Safety Study CCS and Offshore Wind Farms

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List of Abbreviations

CC(U)S: Carbon Capture, (Usage) and Storage

HVAC : high-voltage alternating current

ESCA: European Subsea Cables Association

IGN: Instituto Geográfico Nacional,

IEAGHG: International Energy Agency Greenhouse Gas

ICGC: Institut Cartogràfic I Geològic de Catalonya

InSAR: Interferometric Synthetic Aperture Radar

KEM: Knowledge Programme on Effects of Mining.

MMV : measure, monitoring, and verification

NPP: Nuclear Power Plant

OBE: Operation Basis Earthquake

OWF: Offshore Wind Farm

PGV: Peak Ground Velocity

PSHA : Probabilistic Seismic Hazard Assessment

SRA: Site Response Analysis

SSE: Safety Shutdown Earthquake

SSM : State Supervision of Mines

TLP: traffic light protocol

TLS: Traffic Light System

UGS: Underground Gas Storage

UKOPA: United Kingdom Onshore Pipeline Operators' Association

1. Purpose of the study

The purpose of the study is to provide a current state-of-practice summary to assess whether the simultaneous use of Offshore Wind (OWF) and Carbon Capture, Usage and Storage (CCS) can be safely combined in the same area. This document aims to give the Contracting Authority an overview of the safety aspects of CO2 storage in or near an offshore windfarm. This can impact future policy decisions, as there are locations where CCS and OFW may intersect in the future.

The North Sea has limited space available. In the energy transition it serves various goals that may or may not be combined with each other. Some areas in the North Sea that are considered very suitable for Offshore Wind may also be interesting for CCS due to the presence of (almost) exhausted oil and gas fields. This overview safety study is presented to better understand the degree to which these types of projects and activities can be carried out simultaneously.

The principal research question is: are these two activities compatible? Specifically:

- What are the risks of conducting these two activities in the same location?
- And what are the recommended best practices for reducing these risks?

The ultimate goal is to use this overview to form policy and shape concrete policy intentions. To guide this overview, five specific research questions are addressed. They are:

1. *At what distance from a CO_2 pipeline can a wind turbine be placed safely?*
    a. *What is the effect of placing a turbine close to a CO_2 pipeline for both the turbine and the pipeline?*
    b. *What is a safe distance as a result?*

2. *What are the seismic risks of CO_2 storage?*
    a. *What literature/studies are (public) available on this topic?*
    b. *Are there any risks of soil movement (e.g. tremors/induced seismicity, subsidence)?*
    c. *What are any other consequences for the soil?*
    d. *Are there any other risks beyond seismicity (e.g. chemical or physical? If so, what are the consequences for the turbine?*
    e. *If "yes" for D - what are possible mitigating measures (e.g. Foundation, type of turbine), and what costs are involved?*

3. *What are the possibilities for seismic (reflection and/or refraction seismology) in existing wind farms, or wind farms under construction?*

4. *Is monitoring of seismicity necessary in offshore wind farms where CCS is taking place (beneath or near it)?*

5. *If "yes" for 4 - what would be the frequency that the monitoring should take place?*

2. Research Approach

The key issues concerning the compatibility of OFW and CCS are associated with two main topics, operational risks and operational limitations. These topics involve:

- Operational risks associated with **induced seismicity** that could occur during CCS operations and its potential effects on overlying OWF projects. Research questions 2, 4 and 5 are linked to induced seismicity and its monitoring.
- Operational limitations related to the potential hinderances to performing **geophysical surveys** for CCS monitoring once OWF infrastructure is operational or under construction. The research question 3 is related to this topic.

To address these topics, Fugro performed a bibliographical review of the reports and articles associated to the site-characterization of OWF and CCS and specially, of those publications dealing with the 2 main topics requested for this study: induced seismicity and geophysical monitoring. Special attention was given to publications dealing with the overlap between OWF and CCS projects.

A general overview of the induced seismicity associated with different types of projects and specifically for CCS is presented. The general overview summarizes different solutions and recommendations used in different types of projects. Finally, using this analysis, some recommendations are provided for future development of overlapping OWF and CCS projects based on Fugro's extensive experience in site characterization and seismic hazard for large infrastructure projects.

The report is divided in the following sections:

1) Bibliographical review of OWF and CCS projects (Chapter 3), including the following:

    a. A brief description of the different types of Offshore Wind Farms (OWF) and Capture carbon Storage sites (CCS).

    b. A brief description of the site-characterization activities required for OWF and CCS projects.

    c. A review of interaction between OWF and CCS projects.

2) A review of induced seismicity in different types of infrastructure projects and how the induced seismicity is considered in seismic hazard assessment (Chapter 4).

3) Specific responses to the 5 research questions and analysis of the interaction between OWF and CCS projects (Chapter 5).

4) Recommendations for future projects where OWF and CCS could interact/overlap due to geographical proximity (Chapter 6).

3. OWF and CCS Projects

The objective of this Chapter is to provide a global view of the main components of OWF and CCS projects that could impact their congruent operation and their site-characterization requirements. This chapter deals also with the possible interactions between OWF and CCS.

3.1 Offshore Wind Farms (OWF)

There are 2 main types of OWF (see Figure 3.1):

- fixed foundation (e.g. a monopile or jacket structure)
- floating foundation (e.g. tension leg platform, spar or semi-submersible)

The type of foundation selected for the wind turbine construction is basically driven by the water depth at the wind farm location as well as the ground conditions. For water depths less than 50 m, generally the fixed foundations are more commonly used. The OWF have the following characteristics:

- *Foundation depth:* The foundations for fixed monopile foundations vary depending on the size of turbine and water depth but tend to be on the order of 5 to 10 metres in diameter with a pile depth below the seabed between 25 and 40 metres. Jacket type substructures tend to be less common than monopiles and tend to have longer pile depths. Floating foundation systems broadly consist of multiple mooring configurations that form anchorages for each turbine and may penetrate the seabed in the order of 15 m or shallower.
- *Seabed Footprint:* Regardless of the foundation type, the turbines are tied to high-voltage alternating current (HVAC) transmission lines laid on the seabed and run to shoreline to connect with the energy grid. The spacing of turbines generally relates to the diameter of the rotor and is variable, ranging from 1000m to many 1000m's. The foundation type, turbine layout, and cable network provide logistical constraints to subsequent monitoring activities (e.g., seismicity monitoring, geophysical surveys).
- *Site characterization requirements:* site characterization activities to support placement and engineering of OWF focuses on the upper 100 m of soil beneath the seabed. The studies typically involve using offshore high-resolution geophysical surveys and geotechnical investigations to determine the engineering characteristics foundation bearing materials to the design the best foundations for the turbines. .

An additional consideration for operational OWF projects is the ambient "noise" (vibratory effects) generated by the operating turbines. This noise is transmitted through the seabed through the foundations and can affect geophysical data collected in the area. This topic is addressed in Section 5.3 of this report.

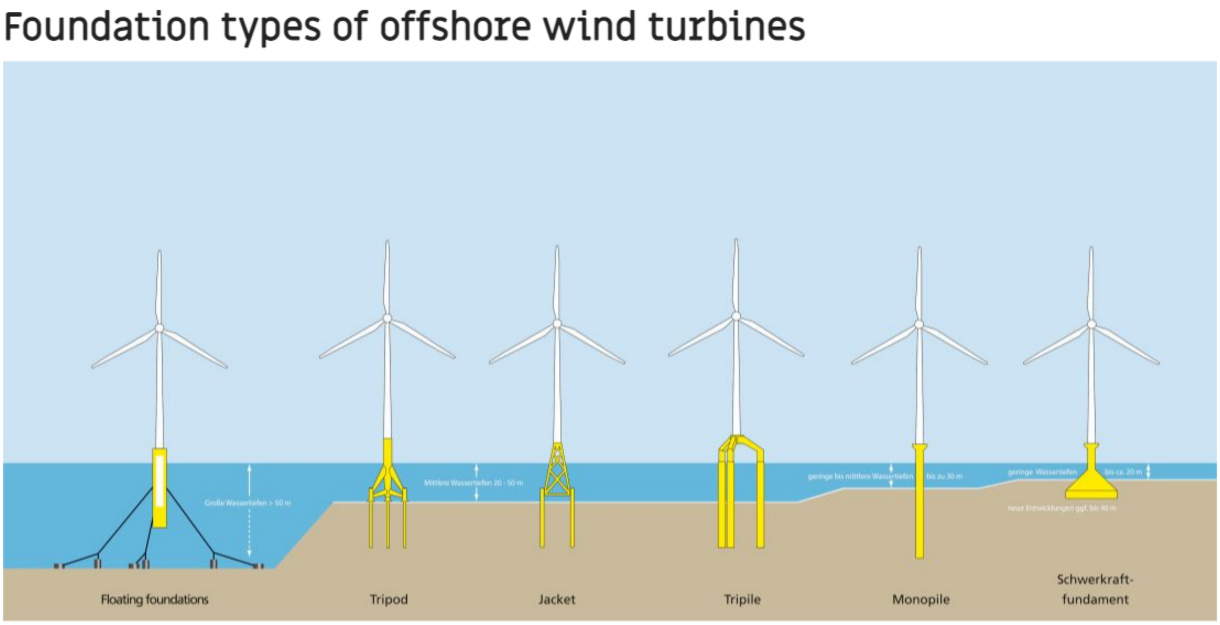

Figure 3.1 : Fixed versus floating OWF structures. (Source: Stiftung Offshore Windenergie (SOW)).

3.2 Carbon Capture and Storage (CCS)

Two main types of geological storage site are likely to be used for CCS: saline aquifers and depleted hydrocarbon reservoirs.

Saline aquifers: Are porous and permeable formations that contain saline water. These formations generally cover large areas (in the order of several tens of kilometres across) and CO2 is stored by displacing saline water from the storage formation. They consist of large porous rock formations that are overlain with a low permeability layer that prevents upward migration of CO_2. There are 4 types of aquifer: 1) Open with structure, 2) Open, without some structure, 3) Structural trap and 4) Fully confined (see Figure 3.2)

Open (with or without structure) Figure 3.2 : Open Saline aquifers tend to not be "tightly constrained" and bulk storage of CO_2 generally involves displacement of saline water to other, hydraulically connected parts of the surrounding aquifer and relatively small pressure rise. Notably, the store capacity in open aquifers are likely limited by the need to ensure that CO_2 is constrained to within the bounds of the licenced area (ETI, 2018). The initial pressure within the storage site is approximately equivalent to the hydrostatic head for the formation depth, which results in CO_2 being stored as a "super-critical liquid", which is equivalent to a low viscosity liquid with a density that is ~1.5 x greater than saline water at the storage conditions.

Structural traps and fully confined aquifers Figure 3.2: Structural traps within an hydraulically connected open aquifer are prime CO_2 storage sites given the natural buoyancy effect of the CO_2 within the aquifer that concentrates large quantities of CO_2 in a smaller area (top of the trap). Local pressure is alleviated when brine is displaced by the buoyant CO_2. ETI, 2018 suggests as much as 20 % 'pore space' can be utilised in some traps contrasted with unstructured stores >2%.

There may be a requirement for small or "fully confined" saline aquifers to drill brine release wells to limit the pressure rise in the aquifer due to CO_2 injection, but it is likely that the majority of CCS schemes will plan to utilise aquifers where this is not required and would likely only be required if the aquifer does not respond as expected to CO_2 injection. The saline aquifers have the following characteristics:

- *Formation depth: between circa 800 and 2,500 metres below seabed level.*
- *Seabed Footprint: A large volume of reservoir per amount of* CO_2 *injected is required for saline aquifers due to their storage mechanism and initial reservoir conditions, resulting in a large seabed footprint being required.*
- *Site characterization requirements: Saline aquifers tend to require a significant amount of survey and study work to determine their suitability for storing* CO_2 *and their potential storage capacity. As a result, the site activities required to characterise saline aquifers will tend to require extensive surveys and appraisal well drilling.*
- Key geological selection criteria for storage site suitability can be divided into reservoir efficacy, reservoir properties and caprock efficacy categories. These include reservoir depth, thickness, porosity, permeability, seal integrity and salinity (see Figure 3.3 below)

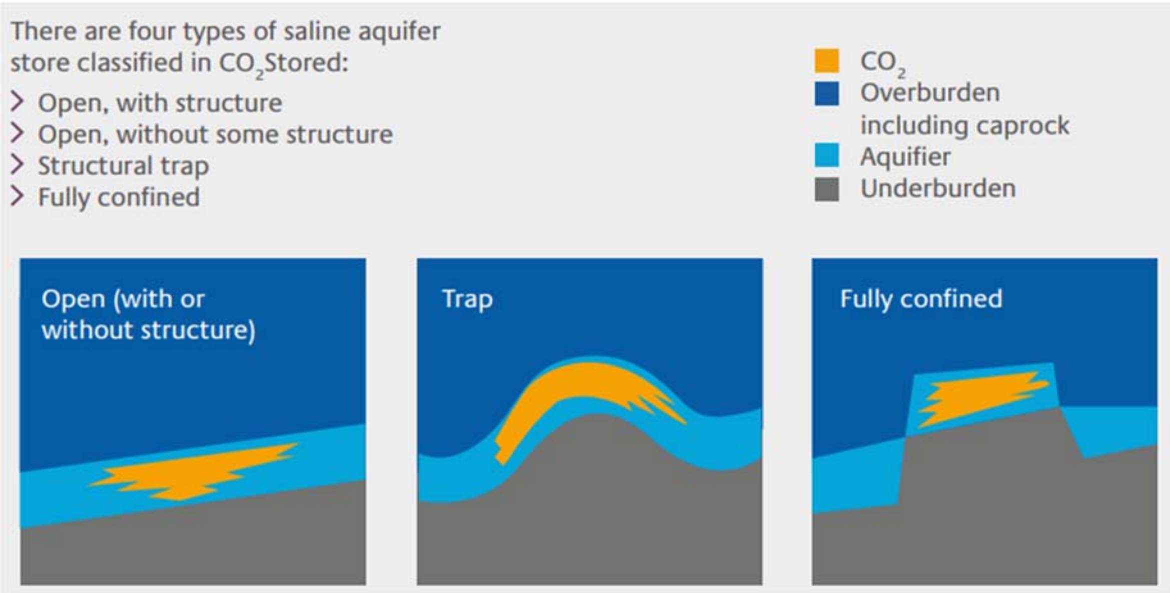

Figure 3.2 : Types of Aquifer (ETI, 2018)

	Positive indicators	Cautionary indicators
RESERVOIR EFFICACY		
Static storage capacity	Estimated effective storage capacity much larger than total amount of CO_2 to be injected	Estimated effective storage capacity similar to total amount of CO_2 to be injected
Dynamic storage capacity	Predicted injection-induced pressures well below levels likely to induce geomechanical damage to reservoir or caprock	Injection-induced pressures approach geomechanical instability limits
Reservoir properties		
Depth	>1000 m < 2500m	< 800 m > 2500 m
Reservoir thickness (net)	> 50 m	< 20 m
Porosity	> 20%	< 10%
Permability	> 500 mD	< 200 mD
Salinity	> 100 gl^{-1}	< 30 gl^{-1}
Stratigraphy	Uniform	Complex lateral variation and complex connectivity of reservoir facies
CAPROCK EFFICACY		
Lateral continuity	Stratigraphically uniform, small or no faults	Lateral variations, medium to large faults
Thickness	> 100 m	< 20 m
Capillary entry pressure	Much greater than maximum predicted injection-induced pressure increase	Similar to maximum predicted injection-induced pressure increase

Figure 3.3 : Key geological indicators for storage site suitability. (Chadwick et al, 2008)

Depleted hydrocarbon reservoirs: Formations from which hydrocarbons have previously been produced. This type of store usually has a smaller footprint than saline aquifers (in the order of a few to a few tens of kilometres) and the CO_2 is stored by effectively filling up the interstitial space left in the formation from the previously produced hydrocarbons. Depleted hydrocarbon reservoirs are similar to saline aquifers in geology but tend to be smaller and more constrained.

Depleted oil and gas reservoirs offer prime candidates for storage sites (1) as they have demonstrated their capacity to contain CO_2 (and other fluids) for geological timescales, (2) a large amount of data is available to characterise the reservoir quality. (3) Historical production rates provide indications of future CO_2 injection rates, whilst the total amount of extracted oil and gas provides a crude estimate of the CO_2 volume that can be stored in the future (GCSSI, 2020)

The pressure within such reservoirs at initial injection will tend to be significantly lower than at original oil in place (OOIP) reservoir conditions resulting from previous production of hydrocarbons from the formation. Remaining hydrocarbons will still however, be present and remain within the upper most parts of the trap due to the buoyancy effects. Injected CO_2 can be stored in the remaining reservoir pore space assuming the reservoir is not re-pressurised by brine influx. As such, the storage mechanism for hydrocarbon reservoirs will tend to be mainly by pressurisation of the reservoir rather than displacement of reservoir contents to an adjoining formation. As a result, the pressure within the reservoir will rise over time with CO_2 stored as a “super-critical liquid”. It is highly unlikely that any brine release wells would be required for CO_2 storage in depleted hydrocarbon reservoirs. The depleted hydrocarbon reservoirs have the following characteristics:

- *Formation depth:* Tend to be deeper than saline aquifers with a typical formation depth of between <1,000 metres below seabed level. Notably, there are some shallow hydrocarbon fields such as the Captain field as part of the larger Captain aquifer which has the fields sandstone crest at ~823 m TVDss (Pinnock et al, 2003).
- *Seabed Footprint:* Depleted hydrocarbon reservoirs can store significantly more CO_2 per unit reservoir volume than saline aquifers resulting in a smaller seabed footprint for such stores.
- *Site characterization requirements:* The geology, extent and trapping mechanisms for depleted hydrocarbon reservoirs tend to be very well known given their previous operational history of producing hydrocarbons. As a result, the data acquisition activities associated with site characterisation for understanding the reservoir's potential for storing CO_2 may be significantly less than those required for saline aquifers and may be limited to local seabed surface geophysical surveys. It is also highly unlikely that any appraisal well drilling would be required for depleted hydrocarbon reservoirs.

