = 1µm2.
Deep saline aquifer	A deep underground rock formation composed of permeable materials and containing highly saline fluids.
Dense fluid	A gas compressed to a density approaching that of the liquid.
Dense phase	A gas compressed to a density approaching that of the liquid.
Depletion	Of a reservoir: where production is significantly reduced.
Dissolution	With respect to CO_2, the process by which CO_2 separates into its component ions in water.
EOR	Enhanced oil recovery: the recovery of oil additional to that produced by standard production methods.
Fault	In geology, a surface at which strata are not longer continuous but displaced.
Flood	The injection of a fluid into an underground formation.
Formation	A body of rock of considerable extent with distinctive characteristics that allow geologists to map, describe, and characterise it.
Formation water	Water that occurs naturally within the pores of rock formations.
Fracture	Any break in rock along which no significant movement has occurred, but where the permeability may be significantly enhanced.
Geochemical trapping	The retention of injected CO_2 by geochemical reactions.
Geological time	The time over which geological processes take place.
Geomechanics	The process of movement or potential movement of rocks within the Earth's crust.
Geosphere	The Earth, its rocks and minerals, and its ground waters.
GHG	Greenhouse gases: carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6).
Hazard	The potential to cause harm.
Hydro-geological	Concerning water in the geological environment.
Hydrostatic	Pertaining to the properties of a stationary body of water.
IEA GHG	International Energy Agency – Greenhouse Gas R&D Programme.

Igneous	Rock formed when molten rock (magma) has cooled and solidified (crystallised).
Injection well	A well in which fluids are injected rather than produced.
Injectivity	A measure of the rate at which a quantity of fluid can be injected into a geological formation.
In-situ mineralisation	A process whereby carbon dioxide injected into a geological formation reacts with silicate minerals, forming stable carbonate minerals.
IPCC	Intergovernmental Panel on Climate Change.
Leakage	In respect of storage of CO_2 streams, the escape of that CO_2 stream from the storage formation into overlying formations, the water column and the atmosphere.
Log	Records taken during or after the drilling of a well.
Long term	The term following the closure of the CO_2 storage site. This could extend to several thousand years into the future.
Mature sedimentary basins	Geological basins formed by the deposition of sedimentary particles and grains under sub-aqueous and sub-aerial conditions and in which deposited organic matter has matured into hydrocarbon reserves.
Microseismicity	Small-scale seismic activity, usually only detectable by the use of sensitive instrumentation.
Migration	The movement of fluids within or out of formations.
Mitigation	The process of reducing the adverse impact of any failure in the CO_2 storage system.
Monte Carlo simulation	A modelling technique in which the statistical properties of outcomes are tested by random inputs.
Mudstone	A very fine-grained sedimentary rock that commonly provides a seal, thus preventing the upward migration of fluids.
Observation well	A well installed to permit the direct observation of subsurface conditions.
Operational phase	It is the period that begins when carbon dioxide injection commences and ends when carbon dioxide injection permanently ceases.
Other substances (or associated substances)	Associated substances originating from the source material and the capture, transport and storage processes used.
Overburden	Rocks and sediments above any particular stratum.
Overpressure	Pressure created in a formation that exceeds the pressure inherent at the formation’s depth.
Permanence	The term to indicate the likelihood that the situation will stay unchanged.
Permeability	Ability to flow or transmit fluids through a porous solid such as rock.

Pore space	Space between sedimentary grains that can contain fluids.
Porosity	Measure of the amount of pore space in a rock.
Post-closure phase	It is the phase that follows the closure phase and is the period that begins when the geological storage site has been closed.
Regional scale	A geological feature that crosses an entire basin, or other geological provinces.
Remediation	The process of correcting any source of failure, for example in a CO_2 storage system.
Reservoir	A subsurface body of rock with sufficient porosity and permeability to store and transmit fluids.
Risk	Probability of occurrence of an undesired event, multiplied by the (HSE) impact of that event.
Risk assessment	Part of a risk-management system, consisting of exposure assessment, effect assessment and risk characterisation.
Risk characterisation	Risk characterisation is the step in the risk assessment process which determines the likelihood and severity of impacts on the marine environment.
Saline formation	Sediment or other rock formation containing brackish water or brine.
Seal	An impermeable rock that forms a barrier above or around a formation such that fluids are held in the formation.
Seismic technique	Measurement of the properties of rocks by the refraction and reflection of sound waves generated artificially or naturally.
Shale	Impermeable very fine-grained and finely laminated sediment that commonly provides a seal to the movement of underlying fluids.
Short term	The near term prior to closure of the CO_2 storage site. This could extend to some one hundred years into the future.
Sour gas	Natural gas containing significant quantities of acid gases, such as H_2S and CO_2.
Spill point	The structurally lowest point in a structural trap (q.v.) that can retain fluids lighter than background fluids.
Storage	A process for retaining captured CO_2 streams in deep geological formations so that it does not reach the atmosphere. The terms sequestration and storage are also used interchangeably.
Storage site	The location for storage in geological formations, comprising one or more wellheads and surface facilities.
Structure	Geological feature produced by the deformation of the Earth’s crust, such as a fold or a fault; a feature within a rock such as a fracture; or, more generally, the spatial arrangement of rocks.
Supercritical	At a temperature and pressure above the critical temperature and pressure of the substance concerned. The