Another consideration for CCS projects is their potential to generate induced seismicity due to injection-induced pore-pressure, temperature, and state-of-stress changes at the injection depths. White and Foxal (2016) provided a summary of the induced seismicity risk at CO_2 storage sites and performed a summary of seismicity observations at recent CO_2 injection operations.

Another consideration, specifically for CO_2 injection into saline aquifers is the risk of corrosion damage to offshore wind infrastructure caused by saline brine displacement at depth migrating upwards into the near surface. The salinity of brine is typically more concentrated than that of saturated soils with sea water near sea bed. Aquifer brine has the potential to leak via fluid pathways to the seabed and or be released via brine release wells. The placement of the wells with respect to wind turbine foundations and substructures should be considered.

There are important similarities between CO_2 injection and fluid injection for other projects that have induced seismic events (e.g., geothermal systems). Typically, a local seismic monitoring network is installed to control the operations and adapt the injection (or extraction) rates to mitigate the risk of induced earthquakes. In addition, the analysis of the microseismicity is, in some cases, an efficient tool for monitoring the distribution of gas (or other fluids) within the reservoir and to assess possible fluid leakage paths.

3.3 Interaction between CCS and OWF

The key points of interaction between CCS and OWF are:

- The operational limitations driven by the OWF in terms of the design layout and potential ambient noise interfering with or denuding subsequent geophysical data acquisition, and
- The operational risks of CCS that could generate induced seismicity (5.2.2.2), as well as, surface uplift and subsidence (5.2.2.2).

Robertson & McAreavey (2021) identified several challenges related to these interactions. These are:

- The current “go to” technology for characterising a CCS reservoir and a major element of most measure, monitoring, and verification (MMV) schemes for CCS projects use a “towed streamer seismic survey.” This type of geophysical investigation has a large footprint that is usually not compatible with the grid spacing between turbines for Offshore Wind projects. The survey vessels and the geophysical sensors that they tow have difficulty navigating within the footprint of a OWF.
- Potential degradation of MMV survey data due to background “noise” from Offshore Wind operations and, potentially, signal interference from the foundations of fixed wind structures (turbines and substation platforms).

4. Lessons learned from past fluid injection projects

For years, it is well-known that seismic events can be induced by anthropogenic phenomena such as, but not limited to, fluid injections, impoundments of reservoirs, underground nuclear explosions, or hydrocarbon extraction.

Even if this study is focused on the induced seismicity related to CCS (OWF cannot produce induced seismicity), there is some kind of agreement in the scientific community (White & Fox, 2016) that the induced seismicity originated in different types of projects show some similitudes and, therefore, we think that a global analysis of induced seismicity originated in other types of projects than CCS would be beneficial for the analysis and recommendations provided in this study. The past experiences and lessons learnt from different cases where induced seismicity occurred will allow to define some general patterns recommendations.

In the following sections, different examples are presented regarding the anthropic phenomena produced induced seismicity in the past were analysed. From them, some feedback experiences and lessons can be explored.

We note that the projects selected don't correspond to CCS projects. However, some lessons can be learnt from them.

4.1. The Castor Project, Spain

The Castor field, located 22 km off the coast in the Gulf of Valencia, is the biggest underground reservoir of natural gas in Spain with an average reservoir depth of more than 1700 m. Note that this project relates to natural gas storage and not CO_2 capture but the processes is similar: the conversion of a depleted oil field into an underground gas storage reservoir for gas injection (the Amposta oil reservoir exploited from 1973 to 1989).

During the design of the facility, no site-specific seismic studies were performed to analyse the potential for induced seismicity produced by the facility although some Spanish civil associations recommended this. According to the Spanish regulations, the Contractor did not have the obligation to perform these kinds of seismic evaluations because the facility was situated in one of the lowest seismic areas of Spain (Benito and Gaspar-Escribano, 2007). Consequently, the owner of the installations decided that a site-specific seismic hazard study was not needed, and the installation of a local seismic monitoring network able to record and to locate possible induced seismicity during injection operations was not undertaken.

From the 5th of September 2013, a seismic crisis with more than 1000 events reaching a magnitude Mw of 4.2 were recorded (Figure 4-2) over a period of 40 days (Cesca *et al.*, 2014). This seismic sequence raised great interest among the scientific community and civil society, given its temporal coincidence with the nearby gas injection session performed by the Castor project from the 2nd to the 16th of September. Prior to this injection session, test injections were performed since 2013 June, not accompanied by seismicity. Cesca *et al.* (2014) conclude from the analysis of this seismic sequence, that it shows a temporal variation, correlated with the beginning and the end of the injection process. Earthquake activity started with the beginning of fluid injection, and changed from the injection to the post-injection phase. Both analyses indicate that the events could have been triggered by pore pressure changes on pre-existing faults. This study mentions that seismicity is confined to a very small region in proximity to the gas injection wells.

The maximum magnitude observed in these kinds of installations was typically lower than Mw 2.0, however, a Mw 4.2 earthquake occurred on the1st October 2014 that was felt by many in nearby villages (Alcanar, Benicarló, Las Casas de Alcanar, Cervera del Maestre, Cálig, Peñíscola, San Carlos de la Rápita, Ulldecona y Vinarós). Although the seismic activity did not affect the integrity of the facilities or underground reservoir, the Spanish authorities mandated suspension of injection activities at the Castor Project.

In 2016, the Spanish Government contracted researchers with the Massachusetts Institute of Technology (MIT) and Harvard University to conduct a seismicity analysis to assess the origin of the seismicity and possible consequences. Based on this study (Juanes *et al*., 2017), the researchers determined that the seismicity occurred along the Amposta fault and associated splays and was considered to be triggered seismicity, or seismicity that would have occurred naturally at some time in the future but were "triggered" to occur sooner by the temperature and pressure changes from fluid injection. According to the recommendations of this study, in 2017, the Spanish Government decided to close definitively the project. The study however recommends, in the case that a determination is made to resume operations, a number of approaches to mitigate the risks associated with induced seismicity. They are:

- Deployment of a dedicated seismic network of ocean bottom seismic stations with good proximity and azimuthal coverage.
- Slow ramp-up of injection in several phases, with dedicated analysis of seismicity, reservoir pressure, and updating of geomechanics model, after each phase.
- Develop a protocol for actions to be taken if seismicity occurs or increases during injection (e.g., a traffic-light system).

This study also points out the need for new standards to quantify the seismicity risks associated with underground operations, especially in areas where active faults are present. Saló Salgado (2016) agrees with this statement.

Some posterior studies were performed (*e.g.,* Saló Salgado, 2016) leading to the following suggestions:

- A geological model should be defined for these kinds of projects (*i.e.,* Figure 4-2).
- The operational practice should be defined. The primary controlling parameters (injection ratios) need to be monitored in real time. The injection procedures have to be adapted to the geo-mechanical properties.
- Potential triggering should be considered, and the operation procedure must be evaluated in line with them.

- A seismic hazard analysis, integrating all possible triggers and outcomes, should be required.
- Real time monitoring of seismicity should always be carried out (spatial distribution, analysis of frequency and magnitudes, pattern, etc).

Finally, due to the uncertainties associated with the site conditions and lack of monitoring, €1.46 billion were spent and "lost" as the facility formally closed and operations ceased prior to starting planned gas storage activities. It is important to point out that the post-mortem evaluations of the Castor project conclude that the problems encountered during the project could have been avoided or mitigated if appropriate site characterization work had been completed. This example highlights the value of early project site characterization studies, seismic hazard analysis, and seismicity monitoring, that can reduce project risks.

To summarize, the main lessons learnt from this project are:

1. **Lack of previous seismic hazard studies**: No previous seismic hazard studies (seismic induced and/or seismotectonic studies) were performed in the region of study during the feasibility phase of the project. The Spanish laws (mainly based on the EC8), did not give the obligation to the ownership to perform this type of studies. And the Spanish regulators did not ask for site-specific studies to the ownership, even if the facility, due to its special characteristics, could be considered as a "special" or critical facility.
2. **Lack of seismic monitoring from the very beginning steps of the project**: A local seismic network was no installed during the very early stage of the project. Therefore, when the injection of fluids started, and the induced seismicity occurred, the location of earthquakes and their characteristics (depth, magnitude, focal mechanism, etc.) were only calculated using only regional seismic networks (belonging to *Instituto Geográfico Nacional, IGN* and *Institut Cartogràfic I Geològic de Catalonya, ICGC*).
3. **Communication program to the population**: The communication with local population was poor. Therefore, the population of the villages where the earthquakes were felt (*i.e.,* Vinarós) was not prepared to feel seismic ground motions. In some villages holding other critical facilities near Castor project, as the Vandellós Nuclear Power Plant (NPP), the population is aware about the risks and advantages (additional financial resources, job positions in the critical facility) produced by the existence of a Nuclear Power Plant in the surroundings of the municipality. In Vandellós, for example, the population accepts the risk of holding a NPP and recently, for example, Vandellós offered its region to hold a future deep geological repository site for nuclear waste products. The municipality and the population estimated that the advantages related to have nuclear installations compensate the risks. This fact was only possible after a good communication campaign about risks and advantages. This communication program was not fully followed in Castor project.
4. **Seismic studies only performed after the finalization of the project**: The seismic studies were only performed after the seismic crisis, when the population was strongly against the new installations and when the installations were constructed. The seismic

study performed by MIT was useful to take the final closing decision, when the construction of the facility was finished, and when the money to build the facility was spent. But the seismic studies were not useful at the beginning of the project in order to decide if the location for the installations was adapted or some exclusion criteria existed (as finally occurred).

Figure 4-1: Location of the Castor project site, in Spain.

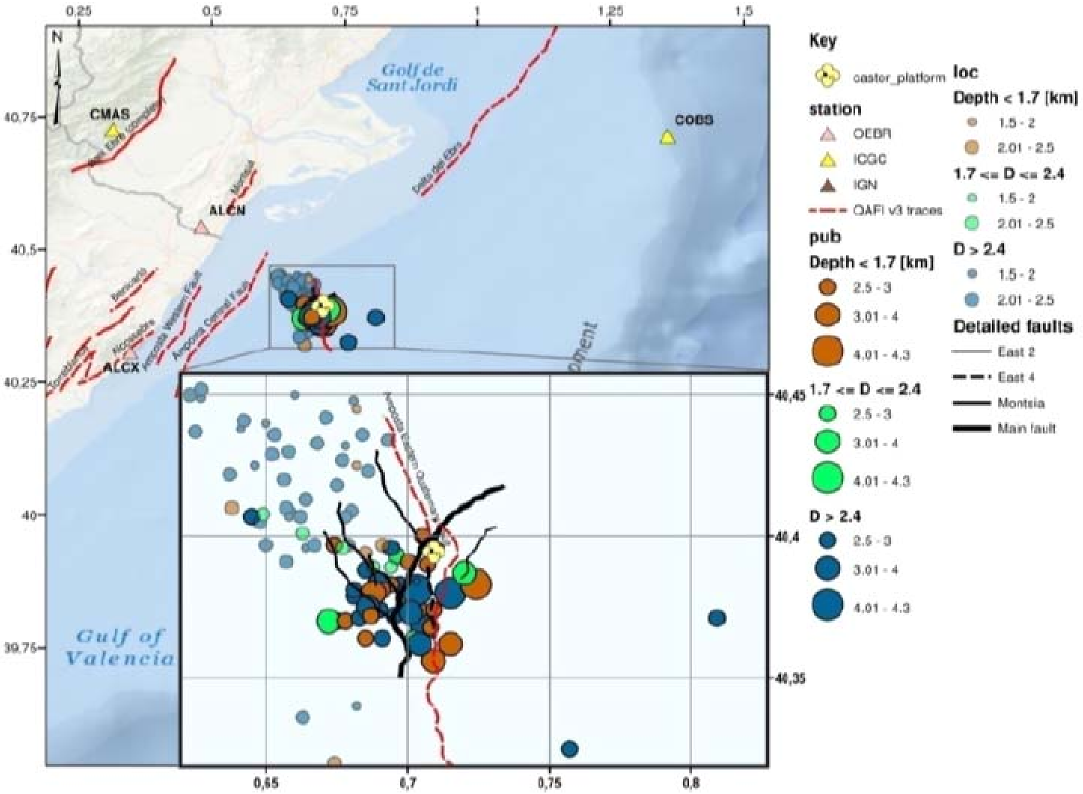

Figure 4-2: Main earthquake locations during the induced seismicity crisis and main faults in the region (Source: Saló Salgado, 2016).

4.2. Serianex Project, Switzerland

The Serianex project is an enhanced geothermal project developed on Basel (Swwitzerland) at the beginning of this century. The injection phase stared in 2006.

Serianex is another significant project where the induced seismicity occurred during the initial phase and it caused significant problems and finally lead to the cancellation of the project. During the development of the enhanced geothermal reservoir at a depth of about 5 km beneath the city of Basel, a felt earthquake of magnitude ML 3.4 was triggered on December 8th, 2006. The operator's insurance paid out property damages of about 7 million CHF, which were attributed to the earthquake. The geothermal project has been suspended ever since.

After operations ceased, the Kanton Basel-Stadt commissioned a study of the seismic risk resulting from continued development and subsequent operation of the geothermal system (SERIANEX study, with participation of Fugro-former Geoter), who were responsible for the seismic hazard assessment and a seismic risk analysis.

Besides seismicity produced directly by the geothermal project (called *induced* seismicity), the study also considered the impact of the geothermal reservoir on natural seismic activity in the Basel region (called *triggered* seismicity). To analyse the issue, a 3-dimensional geologic model of the subsurface of the Basel region was developed (Figure 4-3). The SERIANEX study found that the geothermal reservoir could have an impact on the recurrence times of these natural earthquakes by modifying subsurface stresses. The development and operation of the project is expected to result in seismic activity in the immediate vicinity of the geothermal reservoir. However, numerical simulations demonstrate that these variations are very small and represent a non-significant risk. A numerical model was developed to investigate how future seismic activity might evolve over the life of injection activities (injection phase and circulation phase of the project).

The study also estimated anticipated property damage associated with seismicity. For that, the vulnerability of the building stock within a radius of 12 km around the facility was analysed and a seismic risk assessment using probabilistic modelling was performed. The study concluded that, during the projected facility's operational period of 30 years, the most probable property damage was set at 6 million CHF per year, 20 to 200 million CHF during the life of the project. The projected property damage was considered unacceptable according to the risk criteria of the Swiss ordinance on major accidents. This is an example of project where *induced* and *triggered* seismicity analysis let to the recommended closing of the project, based on pre-stablished risk criteria.

The earlier site characterization studies performed and the installation of a local seismic network during the initial project phase allowed recording and locating the seismic events at the start of fluid injection. These recorded data were used to develop empirical and numerical models to forecast future induced and triggered seismicity. Based on these data, new seismic hazard studies were performed taking into account induced/triggered seismicity and, finally, combining seismic hazard with vulnerability of buildings, an assessment of seismic risk in terms of economical cost and human lives was performed. This seismic risk assessment provided the Swiss local and regional authority's valuable information upon which to base their regulatory and policy decisions.

To summarize, the main lessons learnt from this project are:

1. **Installation of a seismic monitoring from the very beginning**: A local seismic network was installed during the very early stage of the project. Therefore, when the injection of fluids started, and the induced seismicity was characterized and located.
2. **Seismic studies:** They were performed after the first seismic events, when the construction of the installations were not yet finished. The seismic studies (including seismic hazard, vulnerability and seismic risk assessments) used the seismic signals recorded by the local seismic network.
3. **Communication program:** One of the Appendix of the SERIANEX study was related to the definition of a clear communication program with the population. Some recommendations were performed to define this communication program.

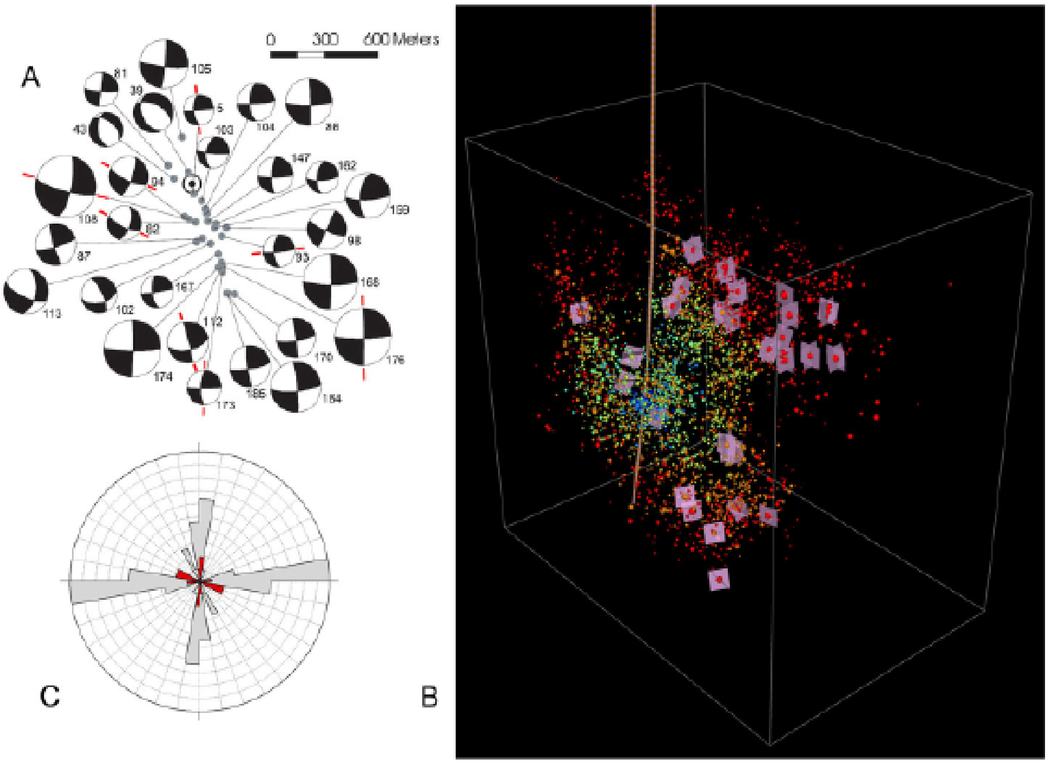

Figure 4-3: Seismic catalogue and focal mechanism of seismic induced crisis recorded during injection in Serianex project. Source: SERIANEX report AP2000.

4.3. Groningen Gas field, the Netherlands

The Groningen extraction gas field is situated in the northern part of Netherlands (Figure 4-4) and it is the largest gas field in the Netherlands.

Since the 1960's a number of large, multi-decade gas production projects were started in the Netherlands. Extensive, well-documented subsidence prediction and monitoring technologies were applied. Predicted subsidence and rates of induced seismicity have changed over the life of the project (100 cm of subduction predicted in 1971 and 49 cm in 2013). And the wealth of data collected during the gas fields operations indicate that subsidence is directly associated with the induced seismicity. Compaction, subsidence and seismicity are strongly interlinked and relate in a non-linear manner to fluid extraction and pressure changes.

The strongest tremor to date occurred near the village of Huizinge in August 2012. It had a magnitude of 3.6, caused significant damage and triggered the regulator into an independent investigation. Late 2012 it became clear that significantly larger magnitudes cannot be excluded and that values up to magnitude 5.0 cannot be excluded or ruled out.

Then, the regulator advised early 2013 to lower Groningen gas production by as much and as fast as realistically possible. Before taking such a decision, the Minister of Economic Affairs requested further studies. The results became available early 2014 and led to the government decision to lower gas production in the earthquake prone central area of the field by 80% for the next three years. In addition, further investigations and a program to strengthen houses and infrastructure were started. The studies in Groningen area are still underway nowadays.

Important lessons have been learned from the studies carried out to date. It is now recognised that uncertainties in predicted subsidence and seismicity are much larger than previously recognised. Compaction, subsidence and seismicity are strongly interlinked and relate in a non-linear manner to production and pressure drop. The latest studies by the operator suggest that seismic hazard in Groningen is largely determined by tremors with magnitudes between 4.5 and 5.0 even at an annual probability of occurrence of less than 1 %. And that subsidence in 2080 in the centre of the bowl could be anywhere between 50 and 70 cm. Initial evaluations by the regulator indicate similar numbers and suggest that the present seismic risk is comparable to Dutch flooding risks.

Different models and parameters can be used to describe the subsidence and seismicity observed so far. The choice of compaction and seismicity models and their parameters has a large impact on the calculated future subsidence (rates), seismic activity and on the predicted response to changes in gas production. In addition, there are considerable uncertainties in the ground motions resulting from an earthquake of a given magnitude and in the expected response of buildings and infrastructure.

Early 2013, SSM (State Supervision of Mines) estimated the seismic risk level in Groningen as "high", based on the realisation that events with a magnitude well above 3.9 could not be excluded. Based on SSM's analysis an upper magnitude limit of 5.0 was considered, a level at which serious damage cannot be excluded as houses in the Netherlands are not built to sustain seismic ground motions. By end 2013 a more detailed risk analysis was made for the central area of the field (Staatstoezicht, 2013; Muntendam *et al.*, 2013).

Based on a probabilistic analysis of the ground motions that can occur and taking into account the fragility of the local housing stock, a seismic risk study was performed in Groningen. It concluded that the seismic risk was comparable to the highest flooding risk levels in the Netherlands.

During gas extraction, the rates of induced seismicity and the magnitudes induced earthquakes increased. These rates have been correlated to the rates of well production and fluid extraction. The detailed studies of Groningen have included generating 3D geological models of the reservoir and simulated pressure and temperature changes at depth due to fluid injection and extraction. These studies have demonstrated the value of local monitoring networks as a tool for guiding injection-extraction rates.

The important facts learnt from Groningen project are:

1. **Seismic monitoring**: The seismic monitoring is very useful for seismic studies performed in the region, to calibrate predictive empirical models to really recorded seismicity.

2. **Seismic studies performed:** The complex seismic studies performed in Groningen region, involving the main experts in this subject around the world, allowed a good knowledge about the existing seismic risk. The authorities can use the existing information in order to reduce the risk.
3. **Communication program:** Due to the damages observed in the region linked to the induced seismicity, the communication with local people is a key subject.

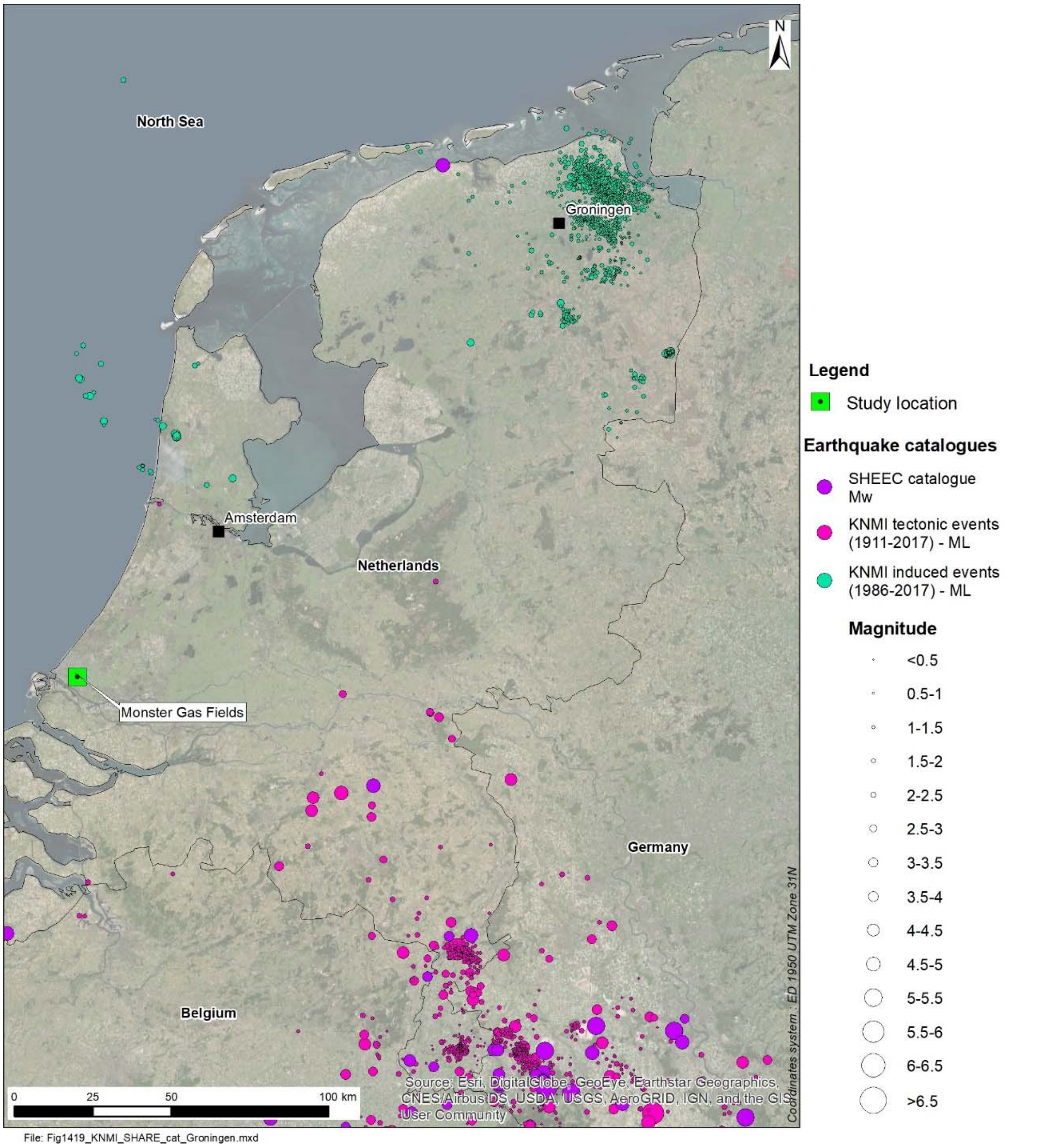

Figure 4-4: Seismic events in Groningen gas field region.

4.4. Itoiz And Yesa Large Dams, Spain

Large dam projects are conceptually different from Cos, natural gas sequestration projects, or geothermal projects. However, during the impoundment of the dam, the infiltration of water can contribute to the generation of induced seismicity, in a similar way than it is produced in fluid injection projects. It is a well-known phenomenon during impoundment periods of large dams (described in ICOLD Bulletins).

Reservoir Induced Seismicity (RIS) or Reservoir-triggered earthquake (RTE) involve the failure of a pre-existing fault due to reservoir impoundment after initial infill or by seasonal water level fluctuations.

Since the beginning of the monitoring of RIS events, there have been more than one hundred cases reported around the world. Among them, less than 10 cases produced strong earthquakes ($M \geq 6$), around 15 cases produced moderate earthquakes ($5.9 \geq M \geq 5$) and around 30 cases produced small earthquakes ($4.9 \geq M \geq 4$). Case investigations indicate that strong correlations exist between the occurrence of induced seismicity and reservoir size and filling history, hydrogeological conditions, faulting regime, and rock types.

Anthropic seismicity around large dams can have 2 origins:

- <u>*Induced* seismicity</u>: produced by the modifications of stress conditions at depth. The ruptures are situated very close to the site project and the ruptures occur in weakness zones not identified before the occurrence of induced seismicity. The maximum magnitude normally produced by this kind of seismicity is low ($ML<5.0$). However, the annual occurrence rate of these small earthquakes could be relevant. They can contribute to an increment of the seismic hazard due to the repetition of earthquakes rather than the magnitude associated.
- <u>*Triggered* seismicity on known tectonic faults</u>: This kind of seismicity occurs in well-identified tectonic faults when the modification of soil conditions due to the existence of the dam affects the normal return period of occurrence of the characteristic earthquakes of these faults. The maximum magnitude is associated to the geometric characteristics of the fault and could be high ($M>7.0$). These Earthquakes would occur without the existence of the dam, but the presence of the dam can trigger the occurrence of earthquakes that without the presence of the dam would occur later.

The case of Yeta and Itoiz dams, situated in the north of Spain (Figure 4-5), are good example of these phenomena. In September 2004, an earthquake of $ML=4.6$ (source IGN), with possible induced origin occurred. After this event, the *Confederación Hidrográfica del Ebro*, the Spanish institution in charge of the vigilance of the dams, asked to Universities and institutions to engage different investigations.

In addition, a local seismic network was installed, in collaboration with the IGN (*Instituto Geográfico Nacional*), to record data (Figure 4-6) over a few years of operational period. In 2010, Fugro was asked a new estimation of the seismic hazard taking into account the recorded seismicity and to provide an estimation of the seismic risk in Aoiz, a village of about 20.000 inhabitants, located close to the Itoiz dam (see Figure 4-5).

The study used the methodology developed for Serianex Project, in Basel. The origin of the induced seismicity was very different (due to the impoundment of the dam in case of Itoiz and due to fluid injection in Basel), but it can be analyzed using same tools.

Finally, in the light of the new interpretations, the local authorities considered the increase in seismic risk acceptable, and no additional measures to the normal management of the hydropower plant were taken.

The main lessons learnt from this project are:

1. **Installation of a seismic monitoring from the very beginning of the project**: A local seismic network was installed after the occurrence of the first significant induced earthquakes. Therefore, the occurrence of the main induced seismicity crisis was recorded.
2. **Seismic studies performed after the first seismic crisis, when the reservoir was not yet fully filled**: Seismic studies used the seismic events recorded by local seismic network. Then, a comparison between the seismotectonic hazard and the induced seismic hazard was performed. In addition, a comprehensive seismic risk study was carried out for Aoiz village, located only 3 km from the dam. The results were useful for the local authorities to modify the filling process and reduce the seismic risk.

Figure 4-5: Location of the Itoiz and Yesa dams, in Spain.

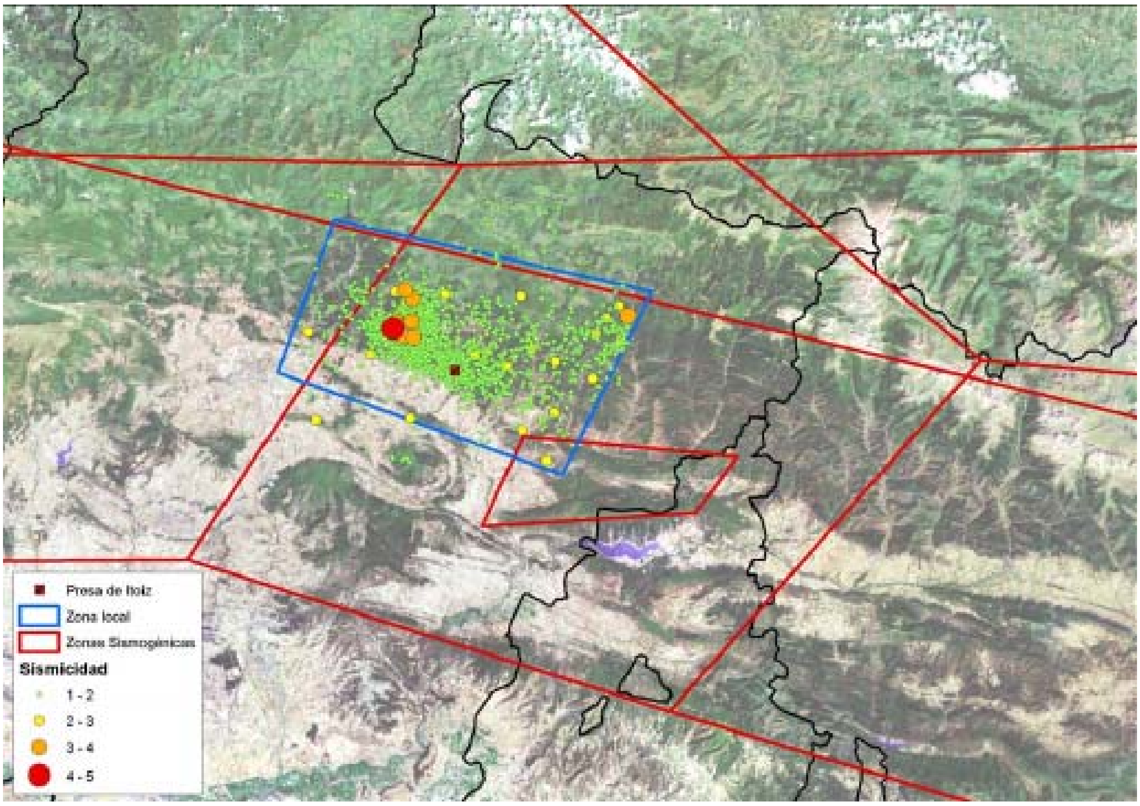

Figure 4-6: Induced seismicity recorded between 2004 and 2010 in Itoiz region.

4.5. Wastewater injection for fuel extraction in Oklahoma state (USA)

Oklahoma state is affected, since 2009, by a rise of seismicity, mainly caused by fuel extraction activities. Most of the seismic activity is caused by an industrial practice known as "wastewater disposal" in which fluid waste from Oil and Gas production is injected deep underground, far from ground water or drinking water aquifers.

In Oklahoma state, over 90% of the wastewater injected is a product of oil extraction process.

In this process, the role of injection depth is an open and complex issue, yet critical for hazard assessment and regulation in USA. Research carried out by Hincks et al. (2016) identified correlations between induced seismicity rates and geological parameters. This study exploited a 6-year record of fluid injection to develop a comprehensive understanding of the controls on induced seismicity. Their model quantifies the joint effects of operational parameters (i.e., injection rates) and latent spatial features on seismic moment release (i.e., fault system, depth to the crystalline basement), facilitates regular model updating, and offers improved forecast performance.

These authors found the critical joint effects of depth and injected volume, as injection rate becomes more influential near the basement interface.

Figure 4-7 shows the total seismic moment release from 2011 to 2016, with mapped faults in the sedimentary cover. The geospatial analysis of induced seismicity showed the strongest correlation with the occurrence of earthquakes (Figure 4-7, C), supporting the observation that lithologic and fault network characteristics collectively play a critical role in determining susceptibility to induced seismicity. In Oklahoma state, the permeability structure of the Arbuckle Group permits downward fluid migration into crystalline basement, causing reactivation of optimally oriented strike-slip faults.

One of the mitigation measures proposed, to reduce annual seismic moment release by a factor of 1.4 to 2.8, is the limitation of injection depths to 200 to 500 meters above basement.

This work helped to the identification of sub-regions where targeted regulation may mitigate induced earthquakes effects, helping operators, and regulators in wastewater disposal regions.

Some lessons can be learnt from this study:

- **Importance of monitoring:**
  - Injection rates: The study showed the strong relation between induced seismicity and injection rates.
  - Seismic monitoring of induced seismicity: The installation of a seismic network is a key point to have a good microseismic recording. The analysis of seismic records offers the possibility to perform further detailed studies, which would not be possible without seismic records.

- **Importance of geology:**
  - The strong relationship between the geographical position of injection of fluids and the existing seismotectonic fault network. Therefore, the regional fault system should be studied (i.e., using geophysical surveys);
  - The strong relationship between the induced seismicity and the depth of injection, mainly the distance to the crystalline basement, showing that only fixing a minimum distance to the basement could reduce the induced seismicity (seismic moment release) in a factor ranging from 1.4 to 2.8.