	critical point represents the highest temperature and pressure at which the substance can exist as a vapour and a liquid in equilibrium.
Tectonically active area	Area of the Earth where deformation is presently causing structural changes.
Trap	A geological structure that physically retains fluids, which are lighter than the background fluids.
Well	Manmade hole drilled into the Earth to produce liquids or gases, to allow the injection of fluids, or to enable observations of subsurface process.
Well integrity	The ability of a well to prevent any leaks from occurring, either along the (cemented) annulus (casing / open hole) or between the plugs and the casing.
Wellhead pressure	Pressure developed at the top of the well.

APPENDIX IV - Bibliography

Bachu, S. 2000. Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change. Energy Conversion and Management, 41: 953–970.

Bachu, S. and Dusseault, M. B. 2005. Underground injection of carbon dioxide in salt beds. Developments in Water Science, 52: 637–648.

CO2GeoNet European Network of Excellence. 2012. Position paper on geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful.

CSLF. 2005. Draft Discussion paper from the Task Force for Reviewing and Identifying Standards with Regards to CO2 Storage Capacity Measurement, CSLF 2005.

CSLF. 2010. Carbon Sequestration Leadership Forum Technology Roadmap: A Global Response to the Challenge of Climate Change. (Available online at: http://www.cslforum.org/publications/documents/CSLF Technology Roadmap 2010.pdf).

DIRECTIVE 2009/31/EC of the European Parliament and of the European Council of 23 April 2009 on the geological storage of carbon dioxide.

IEA. 2010. Energy and Technology Perspectives (ETP).

IPCC. 2005. IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

IPCC. 2006. Guidelines for National Gas Inventories. Intergovernmental Panel on Climate Change.

Juanesa, R; Hager BH. and Herzog HJ. 2012. No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful. PNAS 2012 109 (52) E3623

London Convention and Protocol (2007) Risk Assessment Framework on carbon dioxide capture and storage on sub-seabed geological structures.

National Research Council (2012) Induced Seismicity Potential in Energy Technologies (National Academy Press, Washington, DC).

OGP. 2000. Guidelines for Produced Water Injection. Report 2.80/302, January 2000, International Association of Oil and Gas Producers.

OSPAR. 2001. Environmental Aspects of On and Off-Site Injection of Drill Cuttings and Produced Water. Oslo Paris Commission ISBN 0 946956 69 3.

OSPAR. 2006. Effects on the Marine Environment of Ocean Acidification Resulting from Elevated Levels of CO2 in the Atmosphere.

OSPAR. 2007. Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations

Pires, J.C.M.; Martins, F.G.; Alvim-Ferraz, M.C.M. and Simões, M. 2011. Recent developments on carbon capture and storage: An overview. Chemical Engineering Research and Design 89: 1446–1460

Plan Bleu nº 22 June 2012. Blue Plan Notes. Environment and Development in the Mediterranean

Poremski. 2004, in LC/SG-CO2 1/INF.2.

Zoback MD and Gorelick SM. 2012. Earthquake triggering and large-scale geologic storage of carbon dioxide. Proc Natl Acad Sci USA 109(26):10164–10168.

---

[i] Draft Discussion paper from the Task Force for Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity Measurement, CSLF 2005.

[ii] IPCC SRCCS: p. 141.

[iii] IPCC SRCCS: pp 244-246.

[iv] IPCC SRCCS: pp 244-246 and 250-251.

[v] IPCC SRCCS: p. 197; p. 249.

[vi] According to the IPCC SRCCS, there are two types of leakages, i) abrupt leakages and ii) gradual leakages.

[vii] OSPAR 2006. Effects on the Marine Environment of Ocean Acidification Resulting from Elevated Levels of CO_2 in the Atmosphere.

[viii] Poremski, 2004, in LC/SG-CO_2 1/INF.2.

[ix] OGP 2000. Guidelines for Produced Water Injection. Report 2.80/302, January 2000, International Association of Oil and Gas Producers.

[x] OSPAR. 2001. Environmental Aspects of On and Off-Site Injection of Drill Cuttings and Produced Water. Oslo Paris Commission ISBN 0 946956 69 3.

[xi] IPCC 2006. DRAFT Guidelines for National Gas Inventories. Intergovernmental Panel on Climate Change.

[xii] See IPCC SRCCS, Chapter 6, for an overview of existing data.

[xiii] IPCC SRCCS, p. 311.