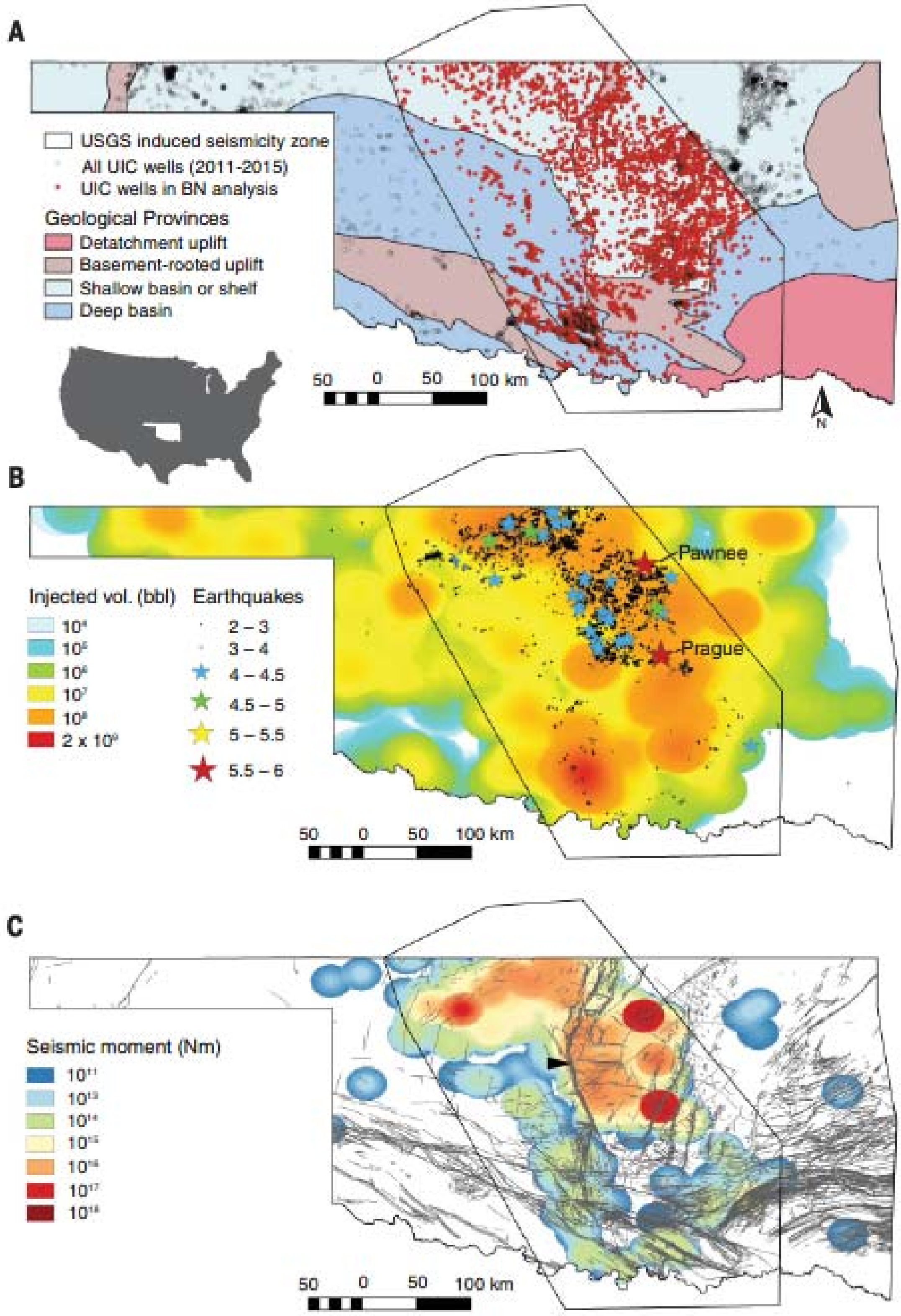

Figure 4-7: Geographical situation of injection wells (A) and Induced seismicity recorded in Oklahoma (B) and relation with existing fault systems (C). Source: Hincks et al. 2016.

4.6. Summary of Lessons Learned for comparable Fluid Injection projects

The characteristics of the induced seismicity are different depending on the activity:

- The induced seismicity associated with injection of fluids (storage gas sites or deep geothermal projects) typically occurs at higher rates during the beginning of the projects.
- In case of fluid extraction, the induced seismicity tends to be observed after some years of extraction. The induced seismicity is associated with the settlement of geological materials due to the collapse after gas extraction.

There appears to be good correlation between injection/extraction activities and induced seismicity in terms of frequency and magnitude of earthquakes. This suggests that the risks associated with induced seismicity are manageable. Given the pattern of induced seismicity related to fluid injection projects a prevailing theme of the lessons learned is that a robust understanding of the site geology and natural seismic hazard is need prior to commencing injection activities.

- **To develop a Geological site characterization and a 3D Geological model (recommended for CCS and also for OWF)**
- **To perform fluid injection modelling (highly recommended for CCS)**
- **To install a Seismic monitoring system (mandatory for CCS where seismotectonic faults are identified in the area of interest and recommended in other case). The monitoring should be installed from the very beginning (feasibility phase) and should be maintained during the site-characterization and operational phases.**
- **To implement a Traffic Light System (necessary for CCS)**

From a project risk mitigation point of view, specific actions that could reduce project risk, broadly cover 4 subjects:

1. **Geological Site Characterization / 3D geological modelling:** Some projects have shown the strong correlation between the induced seismicity and the geological context of the region. For example, the Castor project showed that the induced seismicity was mainly related to the reactivation of an existing seismotectonic fault (triggered seismicity). In the case of Oklahoma, the analysis of induced seismicity showed that it is strongly correlated with the presence of faults in the sedimentary cover and the distance between the injection depth and the depth of crystalline basement. Therefore, developing a robust 3D geological model of the CCS injection area prior to commencing activities will enable risk analysts to identify the locations, geometries, and nature of structural features such as geological faults that could be activated by injection activities. This is the current standard of practice for identifying injection locations, reservoir extent and capacity, and the characteristics of the geological materials in which the fluid is being injected.

2. **Seismic Monitoring**: the installation of a seismic monitoring network in the project area should be done at the early stages of the project. Monitoring should be used to develop "background" or natural seismicity rates in the region of interest prior to initiating injection activities. Monitoring should be continuous throughout project operations and tied to a traffic light system that provides specific project actions to a set of predefined criteria when certain induced seismicity thresholds are observed (e.g., number of earthquakes in a certain amount of time, in a certain location, or of a certain magnitude). The Traffic Light Systems normally are defined connected with the local seismic network.
3. **Seismic Hazard Assessment**: a seismic hazard assessment should be performed for the injection site that establishes the anticipated natural and induced ground motions that the project may experience during operations. It should be done mainly when induced seismicity is expected to be significant.
4. **Seismic risk analysis:** A seismic risk analysis is often performed in sites where induced seismicity is supposed to create damages (mainly economic losses). This kind of seismic risk analyses were performed in 3 of the 6 projects presented earlier (Groningen gas field, Itoiz dam and Serianex projects). The decisions adopted (to continue with the normal operation in Itoiz, to cancel the project in Basel or to adopt corrective measures in Groningen) were taken considering the seismic risk analysis data. In the case of Oklahoma, the authors also mention the necessity to perform complementary studies.

The fluid modelling is also required in many seismic induced projects, but not in all of them. For induced seismicity associated to large dams, the geomechanical model is not strictly needed.

5. Responses to the 5 research questions

5.1 Question 1: At what distance from a CO_2 pipeline can a wind turbine be placed safely?

This question needs to be addressed from two perspectives, discussed separately in the sections 5.1.1 and 5.1.2:

a. Does the actual operation of a wind turbine pose any risk to the integrity of a nearby CO_2 pipeline (or any other type of pipeline)? If so, what are these risks and what is a safe distance to mitigate against these risks? (see Section 5.1.1).
b. What level of separation is required between a proposed wind turbine and an existing CO_2 pipeline (or any type of pipeline or sub-sea installation) to enable the safe installation of the wind turbine and the ongoing maintenance, repair and eventual decommissioning of both the offshore wind farm infrastructure and the CO_2 pipeline? (see Section 5.1.2).

5.1.1 Question 1a: What is the effect of placing a turbine close to a CO_2 pipeline for both the turbine and the pipeline?

This question includes the following:

> *Does the actual operation of a wind turbine pose any risk to the integrity of a nearby CO_2 pipeline? If so, what are these risks and what is a safe distance to mitigate against these risks?*

Fugro are not currently aware of any specific studies into the effects of the normal operation of a wind turbine on nearby pipelines or infrastructure (e.g. the long term effects of vibrations from the wind turbines etc.). It is not therefore possible to derive any specific safe distance to mitigate against such risks. However, in the absence of existing data, it is the opinion of the authors of this report that the level of separation required for installation, maintenance, repair and decommissioning (as discussed in Section 5.1.2) is likely to be sufficiently large to mitigate against any risk (to the integrity of a CO_2 pipeline) arising from the normal operation of a wind turbine.

Another potential risk from the operation of a wind turbine is that arising from the failure of the wind turbine during operation.

Although very rare, there have been several wind turbine failures over the last 30 years. In the onshore wind farm industry this prompted a study to determine the safe distance between wind turbines and buried energy infrastructure (e.g. high pressure gas, gasoline and oil pipelines).

This study undertaken by the UK Onshore Pipeline Operators' Association (UKOPA, 2012) specifies a separation distance, developed using a risk-based approach, to ensure that the risk of pipeline failure is acceptably low in the event of a wind turbine failure.

The safe distance calculated in the UKOPA study is 1.5 times the turbine mast height. Assuming that a typical offshore turbine tower height for current offshore windfarmsF ~100 - 115 m (Siemens Gamesa 14MW – Sofia OWF (RWE, 2021) (then this gives a minimum separation of 150 -174) m. Notably, it is anticipated that future 17 MW offshore turbines will have a turbine tower hight of 495 ft (~151m) with rotor diameter of 820 ft (~250 m) by 2035.

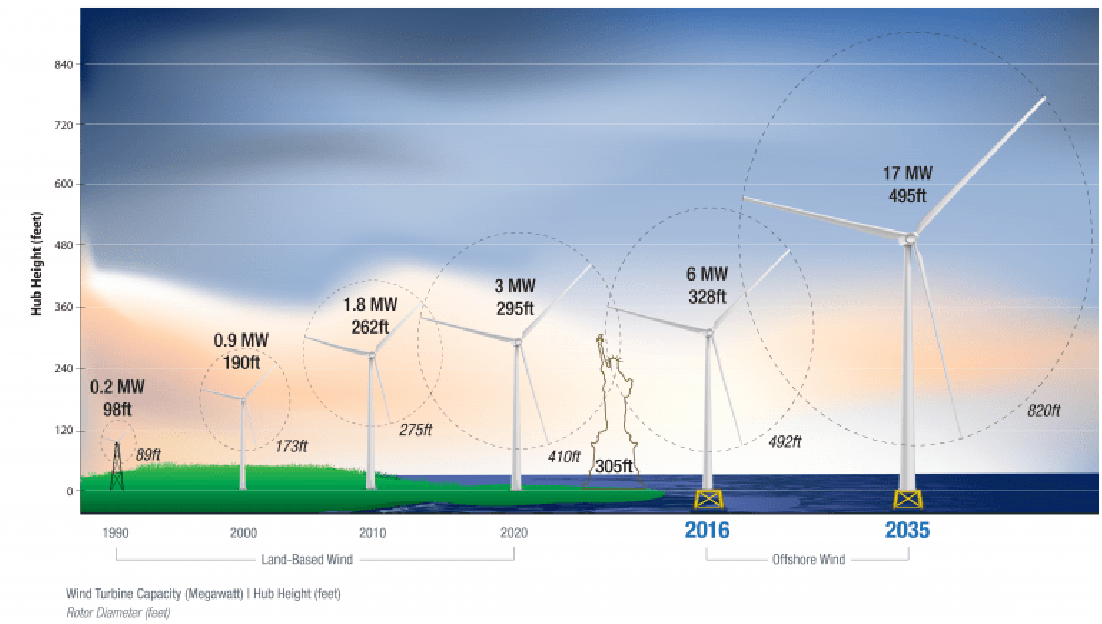

Figure 5-1: Wind Turbine Capacity (MW) (Source: Energy.gov, 2021)

This separation considers the following modes of wind turbine failure:

- A blade detaching from the hub or root, leading to loss of the blade which then impacts the pipeline;
- Collapse of the mast, essentially rotating about the base or a point near to the base and falling linearly to the ground;
- Collapse of the mast, essentially rotating about the base or a point near to the base and falling linearly to the ground;

The UKOPA study relates specifically to the onshore environment and so is not directly applicable offshore. However, in the absence of similar studies for the offshore environment it is perhaps a useful point of reference. In any case, it is expected that this minimum separation distance (1.5 times mast height) is likely to be exceeded by the level of separation required for installation, operation, maintenance and repair (as discussed in 5.1.2).

5.1.2 Question 1b: What is a safe distance as a result?

This question includes the following:

What level of separation is required between a proposed wind turbine and an existing CO2 pipeline (or any type of pipeline or sub-sea installation) to enable the safe *installation of the wind turbine and the ongoing maintenance, repair and eventual decommissioning of both the offshore wind farm infrastructure and the CO2 pipeline?*

Based on Fugro's experience of working with offshore wind farm operators (during the early planning and pre-construction phases of offshore wind farm developments) it is understood that the wind farm operator will agree the closest approach of any wind farm infrastructure to existing infrastructure through a consultative process with key stakeholders. This process is carried out on a project-specific basis and will typically include, but not be limited to, the following stakeholders:

- Offshore windfarm developer/owner;
- 3rd party operators (e.g. of any existing CO_2 pipeline, oil and gas pipeline or submarine cable that runs through or near to the proposed wind farm development);
- Offshore wind farm developer's construction contractors (e.g. wind turbine installation contractors, offshore sub-station installation contractors inter-array and export cable contractors etc.);
- Relevant regulatory authorities.

This takes place at the earliest opportunity in the planning process but may evolve during the pre-construction phase as, for example, the construction contracts are awarded as different contractors may have different operational tolerances (in terms of how close installation equipment can approach to existing infrastructure etc.).

Some of the factors that will need to be considered by the wind farm developer and key stakeholders will be to ensure sufficient separation is factored into the design to allow sufficient space (sea room) for the following:

- Installation methodology (for the wind turbines, offshore sub-stations, inter-array and export cables);
- Ongoing maintenance of the wind farm infrastructure;
- Ongoing maintenance of the existing 3rd party infrastructure (e.g. CO_2 pipeline, oil and gas pipeline or submarine cable);
- Accessibility for maintenance or repair of the wind farm infrastructure;
- Accessibility for maintenance or repair of the 3rd party infrastructure (e.g. CO_2 pipeline, oil and gas pipeline or submarine cable);
- Decommissioning requirements.

As a result of the stakeholder discussions and consideration of the bullet points above, the wind farm operator may then define a 'developable area' within their licensed area. The developable area will place an agreed buffer around features such as existing pipelines and cables but also around other features such as wrecks, steep slopes or adverse soil conditions identified during preliminary and/or preconstruction geophysical and geotechnical site investigations.

Given the considerations and processes outlined above it is clear that there is not a definitive set distance, of closest approach, that can be applied to all wind farm developments. Rather it will be a site-specific, risk-based decision based on early engagement with key stakeholders.

5.1.3 Useful Examples of Guidelines from Related Industries

The following text provides some examples from other offshore industries that are considered relevant to this discussion. The text specifically refers to published guidelines within those industries. In the absence of any specific guidelines relating to CO_2 pipelines these are considered as potentially useful analogues in support of the discussion presented in Sections 5.1.1, 5.1.2 and 5.1.4.

5.1.3.1 Example from the Subsea Cables Sector

The European Subsea Cables Association (ESCA) published ESCA Guideline No.6 titled 'The Proximity of Offshore Renewable Energy Installations and Submarine Cable Infrastructure in UK Waters (ESCA, 2016). The following extract is from ESCA Guideline No.6 and outlines the objective of the publication:

"*This document provides guidance on the considerations that should be given by all Stakeholders in the development of projects requiring proximity agreements between offshore wind farm projects and subsea cable projects in UK Waters. The Guidelines address installation and maintenance constraints related to wind farm structures, associated cables and other submarine cables where such structures and submarine cables will occupy proximate areas of seabed*" (extract from ESCA, 2016).

The ESCA guidelines further state that:

- "*The importance of early Stakeholder consultation should be appreciated at the outset and it is recommended that this is actioned as early as possible*" (extract from ESCA, 2016);
- "*The Guidelines are not intended to provide a prescriptive solution on proximity but offer some guidance for indicative separation distances that are intended as a starting point for Stakeholder discussions*" (extract from ESCA, 2016);
- "*It is expected that the Guidelines will provide the underlying basis upon which all Stakeholders can reach a mutually acceptable proximity agreement*" (extract from ESCA, 2016).

The ESCA guidelines emphasise the importance of stakeholder engagement to reach a proximity agreement that is applicable to the specific project. The guidelines also state the following with respect to the circumstances where stakeholder discussion and proximity agreements are and are not required:

- No proximity agreement is required where the minimum approach of planned subsea development and planned/existing sub-sea infrastructure exceeds nautical mile 1NM (1.852 km);

- For a planned subsea development that is within 1 NM of existing subsea infrastructure, dialogue needs to be established between the stakeholders
- The ESCA guidelines provide an indicative separation distance of 750 m but state that this "*is not intended to provide a prescriptive solution on proximity but should be used as a sensible base case to begin Stakeholder discussions to determine actual, case specific separation distances*" (extract from ESCA, 2016).

5.1.3.2 Example from the Oil and Gas Pipeline Sector

Gassco is an operator responsible for gas transport from the Norwegian continental shelf to various European countries, via an extensive sub-sea pipeline network.

Gassco publish a document titled: Technical Requirements for Offshore Operations in the Vicinity of Pipelines (Gassco, 2019).

The document is intended to specify the minimum technical requirements for any third-party offshore activity in the vicinity of pipelines operated by Gassco AS, this includes the construction of wind turbines and related infrastructure. Some key points from this document may be summarised as follows:

- The document defines the 'vicinity' of the pipeline as being 500 m either side of the pipeline.
- The document states that Gassco will provide pipeline condition details to the 3rd party but that it is the 3rd party's responsibility to check and verify the pipeline condition in the form of a pre-lay / as-found survey of the pipeline and surrounding area to determine:
  - Pipeline lay condition.
  - Pipeline burial depth.
  - Pipeline freespans, including height and length measurements.
  - Pipeline features.
  - Seabed features.
  - Pipeline longitudinal and transverse profiles relative to the seabed.

It is Fugro's opinion that this information (detailing the pipeline condition) will be an important input for the stakeholders involved in the decision-making process. In the example being considered here, it would be the wind farm developer responsibility to carry out the required survey work (of the existing CO_2 pipeline) as part of the pre-construction geophysical survey scope.

5.1.4 Conclusions

To the authors knowledge there is currently no published information relating to the effects of the normal operation of a wind turbine (e.g. the long term effects of vibrations from the wind turbines etc.) on a nearby CO_2 pipeline, or any other type of pipeline.

A study by the UK Onshore Pipeline Operators' Association (UKOPA, 2012) that provides a suggested safe separation distance to minimise the risk to any existing pipelines in the event that there is a failure of a wind turbine. The safe distance calculated in the UKOPA study is 1.5 times the turbine mast height. Assuming that a typical offshore turbine tower height is currently ~100 to 115 m then this gives a minimum separation of 150 to 174 m.

However, rather than being related to the effects of the operation or failure of a wind turbine, the separation distance is far more likely to be determined by the space (sea room) required to install the wind turbines (and associated infrastructure such as inter-array and export cables) and also the space (sea room) required to maintain, repair and eventually decommission the wind farm infrastructure and the existing CO_2 pipeline.

It is also clear that separation distances should be site-specific, risk-based decisions based on early engagement with key stakeholders and there is a good example of this approach being used in the subsea cables industry (ESCA, 2016). The ESCA guidelines do not provide a prescriptive solution but stress the need for proactive dialogue about a site-specific, risk-based outcome (ESCA, 2016). The ESCA guidelines do provide some indicative separation distances (750 m) but it is clearly stated that this is only intended to provide a starting point for stakeholder discussion.

It is a conclusion of this report that a similar approach will need to be undertaken when considering the proximity of wind farm developments to CO_2 pipelines.

5.2 Question 2: What are the seismic risks of CO_2 storage?

5.2.1 Question 2a: What literature/studies are(public) available on this topic?

Fluid injection projects, in general, have the potential to induce seismicity. Most of the literature focussing on the seismic risks of CO_2 storage has been published within the last decade with more recent studies focused on improving monitoring technics and approaches.

However, there are very few reports discussing the OWF & CCS overlapping. Very probably, the main reference dealing with the CCS & OWF overlap is the Crown Estate report (Robertson & McAreavey, 2021). Unfortunately, the induced seismicity is not one of the topics analysed in this report.

The IEAGHG (2014) address the potential conflicts between CCS and OWF as more license areas become available for both activities, especially in the North Sea. Their report mentions that "*offshore wind farms could present a physical barrier to accessing any potential storage sites in terms of laying down infrastructure and monitoring above a site, including the safety zones that may be imposed around turbines*".

IEAGHG (2015) reiterates this concern and mentions that "*the extent to which wind-farm development and CO_2 storage will ever be co-incident is uncertain, but the turbine installation and foundations might well compromise the logistics, coverage and quality of seabed monitoring surveys*".

In general, there is little information on induced seismicity for CO_2 storage available in the public domain (IEAGHG, 2013). The lack of information is due to the limited number of sites and the lack of extensive local microseismic monitoring networks at many commercial and experimental sites. Since 2013, only a few examples of induced seismicity related to CO_2 storage have been brought to the public domain (e.g. In Salah project in Algeria). However, induced seismicity by fluid injection and extraction causing changes in rock stress field is a widely observed phenomenon. Then, some lessons can be learnt from other type of fluid injection projects.

The main bibliography analysed related with the induced seismicity associated to a CCS (OWF cannot produce induced seismicity) are presented in Table 5-1. The complete list of references is given in Chapter 7.

Table 5-1: Main bibliography analysed related with induced seismicity in CCS projects

Authors	Title	Comments
IEAGHG, 2013	Induced seismicity and its implication for CO_2 storage risk	The report explains how the risk can be reduced and mitigated. Also, it shows how statistical models can forecast the seismicity
White & Foxall, 2016	Assessing induced seismicity risk at CO_2 storage projects: Recent progress and remaining challenges	This paper reviews recent lessons learned regarding induced seismicity at carbon storage sites
Vilarrasa et al. 2019	Induced seismicity in geologic carbon storage	The authors review the triggering mechanisms of induced seismicity.
Nicol et al. 2011	Induced seismicity and its implications for CO_2 storage risk.	They examine induced seismicity globally using published data from 75 sites dominated by water injection and hydrocarbon extraction
Zoback and Gorelick, 2012	Earthquake triggering and large-scale geologic storage of carbon dioxide	Authors argue that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors.
Takagishi et al. 2014	Microseismic Monitoring at the Large-Scale CO2Injection Site, Cranfield, MS, U.S.A.	This paper describes passive seismic monitoring at the large-scale CO_2 injection site, Cranfield oil field, Mississippi, U.S.A.
Gan and Frohlich, 2013	Gas injection may have triggered earthquakes in the Cogdell oil field, Texas	They analysed data recorded by six temporary seismograph stations deployed by the USArray program, and identified and

		studied 93 well-recorded earthquakes
Verdon et al., 2015	Simulation of seismic events induced by CO2 injection at In Salah, Algeria	They develop an approach to simulate microseismic activity induced by injection, which allows to compare geomechanical model predictions with observed microseismic activity.
Kaven et al., 2015	Surface monitoring of microseismicity at the Decatur, Illinois, CO_2 sequestration demonstration site	The report analyses 19 months of microseismicity monitoring at the Decatur CO_2 sequestration site, which permits a detailed look at the evolution and character of injection-induced seismicity
Bauer et al., 2016	Overview of microseismic response to CO_2 injection into the Mt. Simon saline reservoir at the Illinois Basin-Decatur Project.	The report analyses the microseismicity monitoring at the Mt. Simon saline reservoir
Myer and Daley, 2011	Elements of a best practices approach to induced seismicity in geologic storage	The authors develop a seven-step approach involving historical natural seismicity, assessment of the potential for induced seismicity, and recommended steps for mitigation of the risk of the induced seismicity
Ward et al., 2016	Reservoir leakage along concentric faults in the Southern North Sea: Implications for the deployment of CCS and EOR techniques	Authors used High-quality 3D seismic and borehole data to investigate newly recognised concentric faults formed in salt-withdrawal basins
Being-Zih et al., 2021	Preliminary evaluation of potential induced seismicity risk at a nearshore carbon storage candidate site	Authors developed a coupled hydro-mechanical model to evaluate the potential induced seismicity risk for carbon storage in a deep saline aquifer
Ringrose et al., 2011	Characterisation of the Krechba CO_2 storage site: critical elements controlling injection performance	The paper talks about the reservoir features proven as the most critical in controlling the injection performance

The basic principle of induced or triggered seismicity is that pressure or temperature changes caused by fluid injection can reduce effective stresses at depth and bring the stress state closer to failure. Failure may occur seismically as blocks of the earth's crust suddenly move against each other causing an earthquake. Vilarrasa *et al.* (2019) mention a list of processes which may induce seismicity, among them:

- pore pressure variations and the possible effect that properties of the injected fluid have on fracture and/or fault stability (e.g., fault lubrication).
- temperature of injection fluid at a lower temperature than that of the rock, inducing rock contraction, thermal stress reduction and stress redistribution around the cooled region.
- local stress changes induced when low permeability faults cross the injection formation, which may reduce their stability and eventually cause fault reactivation.
- stress transfer caused by seismic or aseismic slip.
- geochemical effects related to the injected fluid, which may be especially relevant in carbonate-containing formations.

Induced seismicity may pose risks to the successful completion of CO_2 storage projects if mitigation measures are not incorporated into site development programmes. These risks include (Nicol *et al.*, 2011):

- induced earthquakes may be felt by, and cause concern to, the nearby communities;
- induced earthquakes may result in damage to infrastructure at a storage site, to nearby facilities (such as wind turbines) and/or urban areas;
- induced earthquakes could rupture the primary CO_2 seal, allowing CO_2 to migrate towards the ground surface.

Nicol et al. 2011 examined induced seismicity globally using published data from 75 sites dominated by water injection and hydrocarbon extraction to estimate the timing (relative to injection/extraction), locations, size, range and numbers of induced earthquakes. They identified 4 induced earthquakes with M>5.9 (in oil fields). They indicate that "*Mitigation and monitoring measures at commercial-size sequestration sites, including installation of microseismic networks, public education on the expected seismicity and pressure relief wells, will be key for risk reduction*"

For offshore sites these risks are reduced due to the lack of human habitation or urbanization. However, the risk of seismic shaking causing damage to nearby infrastructure and leakage pathways for CO_2 or caustic fluids (e.g., salt brine) must be considered.

It must be noted that induced seismicity is a key topic for the success of CO_2 sequestration. Zoback and Gorelick, 2012, indicate that "*Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions*".

Therefore, according to the bibliography reviewed, a correct assessment and mitigation of induced seismicity risk appear a key point for CO_2 sequestration projects.

5.2.2 Question 2b: Are there any risks of soil movement (e.g. tremors / induced seismicity, subsidence?

5.2.2.1 Seismicity induced by CO_2 storage

Statements regarding seismicity and CO_2 storage diverge in the literature:

On one hand, Vilarrasa *et al.*, (2019) state that geologic carbon storage projects, both at large scale and pilot scale, have not induced any perceivable earthquake. Focussing on the specific Cranfield oilfield (Mississippi) Takagishi *et al.* (2014) also mention that no seismic events induced by CO_2 injection are observed on this site. The authors justified this by the fact that the stress at this specific injection zone did not increase enough to trigger microseismic events because of the characteristics of the reservoir (high porosity and high permeability).

However, on the other hand, Gan and Frohlich (2013) mention a possible link between gas injection and earthquakes at the Cogdell field in Texas (with an observed maximum magnitude of Mw 4.4). As said previously, Zoback and Gorelick, 2012 were sceptic about the success of CO_2 sequestration projects. And finally, the Castor project in Spain appears as a clear example of induced seismicity due to fluid injection (even if Castor was planned as a natural gas storage site and non a CCS site).

In the case of moderate to even small earthquakes (microseismicity), Zoback and Gorelick (2012) report showed their concern about the seal integrity of the CO_2 reservoir. They comment on the capability of small earthquakes (earthquakes that are unlikely to cause damage at the surface) to be capable of creating a permeable hydraulic pathway that could compromise the seal integrity of the CO_2 reservoir and potentially reach the near surface. Vilarrasa *et al.*, (2019) agree with this statement that induced microseismicity (magnitude < 2) should be avoided in the caprock to prevent CO_2 leakage. The authors also mention that induced microseismicity is however commonly observed projects like:

- In Salah, Algeria, Stork *et al.*, 2015; Verdon *et al.*, 2015),
- Decatur, Illinois, USA (Kaven *et al.*, 2015; Bauer *et al.*, 2016); and
- Otway, Australia (Myer and Daley, 2011))

However, the authors added that the induced seismicity be positive if confined within the reservoir formation as it enhances permeability.

White and Foxal (2016) provided an assessment of the induced seismicity risk at CO_2 storage sites and performed a summary of seismicity observations during recent CO_2 injection operations. The main CCS projects cited in White and Foxal (2016) where induced seismicity has been recorded are:

- Aneth project (USA): 3800 induced earthquakes recorded with moment magnitudes ranging from -1.2 to 0.8. They identified 2 clusters associated with faults. The seismic monitoring included downhole sensors.
- Cogdell project (USA): one event with moment magnitude 4.4 and 18 earthquakes with magnitude higher than 3.0. A regional network was used to record the induced seismicity.
- Weyburn project (Canada): more than 100 microearthquakes (over 7 years) were recorded with moment magnitudes ranging from -3 to -1. A monitoring system was installed using downhole sensors.

- Decatur project (USA): more than 10,000 microearthquakes (over 1.8 years) were recorded with moment magnitudes ranging from -2 to 1. A monitoring system was installed in boreholes and surface stations.
- In Salah (Algeria): more than 500 microearthquakes (over 2 years) recorded with moment magnitudes ranging from -1 to 1. A monitoring system was installed in boreholes and surface stations.

Ward *et al*. (2016) presented a study focussing on concentric faults in the Broad Fourteens Basin area (Southern North Sea). These concentric faults formed in salt-withdrawal basins flanking reactivated salt structures. The authors highlight that heterogeneity in slip tendency along concentric faults, and high degrees of fault segmentation, present serious hazards when injecting CO_2 into the subsurface unless pore fluid pressures do not exceed the pre-existing fault's shear strength.

Site characterisation

Authors that perform studies on CCS topics (regarding either project feasibility, site investigations, monitoring, of tracking test sites or operational sites) gives a special emphasis to the site characterization. The authors agree that the level of induced seismicity risk should be evaluated prior to the site operation (by conducting a site-specific seismic hazard analysis that integrates the potential contribution of induced seismicity from fluid injection) and well managed during the injection stage through carefully designed operational procedures and monitoring programs.

The risks associated with induced seismicity at CCS sites can be reduced and mitigated using a systematic and structured risk management programme.

In their recent study, Being-Zih *et al*. (2021) proposed a general workflow of coupling reservoir flow transport model and geomechanical model for induced seismicity risk analysis. This workflow is summarised in figure 5.2

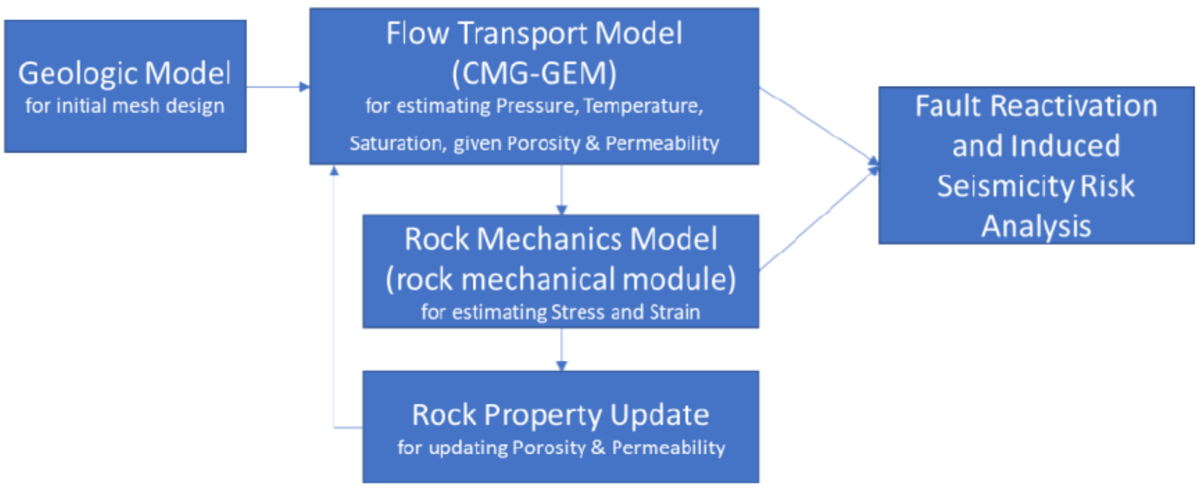

Figure 5.2 : General workflow for induced seismicity risk analysis, Being-Zih et al. (2021)

The preliminary analysis should use and synthesise all existing relevant data regarding the reservoir and overlying rock characteristics, but also the structural features present in the concerned area (fault/fractures orientation, permeability, sealing…). All these data will form a robust geological model.

Information regarding the existing infrastructure such as exploitation wells have also to be taken into consideration. In the case where CO_2 storages are using depleted hydrocarbon fields, most of this required information should already be known and communicated by the hydrocarbon field operator.

Once the geological model of the area of interest is characterised and developed, the storage capacity/pressure build-up issue is critical to assess the potential for triggered seismicity. Small-scale pilot injection projects do not necessarily reflect how pressures are likely to change (increase) once full-scale injection is implemented. Moreover, even though limitations on pressure build-up are among the many factors that are evaluated when potential formations are considered as sequestration sites, this is usually done in the context of not allowing pressures to exceed the pressure at which hydraulic fractures would be initiated in the storage formation or cap-rock. In the context of a critically stressed crust (presence of active fault for example), slip on pre-existing, unidentified faults could trigger small- to moderate-sized earthquakes at pressures far below that at which hydraulic fractures would form (Zoback and Gorelick, 2012).

Vilarrasa *et al*. (2019) also proposed a detailed workflow to minimise the risk of inducing earthquakes. The main steps of this workflow are:

- performing a detailed initial site characterisation, with special emphasis on the geological formations relevant to the site (at least of the storage formation, the caprock, base rock and faults).
- putting in place proper monitoring for performing continuous characterisation.
- carrying out pressure management.

This detailed site characterisation should be performed both before the start of operation of projects and continuously during the whole operational stage.

Ringrose *et al*. (2011) insist on the point that the overburden (integrating the caprock) is just as important as the reservoir itself and so should be well understood and characterised during the preliminary analyse phase.

Therefore, we can conclude the following for the CO_2 sequestration projects:

1) **They can generate induced seismicity and it occurred in many CO_2 sequestration projects.**

2) **The maximum magnitude observed in CO_2 sequestration projects is M4.4, in Cogdell project (USA).**

3) **The maximum magnitude observed in other fluid injection projects normally doesn't exceed M5.0, but these small earthquakes could occur frequently. Other authors, such as Nicol et al. (2011) indicate the possibility to observe maximum magnitudes larger than M6.0.**

4) **The simulation of induced seismicity in other fluid injection projects (i.e. Castor) indicated the possibility to trigger big earthquakes (M>6.0), especially in the context of pre-existing seismotectonic faults.**

5.2.2.2 Surface uplift and subsidence

Few studies (Gourmelen *et al.*, 2011; Yamamoto *et al.*, 2011; Verdon *et al.*, 2013; Vasco *et al.*, 2010) have shown evidences of ground surface movements related to the In Salah CCS project (Algeria). Verdon *et al.* (2013) mention substantial geomechanical deformation that uplifted the surface of the In Salah field (Algeria) by 2 cm. This uplift was associated to thousands of microseismic events and appears to have reactivated a fracture network extending from the reservoir 100–200 m into the overburden.

The uplift was estimated by using InSAR monitoring, a method which can reveal surface displacement with millimetre accuracy. InSAR (Interferometric Synthetic Aperture Radar) is a technique for mapping ground deformation using radar images of the Earth's surface that are collected from orbiting satellites. Note that InSAR monitoring cannot be used for offshore reservoirs. Except from the In Salah field, no evidence of surface deformation is found in the literature.

5.2.3 Question 2c: What are any other consequences for the soil?

According to the article consulted, the main consequences of fluid injection projects by extraction/injection of fluids (CO_2 or others) is the induced seismicity and uplift/subsidence of soil. Groningen gas field is one of the best examples, with a significant induced seismicity (thousands of small earthquakes) generated by many years of gas extraction, the diminution of the pressure of the field, together with significant subsidence recorded.

In the future offshore CCS, the injection of gas (CO_2) will probably produce induced seismicity as it was observed in several existing CCS projects (the mechanism producing induced seismicity is not different onshore and offshore). And probably, they will be affected by subsidence and/or uplift depending on the pressure changes that the reservoir.

No other soil consequences are described regarding CCS projects. Possible fractures and faults may affect the cap-rock in addition to the induced seismicity and uplift/subsidence. If significant seismotectonic faults affect the reservoir, these features could reach the surface, producing potential leakages. The surface faulting is occasionally expected when earthquake magnitude exceeds 5.0 and more likely when magnitude exceeds 6.0. Generally, only seismotectonic faults can produce these relative high magnitudes. The none seismogenic features existing in a reservoir (i.e. those existing in Groningen are) cannot produce surface faulting and, therefore, the cap-rock would be only slightly affected.

5.2.4 Question 2d: Are there any other risks beyond seismicity (e.g. chemical or physical? If so, what are the consequences for the turbine and the possible mitigating measures?

In the literature, some other risks are cited. The 3 main risk found are:

- Geochemical effects on geomechanical properties.
- Leakage
- Slope failure

They are summarized in the following sections.

5.2.4.1 Geochemical effects on geomechanical properties

Vilarrasa *et al*. (2019) study analysed the possible geochemical effects on geomechanical properties in a CCS project context. The effects differ based on the types of CO_2 reservoir host rock. The dissolution of CO_2 into the resident brine forms an acidic solution that has the potential of dissolving minerals, which in turn may lead to subsequent precipitation of other minerals. The authors mention that the fastest geochemical reactions occur in carbonate rocks and in rocks with carbonate-rich cement.

For other types of host rock, laboratory studies have shown that geochemically induced changes in the geomechanical properties are in general minor (Vilarrasa *et al*., 2019). This minor effect has also been observed in fault gouges that have been exposed to acidic conditions for a long period in natural CO_2 reservoirs (Bakker *et al*., 2016).

Caprocks could also be affected to some extent by geochemical reactions. Carbonate and feldspar minerals dissolve in shale, leading to precipitation of other carbonate minerals. But the overall response of caprocks depends on the rock type (Vilarrasa *et al*., 2019). While certain caprocks undergo permeability increase due to interaction with CO_2, others present a self-sealing response to CO_2 flow due to porosity decrease or fracture clogging (Noiriel *et al*., 2007). Nevertheless, CO_2 is only expected to penetrate a short distance, if any, into the caprock because of its high entry pressure, which prevents upwards CO_2 flow (Busch *et al*., 2008). In that case, no specific measures should be considered regarding the type of turbine or foundation (this doesn't take into consideration any potential leakage up to the surface).

However, taking into account the different opinions in the literature, the possible corrosion damage to offshore wind infrastructure caused by saline brine displacement at depth (in the CCS) cannot be excluded and should be analysed.

Therefore, it is recommended to evaluate in laboratory the changes in geomechanical properties of the rocks (especially carbonate-rich rocks) as a result of CO_2 – brine - rock geochemical interactions.

5.2.4.2 Leakage

The majority of offshore CO_2 storage operations offshore the Netherlands will be in moderately shallow continental seas so free phase CO_2 leaks to the seabed will probably be in its dissolved phase or gaseous phase – although the CO_2 will be at a higher density than at the land surface due to the pressure exerted by the water column (Roberts *et al*., 2017).

Whilst the CO_2 density may be affected by tides, the CO_2 is unlikely to be in a liquid phase at the seabed, although this has been observed at deep-sea vents (Lupton *et al*., 2006). Bubble streams of gas phase CO_2 quickly rise and dissolve into the seawater column (Sellami *et al*., 2015) unless the CO_2 emissions are very large (Caramanna *et al*., 2013) or occur in shallow waters.

CO_2 leakages could be responsible for seawater acidification. Despite the impacts on the marine environment (Kadar *et al*., 2010; Basallote *et al*., 2012, Sokołowski *et al*., 2020), this acidification may potentially have an impact on the CCS and wind turbine infrastructures located near the leakage zone. Unfortunately, no information regarding possible damages on infrastructures is found within the scope of this study.

Laboratory analyses on infrastructure damages due to seawater acidification should probably be run before to potential development of an offshore windfarm project on top of a CO_2 storage field.

5.2.4.3 Slope Failure

Slope failures or landslides could be triggered by induced seismicity from CCS operations. Slope stability and landslide hazards should be assessed as part of site characterization activities that would include an overall "Geohazard Assessment" for the project. In many pipeline Oil & Gas projects, slope stability is one of the geohazards that are typically performed when the pipeline crosses a steep slope. The slope stability analysis typically involve:

- A Probabilistic Seismic Hazard Assessment (PSHA) to determine the vibratory ground motion at some depth (for different return periods), often following the API RP 2EQ and ISO 19901-2 guidelines.
- A Site Response Analysis (SRA) to determine the vibratory ground motion at surface, taking into account the site-specific characteristics of the site analyzed.
- A slope stability analysis taking into account the seismic motion previously defined, for different return periods.

Therefore, similarly to the oil& gas pipeline projects, in CCS and OWF, slope stability analysis are recommended if the projects are situated in a zone with a steep slope.

5.2.5 Question 2e: What are the possible mitigating measures?

In the previous section Fugro identified 3 possible risks beyond the induced seismicity. The mitigation measures per risk are:

- **Geochemical effects on geomechanical properties**: The mitigation measures for the geomechanical problems seems to be complex. The best recommendation should be to perform a complete and detailed site characterization, including geochemical studies.

Then, if potential geochemical problems are found, and they can affect the integrity of the project, the selection of a new site should be considered.

- **Leakage**: For the leakage, the mitigation measures are again complex. The best recommendation should be to perform a detailed site characterization and, if potential leakage is identified, (very likely associated to the presence of faults affecting the surface) the selection of the site should be re-analysed and the selection of a new and better site should be considered
- **Slope failure**: In the case of slope failure risk in the CCS and/or OWF projects, a slope stability study is needed in presence of steep slopes in CCS or OWF and engineering solutions should be proposed. Oil & Gas standards could be used for these types of studies.

The available space in the North Sea is very limited, and the locations for CCS and offshore wind are very limited. If no other site is available and the combination of CCS and OWF is seen as highly desirable, the main recommendation would be to reinforce the site-characterization, the analysis of leakage, geomechanical effects or other risks found before refusing the site. When other sites are not available, the exclusion criteria should be the latest option.

5.3 Question 3: What are the possibilities for seismic (reflection and/or refraction seismology) in existing wind farms, or wind farms under construction?

It is Fugro understanding that his question relates to the logistical constraints of conducting a seismic survey within an existing windfarm footprint. It is looking at whether areas of the seabed will become “off limits” or highly constrained for future seismic acquisition during windfarm construction (i.e. geophysical surveys during development of an OWF located on top of an established CO_2 storage) and once a windfarm is in-place and vessel access becomes hindered.

This is a very topical subject at present and one that will grow further as areas of seabed become more congested as developers look to co-locate new technologies. It is evolving at present with for example:

- ongoing discussions between BP and Orsted for the same area of seabed off the east coast of the UK at the Hornsea windfarm location and a potential CCS storage beneath it for the Net Zero Teesside/Zero Carbon Humber initiatives. The problem relates to the practicalities of running regular repeat surveys to monitor wide area CO_2 plumes in the storage site using seismic technique/streamers towed behind vessels with the fixed wind turbines causing a navigational hazard.
- Similarly, off north east Scotland the Acorn CCS project is facing what they call “an interesting challenge” of sharing seabed with an offshore wind farm and the potential problems of running seismic surveys in areas of wind turbines, plus concern about noise created by the turbines.

The O&G industry has dealt with this for many years. The typical process is to undershoot the surface facility so that vessels do not need to approach too closely. For shallow site survey work however the ability to undershoot is more challenging.

An alternative is to use a nodal survey and the Seabed Geosolutions spice rack would be an ideal candidate. For CO_2 storage it is likely that a permanent monitoring array would be required. And this would also benefit the overlying OWF. There may even be benefits in the OWF piles providing a continuous seismic source, thus permitting passive seismic also. I am unaware of any research in this direction. Installation with nodes is minimal impact and would not affect a wind farm installation.

Fugro approach here would be to undertake a literature review of known examples of co-existence and/or disputes or problems caused by such eco-existence. Fugro would then go on to identify mitigation, as touched on above including technology owned by Fugro and others that are presently available on the market, or maybe under development at present that can allow the co-existence of these technologies on the same area of seabed.

We could minimize new acquisition through:

Current Technologies:

- Towed streamer 3D seismic survey
- Assess data from existing wells
- Regional geological evaluations

Future technologies to minimize requirement for new seismic surveys by:
- New efficient methods of re-processing
- Cloud computing to maximize use of existing data
- New imaging algorithms
- Low cost on-bottom node seismic

Further possibilities in table on page 41 of Crown Estate report (Robertson & McAreavey, 2021).

Current practice to characterise a potential site for CCS is to perform 3D seismic survey which is typically performed using a towed streamer. The system requires a survey vessel to tow an array of seismic sensors which can typically measure 3 to 6 km in length and between 500 and 200 m in width. In addition, a seismic source is towed closer to the survey vessel. The size of these typical survey arrays is not compatible with the typical spacing between turbines which can tend to place turbines in the region of 6 to 10 turbine rotor diameters in the direction of the prevailing wind with a lateral spacing width in the order of 4 to 8 turbine rotor diameters (Richard and Stevens, 2016). Typical current turbines lead to spacings of the order of 1.3-2.2 km by 0.9-1.8 km making the possibility of snagging the seismic array on the turbine substructures high. The type of turbine foundation solution may also severely narrow the potential seismic survey corridors further, with typical spread moorings using catenary lines having an anchor radius of the order of 4 to 8 times the water depth.

Alternative seismic survey technologies are available, such as on-bottom nodes, that reduce the dependency on such long cable arrays for gathering seismic data, but still requires the towing of seismic source along a very accurately positioned, regular grid that covers the entire reservoir footprint. This would therefore still requires meticulous planning in advance to run safely between and around turbines and infrastructure in advance to run safely. The costs associated with these surveys can be significantly higher and may not be suitable for surveying wide areas as may be required for the exploration and appraisal stages.

The effects of background noise originating from wind farm foundations on the quality of the seismic data acquisition should also be considered and managed. Insight may be gained from comparison of the noise characteristics wind farms to oil and gas operations and whether lessons can be learned from that industry.

The effects of impact/snagging of seismic arrays on wind farm foundations is highly dependent on the foundation types in use. For example, floating systems and monopiles typically, have fewer redundancies than jacket structures to damage of their components.

In addition to the physical challenges of performing seismic surveys for CCS projects in existing wind farms, indirect impacts such as difficulties in securing insurance cover due to the inability to properly categorise and quantify risks for co-developed areas may exist.

5.4 Question 4: Is monitoring of seismicity necessary in offshore wind farms where CCS is taking place (beneath or near it)?

The seismic monitoring of isolated OWF, which cannot produce induced seismicity, seems to be non-needed. However, what happens if the OWF is situated close to a CCS?

Should CCS be monitored for seismicity due to injection activities? This topic was investigated through a literature review and an analysis of the current industrial practice with active projects to warrant a robust "state-of-practice" assessment.

The Castor example (Spain) showed that the seismic monitoring is a key issue during the initial injection phase. However, the seismic monitoring should not be restricted to the initial injection phase. Ideally, the seismic monitoring should be performed during the whole operation life of the facility even including a pre-operation recording phase for reference. The seismic information could provide very important data for seismic hazard assessment and for fluid mitigation paths analysis. As other projects showed, the seismic records are mainly produced where the fluid is migrating, mainly through faults or fractures in the soil.

The seismic monitoring of industrial facilities usually can have a double objective:

1) **Detection and location of earthquakes which occurred around the facility**. To do this, the installation of a **local seismic network** is needed, often composed by a set of seismograms (velocimeters). The local seismic network is useful to better characterize the site. The installation of a local seismic network is one of the typical recommendations to control induced seismicity. The main objective of a local seismic network is the precise location of induced (and natural) earthquakes (longitude, latitude and depth) and a precise estimation of the magnitude (preferable moment magnitude). The seismic stations of a local seismic network are installed usually around the site, but at some distance of the site. 6 to 8 seismic stations usually are used to install the seismic network.

2) **Recording of strong ground motion (Acceleration**). **accelerometers** are usually installed to record the acceleration of the ground at the site, during the occurrence of an earthquake. The recording of the strong motion is often associated to alert systems. If the ground motion exceeds a pre-defined acceleration thresholds associated to the seismic design levels (usually known as Operation Basis Earthquake, OBE, and Safety Shutdown Earthquake, SSE), actions are activated automatically. Typically, if the acceleration exceeds the OBE level, the facility remains operational, but checks are performed to ensure that the structures and components related with the Safety of the facility were not damaged by the shock. If the acceleration exceeds the SSE level (ultimate seismic design level of the facility), an automatic shutdown of the facility is applied.

For facilities, such as new nuclear power plant sites, the installation of a local seismic network in the surrounding of the site and the installation of at least one accelerometer inside the site is mandatory for the site characterization of new nuclear sites, according the International Atomic Energy Agency (IAEA) SSG-9 guidelines.

For other projects, such as geothermal projects, the installation of local seismic networks and accelerometers at the site are commonly recommended (i.e. SERIANEX project, in Basel, Switzerland, Hudson Ranch Geothermal Production Zone and North Brawley ORMAT geothermal Production Zone, in USA or Eden Project at Bodelva, in UK).

For large dams, it is a common practice, for many years, to install local seismic network . For example, in Nurek large dam (Tajikistan), a local seismic network was installed in 1955 by former Russian authorities and it was operating until 1985. In Itoiz dam (Spain), as explained in Chapter 4.4, a local seismic network was also installed. Additionally, to the local seismic network, the installation of accelerometers inside the dam, theoretically, should be done for all large dams to control the OBE and SSE acceleration threshold exceedance.

If possible, the local seismic network should be connected to the national seismic network. This is a usually recommended because the interconnection of both seismic networks (local and regional) enhances homogeneous magnitude and earthquake location determination. For local seismic network operated completely independently to the national seismic network, the magnitudes and locations given to the same earthquake will be probably different. Therefore, an agreement between the owner of the CCS and the institution in charge of the national seismic network would be always beneficial for the project.

The accelerometers installed inside the facilities (large dams, NPPs, oil facilities, etc.) usually are not connected with the national network and the recorded data are only managed by the owner of the facility.

In the case of offshore CSS, the installation of local seismic networks is always recommended and preferably should be implemented in agreement with the national seismic network, as explained previously. However, the installation of an offshore seismic network is not an easy procedure. It is also more expensive than for onshore sites. It is recommended to install dedicated seismic network of ocean bottom seismic stations (OBS) with good proximity and azimuthal coverage. This local seismic network should have a low detectability threshold and even the smallest earthquakes (or even lower magnitudes) should be detected and located with a low uncertainty.

We recommend the following:

- if large seismotectonic faults are situated inside or close to the CCS (i.e. Castor project), the installation of the local seismic network should be mandatory. The installation of a local seismic network can be done without problems even if the OWF already is built. Therefore, the installation of the local seismic network should be mandatory independently of the existence of the OWF.

- In absence of large seismotectonic faults and only small faults or fractures are detected by geophysical surveys, the installation of a local seismic network should be optional but recommended (it would be useful also to see how the CO_2 flows inside the reservoir) and always recommended, although not mandatory.

The local seismic network could provide to the CCS a way to control the induced seismicity using traffic light systems, the injection rates could be modelled to reduce the induced seismicity.

A specific local seismic network for OWF situated close (or overlapping) CCS doesn't seem to be needed. If the CCS have a local seismic network, the data can be shared.

As a summary, the installation of the local seismic network should be lead by the CCS project and not by the OWF project. Nevertheless, the seismic design of the OWF projects should consider the possible induced seismicity produced in the CCS.

The detailed description of a local seismic network and accelerometers is not the objective of this document, although the main characteristics of them can be found in the bibliography or can be requested to providers of seismic equipment. Nevertheless, a typical local seismic network is composed 6 to 8 seismic stations installed around the site. If it is possible the stations should cover all azimuths (360º) to allow a better location of the earthquakes.

5.5 Question 5: If "yes" for 4 - what would be the frequency that the monitoring should take place?

As we indicated previously, ideally and taking into account previous project experiences (as Castor project), the seismic monitoring of CCS should be performed permanently during the operation life of the infrastructure, mainly in case large seismogenic structures are situated inside or in the site vicinity area of the project. For an offshore wind farm this may be 20-30 years for the initial wind farm but for a CCS project this could be for many decades.

If the OWF is overlapping the CCS region (or the OWF is situated very close to the CCS), the seismic monitoring of the CCS could be used also for the OWF. There is no need to duplicate the local seismic network.

The induced seismicity produced by the CCS and recorded by a seismic monitoring could be used in different ways:

1) In the CCS, to analyse the flow paths of the CO_2, because the micro seismicity could indicate the zones where the fluid is moving. It could help to see possible leakages.

2) In the CCS, to install alarm systems that could be used to manage Traffic Light Systems and to mitigate the possible effects of induced seismicity.

3) In the CCS and OWF, to install alarm systems connected to the operation of the facility. It means, to define an action plan if the OBE or SSE seismic levels are exceeded.

6. Considerations

Based on the review of the current state of practice and lessons learn presented in this report, Fugro has developed a set of considerations to inform regulatory decisions and guide future overlapping CCS and OWF developments. These suggested recommendations are presented in the following sections and have a particular focus on the mitigating the risks related to induced seismicity associated with Carbon Capture Storage, which is the main risk identified.

The main risks for an existing CCS project due to the installation of a new OWF are mainly related with the problems that the OWF could produce (noise of turbines, distance between turbines) for future geophysical surveys needed by the CCS.

To summarize, the main recommendations are:

- **To develop a Geological site characterization and a 3D Geological model (recommended for CCS and also for OWF)**
- **To perform fluid injection modelling (highly recommended for CCS)**
- **To install a Seismic monitoring system (mandatory for CCS where seismotectonic faults are identified in the area of interest and recommended in other case). The monitoring should be installed from the very beginning (feasibility phase) and should be maintained during the site-characterization and operational phases.**
- **To implement a Traffic Light System (necessary for CCS)**

In the following sections a short description of these recommendations are presented. Moreover, the Appendix A and B provides a more detailed description of the 3D geological models and Traffic Light Systems.

The four recommendations above are related. For example, to develop a fluid injection model, we need a geological model. And to define a TLS, a local seismic network to record earthquakes is needed. However, in general we could consider that four recommendations should be followed, independently of the order.

We have to note that the development of a seismic hazard assessment and a seismic risk assessment (combining seismic hazard and vulnerability of buildings) should be considered as an additional recommendation which is mainly required when the induced seismicity predicted by geomechanical models (or recorded) is expected to be significant. It was the case in Castor project, Groningen projects or in SERIANEX project presented in Chapter 4.

Finally, we note that all these considerations depend on the current legislation in the country applicable. The scope is the North Sea, but there are several legal regimes (UK, Norway, and EU (DK, GER, NL, B, France).

6.1 Geological characterization and 3D Geological model

One of the keys for the development of such a project is the development of a 3D geological modelling relying on a comprehensive compilation/interpretation and integration of geological data. Standard practice for CCS projects involves the creation of a reservoir model that parameterizes the material conditions (e.g., permeability, porosity) and spatial extent of the reservoir. For mitigating geohazards and assessing the risk of induced seismicity the 3D model should extend from the base of the reservoir to the seabed. Structural features and geological units should be mapped in 3D space. This should be completed as a complementary effort to reservoir engineering team who are focused siting injection activities, estimating reservoir capacity, etc.

Induced seismicity is likely to occur on faults within the project area, so fault identification is a critical component of 3D model development. If faults are present in the project area additional fault characterization and then numerical modelling of injection scenarios should be completed. Broadly, this involves understanding the likelihood of fault activation under existing (ambient stress) and assessing the limiting earthquake magnitude that the fault could host (how large of an earthquake could the fault produce). With this information, different injection scenarios can be modelled (different injection sites and different injection rates) numerically to determine the impacts to the stress field in the reservoir and potential implications for fault activation.

Figure 6.1 shows a simplified flow chart that could be used to develop 3D geological models in CCS.

In general, the development of a complete and comprehensive 3D geological model is recommended for CCS projects and OWF. For OWF projects, the depth of the geological model is lower. A 3D geological model is a key part of the site characterization of CCS and OWF projects.

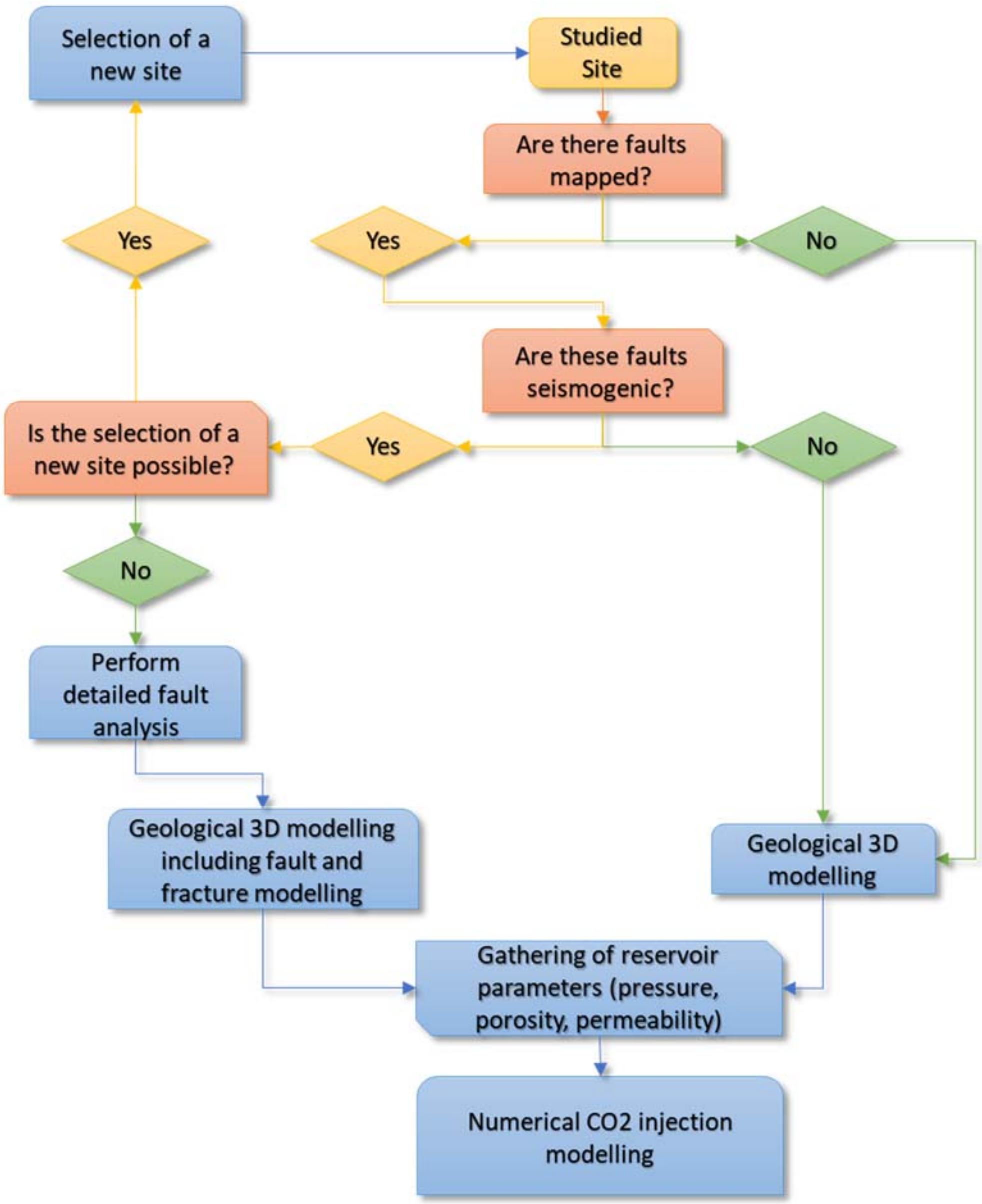

Figure 6.1 : Approach for site characterisation for CCS fault assessment

The development of a 3D geological model involves completing the following Tasks.

- Task 1: Data integration
- Task 2: Geological interpretation
- Task 3: 3D Model Building

These tasks are described in Appendix A.

6.2 Fluid Injection modelling

Numerical models that simulate the injection flow, the stress changes due to the injection and finally, to simulate induced seismicity in CCS have been recently developed. These models are recent, and they have been mainly used in research projects. For example, Verdon et al. (2015), developed an approach to simulate microseismic activity induced by injection, which allows to compare geomechanical model predictions with observed microseismic activity. Verdon et al. (2015) applied this method to the In Salah CCS project, Algeria. These simulation models have been used also in other CCS projects (i.e. CLEAN project in Germany, in the Altmark gas field).

These kinds of models have been used recently in 2 research projects in Netherlands:

- The KEM15 project is related to geothermal fields (conventional and enhanced) and the objective is to create synthetic earthquakes using these models that simulates the injection and the flow of water, the changes in stress and temperature and, finally, they are able to "predict" the induced seismicity that "probably" will occur during the injection and circulation phase of geothermal projects.
- The KEM24 project is related to Groningen field. During the extraction phase of gas, the Groningen field was depleted and suffered a significant reduction of pressure. One of the consequences of this reduction of pressure was a significant settlement (several tens of cm) and a significant induced seismicity. Now the extraction of gas is finished and the objective of the KEM24 project is to simulate or predict the induced seismicity that will probably occur in Groningen area under some hypothesis: injection of nitrogen with different rates and different number of wells and no injection at all.

In the case of Castor project, Juanes et al (2016) used also new models to simulate stress changes in the Castor area. They used a dynamic simulation strategy based on coupling flow and geomechanical models into one simulation framework. The model is capable to simulate stress changes and then, to predict the areas where the earthquakes will occur.

Juanes et al. (2016) pointed out the need for new standards (even if they are yet mainly used in research projects) to quantify the seismicity risks associated to underground operations, especially in areas where active faults are present.

To summarize, the use of an approach to simulate microseismic activity induced by injection fluids during the site characterization and the feasibility phase of the project is highly recommended in CCS projects. If the CCS project is planned to overlap an OWF, the simulated microseismicity should be considered in seismic design purposes of the OWF.

It means, if the OWF is built after the CCS project, a site-specific seismic hazard assessment taking into account the induced seismicity to define the response spectra of the OWF is recommended instead of using the standard response spectra defined in the EC8 or ISO guidelines, for example. The EC8 or ISO guidelines don't consider any kind of induced seismicity.

If the OWF is already built and a CCS is planned in the same region, a site-specific seismic hazard assessment is also recommended. Then, a structural analysis should be carried out to analyse if 1) the seismic margin of the existing seismic design (without induced seismicity considerations) is enough for ground motions considering induced seismicity or 2) some structures and components should be reinforced to resist these higher ground motions considering induced seismicity.

6.3 Seismic monitoring

According the literature reviewed (see Chapter 5.4), and the experience acquired in CCS and other similar projects, **Fugro recommends:**

- **in case large seismotectonic faults are observed within or close to the CCS (i.e. Castor project), the installation of the local seismic network should be mandatory, independently of the previous existence (or not) of an OWF.**
- **In the absence of large seismotectonic faults or if only small faults or fractures are detected with geophysical surveys, the installation of a local seismic network for CCS should be optional** but recommended (it would be useful also to see how the CO_2 flows inside the reservoir and for Traffic Light Systems), although not mandatory**.**

The local seismic network could provide to the CCS a way to control the induced seismicity using traffic light systems, the injection rates could be modelled to reduce the induced seismicity and to mitigate the seismic risk.

A local seismic network for OWF is not needed for isolated OWF. For OWF situated in the site vicinity of CCS, the local seismic network of the CCS can be used also for the OWF owners, avoiding duplication of efforts.

The detailed description of a local seismic network and accelerometers is not the objective of this document, although the main characteristics of them can be found in the bibliography or can be requested to providers of seismic equipment. Nevertheless, a typical local seismic network is composed of 6 to 8 seismic stations installed around the site. If it is possible the stations should cover all azimuths (360º) to allow a better location of the earthquakes.

6.4 Traffic light system

A traffic light system (TLS) is a seismic hazard management plan developed in the industry and government regulators for supporting decision-making process response to the occurrence of earthquakes associated with anthropogenic activities. The original concept of the system was intended to real-time monitoring and management of ground shaking due to induced earthquakes

TLS has been adopted on several geothermal projects (e.g., Diehl et al. 2017; Haering et al. 2008; Baisch and McMahon 2017), wastewater disposal and hydraulic-fracturing operations (Bosman et al. 2016; Wong et al. 2015; Alberta Energy Regulator 2015) where the upscaling of the latter activities in the United States and Canada has led to a significant increase of induced seismicity with earthquakes sometimes exceeding the level of magnitude M 5.0.

A TLS is based on a decision variable (induced earthquake magnitude, peak ground velocity, seismicity rate, injected volume, etc.) and a threshold value above which actions such as reducing flow rates, shutting down operation, or flowing back must be decided.

It must be noted that the TLS has never been implemented in CCS projects. Nevertheless, it has been implemented in many geothermal projects and also in UGS (Underground Gas Storage) which presents a lot of similitudes with a CCS project. Moreover, in the Juanes et al. (2016) report, the TLS was recommended as one of the actions to be implemented in case of continuation of the operations in Castor project.

According to the above, the implementation of a TLS in CCS projects is needed. If the CCS is planned in the same region than an OWF, the seismic risk increases, and the use of TLS is necessary.

A more complete description of TLS and its use is presented in Appendix B.

6.5 Seismic hazard assessment and seismic risk

A site-specific seismic hazard assessment is recommended and should be performed if induced seismicity is supposed to modify the natural or seismotectonic seismic hazard.

The results of the site-specific seismic hazard assessment should be used for seismic design purposes of new structures and components (for new OWF or CCS facilities).

In onshore sites, where the modification of the seismic hazard could affect existing buildings, a seismic risk analysis is recommended, as it was shown in Chapter 4 with part projects. However, in the offshore sites where CCS and OWF could be superposed, normally we don't find existing buildings or facilities except those directly related to the OWF and/or CCS. Therefore, in our case, the seismic risk analysis can be forgotten (except if the site is very close to populated areas on the coast, for example, as Castor project showed).

6.6 OWF planned above existing CCS versus CCS planed underneath OWF

In the previous sections we analysed the interactions between OWF and CCS and different questions were responded. However, 2 different settings are possible:

- **An OWF is planned above an existing CCS project**. In this case:
  - The main risk for the OWF could come from the possible induced seismicity produced by the CCS. The induced seismicity should be taken into account in the seismic design of the OWF. This would be the best mitigation mesueare for the future OWF.
  - The risk for the CCS is that the installation of the OWF can give some problems for future soil investigations that could be needed. The separation between turbines and the general design of the OWF should be agreed with the needs of the CCS and it would represent a recomended mitigation measure for the existing CCS. A dialogue between OWF and CCS stakeholders is needed.
- **A CCS project is planned underneath an existing OWF**. In this case:
  - The main risk for the CCS is that the current situation of the turbines and the noise that they produce could difficult the geophysical acquisition surveys needed to develop, for example, a detailed 3D geological model for the CCS. The technology

and new methodologies in geophysics could help to solve these kinds of problems and it would represent the best mitigation measure.

- The main risk for the OWF is that the CCS could produce induced seismicity in the future. And the OWF has not been designed against possible induced seismicity. The change of the seismic design of the turbines, foundations and anchorages in not possible (or it’s very difficult). The best solution to mitigate the risk is to monitor the induced seismicity and to control it using TLS. The CCS could also affect the chemical composition of soils and increase the corrosion of piles and anchorages of the turbines. These effects should be also monitored and controlled. Again, a dialogue and collaboration between OWF and CCS stakeholders is needed.

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Appendix A

3D geological model

The development of a 3D geological model involves completing the following Tasks.

Task 1: Data Integration

The aims of this task are to collect and analyse input data required for geological interpretation and 3D modelling. An objective of this analysis is to determine whether the existing datasets (typically legacy datasets from oil and gas exploration) are sufficient for building a robust 3D geological model.

Data required for developing a 3D geological model include:

- 2D and 3D geophysical datasets of the project area
- geological and geotechnical data from previous site studies
- boreholes data from reservoir studies (lithological and stratigraphic descriptions)
- bathymetric data or digital terrain models of the seabed

Task 2: Geological interpretation

Task 2 consists of the geological interpretation of 2D and 3D geophysical surveys (e.g., seismic reflection and refraction data) and mapping of seabed features. The seismic interpretation should utilise the geological information from borehole studies to calibrate key seismic horizons to ensure stratigraphic, and structural consistency across the project area. Seismic interpretation shall be performed using a suitable seismic and geological interpretation software (such as Kingdom suite, OpendTect, etc.) allowing the combination of seismic profiles, the integration of drilling data as well as the positioning of faults and other structural features.

The final interpreted product shall be an interpreted geophysical and geological database including (Figure A.1):

- key seismic reflectors calibrated to the site stratigraphy
- structural interpretation, including faults
- geomorphological map of the seafloor including any potential geohazard such as scarps of submarine landslide scars. and particular geological features (salt diapir, entrapped gas, gas seepage, etc.)
- identification of areas with deformed seismic horizons such as gas seepage locations
- uncertainty analysis or confidence assessment in the seismic interpretation

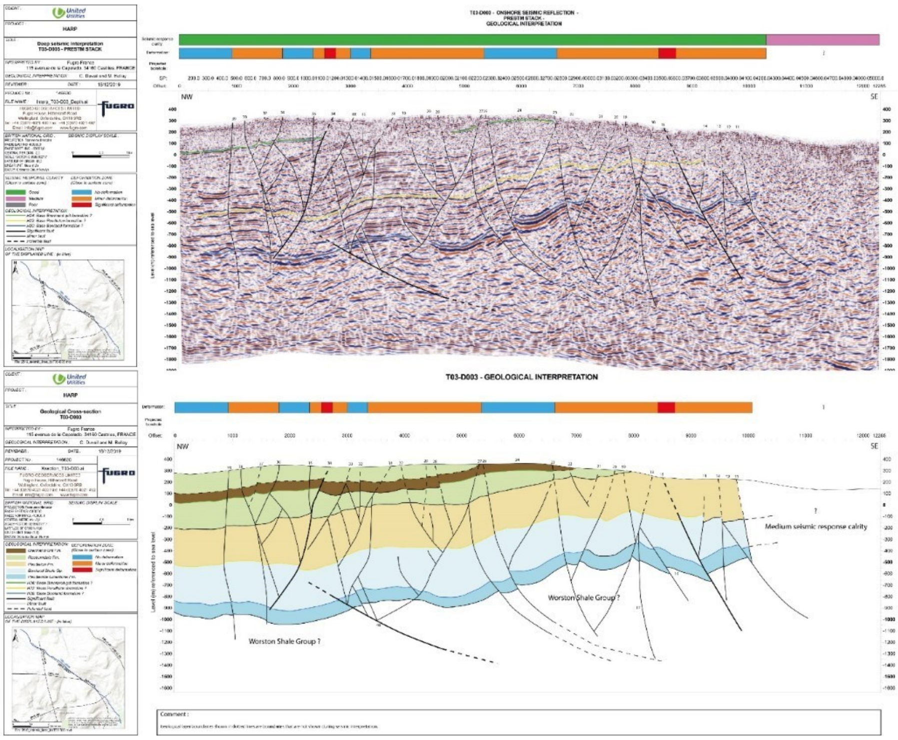

Figure A.1 : Example of an interpreted section

Task 3: 3D Model Building

The process of building a 3D model phase begins with the organisation and structuration of interpretations provided by geologists, geophysicists and geotechnicians.

This includes the updating or creation of a GIS structure containing the available elements and grouping the databases provided in spreadsheet form (Access, Excel). (Figure A.2).

Data from maps, boreholes, geological sections, 2D geophysical profiles, 3D geophysical blocks and geotechnical measurements are visualised in a common 3D space (Figure A.3).

The choice of the elements to modelled is essential, it depends on the lithological and structural context of the site. These shall be identified through the analysis of historical data during the early phases of the desktop study.

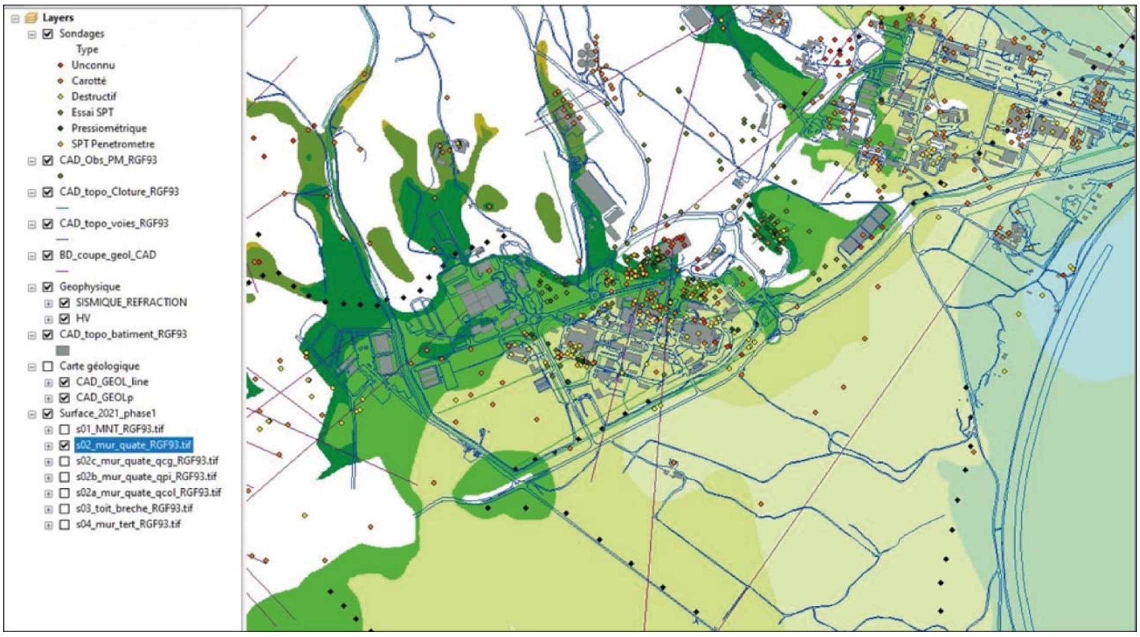

Figure A.2 : Organization and structuring in GIS of input data for 3D geological modeling

A preliminary interpolation of the surfaces shall be carried out by choosing the parameters that best feet to the density of information and to the nature of the geological surface (erosive, stratified). Models with faults are subdivided into blocks and each block is interpolated separately.

Detection of inconsistencies in the 3D geometries is an iterative procedure carried out by both modeller and geologist. This step is essential for ensuring the creation of a geological model that meets the needs and specification of the project.

The detection of geological inconsistencies is based on systematic control of the coherence between the nature of the surfaces, the characteristics of the formations and structural elements (unconformity, incised valley, fault movement) and the geometries resulting from the preliminary interpolation. Sources of inconsistencies are usually the following:

- the spatial positioning of the data;
- the interpretation of the data (drilling, geophysical profiles, geological mapping, geotechnical data). This step requires to step back to the input data (new and historical). The notion of data reliability is essential at this stage and can lead to the discarding of certain elements to increase confidence in the modelling.
- the lack of data in certain areas shall be systematically identified and recommendations shall be made for additional data acquisition. The absence of geometric constraints is often the cause of inconsistencies, fictitious data directly depending on the state of knowledge. The fictitious elements shall be clearly identified in the organisation of the input data so that they can be replaced by any additional investigation elements.

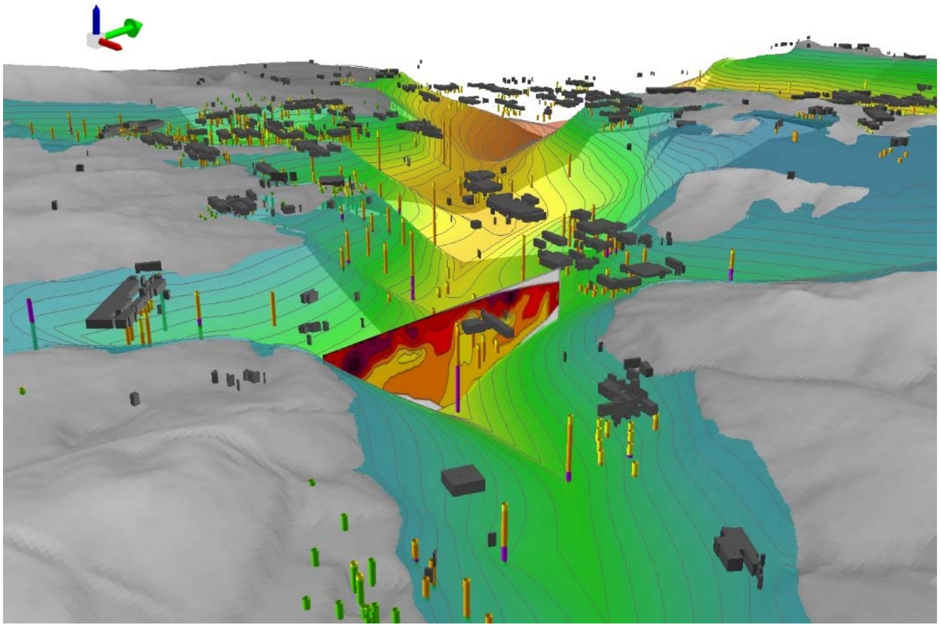

Figure A.3 : Analysis of input data for modeling in a 3D environment

Several back and forth between the input data and the interpolation of surfaces are required until the validation of the geometries based on the knowledge of the site (Figure A.4). The approach shall guarantee the reliability of the data and uncertainty on the 3D model obtained. The uncertainty shall be rendered in different forms according to the needs of the project (cartography, 2D sections, 3D volume).

The final objective of the modelling shall be the provision of a 3D geological model, adapted to the project's problematic and easily revisable. The accessibility and durability of the model shall be considered. For this reason the surfaces shall be delivered in a simple and durable format (GRID, ASCII, TXT files) and a free and easily downloadable viewer shall be provided with the modelled elements. The deliverables of the modelling phase shall include

- a GIS project integrating the interpreted input data with their metadata;
- each of the modelled surfaces in a simple and classic format in a homogeneous coordinate system validated by the other project actors;
- the complete model that can be viewed in 3D using dedicated software that is free and easy to access;
- a model construction report detailing the steps followed, the uncertainties identified and, if necessary, the additional investigations recommended to improve the reliability of the model.

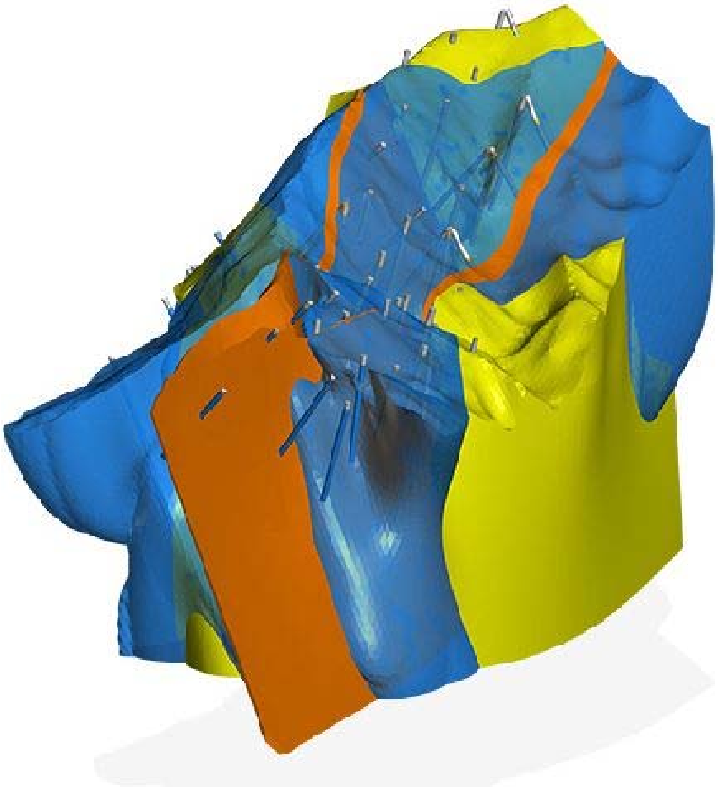

Figure A.4 : Example of a complex 3D geological model on a dedicated viewer.

Appendix B

Traffic Light System

The increasing energy demand around the world and the new underground projects is responsible for induced earthquakes as a result of the anthropogenic activities. The CCS projects are one example of these kinds of projects. Therefore, a proper protocol is necessary to reduce the potential damage and property losses by the induced earthquakes and to mitigate the associated risk by modifying the fluid injection profile. A traffic light system (TLS), also called traffic light protocol (TLP), is a seismic hazard management plan that the industry and government regulators develop for their decision-making processing response to the occurrence of earthquakes associated with anthropogenic activities (Ellsworth 2013; Bosman et al. 2016; Haering et al. 2008). The original concept of the system was intended for real-time monitoring and management of ground shaking due to induced earthquakes, which relies on continuous measurements of the ground motions (Wong et al. 2015).

For example, one of the first early implementation of the TLSs was made for limiting the strength of injection-induced earthquakes in the geothermal field at Berlin, El Salvador by Boomer et al. (2006). The TLS was developed for the project to ensure that the surface ground motions would present no hazard or nuisance to residents living near the geothermal field. The vulnerable nature of the local building stock also made this requirement necessary.

The TLS was based on a range of peak ground velocity (PGV) thresholds using information on human sensitivity to vibration caused by blasting and on vulnerability curves for structural damage expected for the local buildings (Boomer et al. 2006; Wong et al. 2015).

This approach has been adopted on several geothermal projects (e.g., Diehl et al. 2017; Haering et al. 2008; Baisch and McMahon 2017), wastewater disposal and hydraulic-fracturing operations (Bosman et al. 2016; Wong et al. 2015; Alberta Energy Regulator 2015) where the upscaling of the latter activities in the United States and Canada has led to a significant increase of induced seismicity with earthquakes sometimes exceeding the level of magnitude M 5.0.

A TLS is based on a decision variable (induced earthquake magnitude, peak ground velocity, seismicity rate, injected volume, etc.) and a threshold value above which actions such as reducing flow rates, shutting down operation, or flowing back must be taken. Currently, the definition of this threshold is based on expert judgment and regulations (Bommer et al. 2006; Bosman et al. 2016; Haering et al. 2008) and are typically assigned as “green”, where operations proceed as normal, “yellow” or “amber”, where operations proceed with caution, and “red”, where injection is stopped, although additional thresholds levels have been used (e.g. Haering et al. 2008).

TLS thresholds have varied significantly between different jurisdictions (e.g. Kendall et al. 2019): in the UK the red-light threshold was M 0.5 (Clarke et al. 2019), whereas in Fox Creek, Alberta, Canada it is M 4.0 (Kao et al. 2018). Within Alberta, Canada, the regulator has also imposed red-light thresholds of M 2.5 in the vicinity of the Brazeau Dam, and M 3.0 near the town of Red Deer. Other thresholds for hydraulic fracturing-induced seismicity (HF-IS) in

United States include Illinois; M 4.0, Oklahoma, M 3.5; California, M 2.7; and Ohio, M 1.0 (Verdon and Bommer 2020). Therefore, the traffic light system is adapted to the site-specific characteristics of each project.

In the traditional TLSs (Bommer et al. 2006), the thresholds are usually defined ad hoc and primarily based on expert judgement (e.g., Wiemer et al. 2017). This implementation hinders the objectivity of these tools and does not take into consideration the full range of possible scenarios and uncertainty of the process. However, an alternative to traditional TLSs are the so-called adaptive TLSs (ATLSs), which are still under development, but they already proved to be efficient at mitigating risk during some geothermal operations (e.g., Broccardo et al. 2017; Gischig et al. 2014; Mignan et al. 2017). In contrast with the first-generation systems such as those included in the regulations of different countries (such as Italy or UK), these second-generation systems are fully probabilistic, adaptive (in the sense that new data is integrated on the fly to update geo-mechanical and seismicity forecasting models) and risk-based, integrating hazard, exposure and vulnerability, but, they are model-dependent and require sufficient data to be implemented (Grigoli et al. 2017).

The TLSs listed in Table B-1 (Baisch et al. 2019) shows some examples of existing TLSs for limiting the strength of induced seismicity around the world. The variety of technologies where the TLSs are applied (enhanced geothermal system, geothermal production, gas production, hydraulic-fracturing, oil production, underground gas storage, wastewater disposal) proved the wide use and recognition of the governments and the energy industry. The traffic light systems have the advantage of being conceptually simple, easy to explain to non-expert stakeholders and the general public, and relatively immune to model-based assumptions or parametrization (Wong et al. 2015; Verdon and Bommer 2020).

We have to note that the TLS has never been implemented in CCS projects. Nevertheless, it has been implemented in UGS (Underground Gas Storage) which presents a lot of similitudes with a CCS project. Moreover, in the Juanes et al. (2016) report, the TLS was recommended as one of the actions to be done implemented in case of continuation of the operations in Castor project.

Therefore, the implementation of a TLS in CCS projects in recommended. If the CCS is planned in the same region than an OWF, the seismic risk increases and the use of TLS is highly recommended.

Table B-1: Examples of TLS (Source: Baisch et al. 2019.

Table 1
Examples of Existing Traffic Light System (TLS) for Limiting the Strength of Induced Seismicity

Location	Technology	References
Groningen, The Netherlands*,†	GP	Ministerie van Economische Zaken (2016) and Staatstoezicht op de Mijnen (SodM) (2016)
Bergermeer, The Netherlands‡	UGS	TAQA (2011)
Californië, The Netherlands*	GC	Broothaers and Wijnen (2014)
Norg, The Netherlands†,‡	UGS	Nederlandse Aardolie Maatschappij (NAM) (2017)
Landau, Germany*	EGS, GC	Baumgärtner *et al.* (2013)
Insheim, Germany*	EGS, GC	Baumgärtner *et al.* (2013)
Rittershoffen, France‡	EGS, GC	Maurer *et al.* (2015)
Basel, Switzerland*,†,‡	EGS	Häring *et al.* (2008)
Cavone, Italy*,‡	OP, WWD	Terlizzese (2016)
Minerbio, Italy*,‡	UGS	Terlizzese (2016)
Casaglia, Italy*,‡	GC	Terlizzese (2016)
Bowland shale, United Kingdom‡	HF	Department of Energy and Climate Change (DECC) (2013)
California, United States‡	WWD, HF	Bosman *et al.* (2016)
Illinois, United States‡	WWD, HF	Bosman *et al.* (2016)
Ohio, United States‡	WWD, HF	Bosman *et al.* (2016)
Oklahoma, United States‡	WWD, HF	Wong *et al.* (2015)
Newberry, United States‡	EGS	Wong *et al.* (2015)
Berlín, El Salvador‡	GC	Bommer *et al.* (2006)
Cooper Basin, Australia‡	EGS	Baisch and McMahon (2014)
Duvernay, Canada‡	HF	Alberta Energy Regulator (2015)
British Columbia, Canada‡	HF	Wong *et al.* (2015)

EGS, enhanced geothermal system; GC, geothermal production; GP, gas production; HF, hydraulic fracturing; PGA, peak ground acceleration; PGV, peak ground velocity; OP, oil production; UGS, underground gas storage; WWD, wastewater disposal.
*PGV- or PGA-based TLS.
†TLS based on other parameters.
‡Magnitude-based TLS.