Geological Analysis and Resource Assessment of selected Hydrocarbon systems

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ABSTRACT

In this report of the GARAH project we present a catalogue of potential alternative usages, synergies and competitions of a mature offshore area and associated infrastructure after closure. Recent case studies exemplify the different technological developments and address further research needs. Additionally, a catalogue of potential environmental hazards and risks accompanying the use of the subsurface has been compiled. The report is a joint task between WP2 and WP3 of the GARAH project and reports on the work related to Task 2E: Multiple/alternative use of HC reservoirs.

The catalogue groups the different alternative use objectives, CO_2 Storage, Energy Storage (Hydrogen Storage, Underground Natural Gas Storage and others), Geothermal Energy, Re-use of existing infrastructure and other area restrictions and subcategorizes these by their potential geological subsurface targets/reservoirs. We classified these different options according to the technological readiness level (TRL) classification scheme (Table 2-1). We use a case-based approach describing these technologies and focus on most recent developments and projects that are on-going or planned for the North Sea. Our examples employ the current scientific literature as well as project-based data and news reporting. We discuss the current roadmap and strategy situation, technological needs to achieve the current emission targets, time and spatial constraints as well as give a view on the public perception discussion by comparing the onshore versus offshore situation.

The second part of the report focusses on the identification and exemplatory description of hazards related to subsurface use, either through conventional hydrocarbon related activities or from alternative energy applications. A general overview of these hazards is given and a general discussion whether any of the new technologies require in a re-evaluation of the known risks and hazards. We followed a case based approach with examples of risks and hazards chosen from the scientific literature, published reports and datasets, and country-specific legislation. In Chapter 3.2 we also discuss hazards associated with gas hydrates and their impact on alternative sea floor uses. The presence of gas hydrates in marine sediments is a geohazard that has not yet been evaluated in the whole of the European continental margins. This study, analyses the geological hazard by means of the susceptibility assessment. The term ‘‘susceptibility’’ is employed here to define the likelihood of occurrence of hydrates in the sediment column, and subsequently the likelihood of them being affected by dissociation processes resulting from natural or human induced activities (liquefaction, explosions, collapse, crater-like depressions or submarine landslides).

Most of the technologies that are using the subsurface can benefit (financially or technologically) from synergies or re-use of infrastructure and knowledge from other technologies. At the same time, however, several of these technologies are also utilizing similar structures or subsurface environments, which will result in competing interests as well as potential additional hazards. In the third part of the report these potential synergies as well as competitions or competing interests are identified for the described technologies.

The summary of technologies that use the subsurface for energy generation and storage, as well as the list of associated hazards compiled in this report, can be used for planning policy-making (particularly for licensing of areas for exploration), and commercial exploration strategies by EU Member States.

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1 INTRODUCTION

The overall concept of the GARAH project is to collate independent geological analysess and consistent assessments of the conventional and unconventional hydrocarbon resources in Europe in two categories:

- Geological analysis and resource assessment of North Sea petroleum systems
- Hydrate assessment in the European continental margin

As well as examining the hydrocarbon resources of the European shelf and the North Sea, this GARAH report addresses alternative usages of existing exploration and production infrastructure and re-use within a mature hydrocarbon province. Offshore technologies for carbon capture, hydrogen and other energy storage, and even offshore geothermal energy, could contribute to achieve the greenhouse gas (GHG) reduction commitments of the North-Sea bordering states and the “net-zero” target for 2050. These alternative use aspects are discussed here with a catalogue of the multiple-use (or sequential-use) potential, in order to further enable the European community to understand the most efficient, sustainable, and climate-friendly use of the subsurface. The alternative use catalogue is complimented by a risk and geohazard catalogue associated with the use of the subsurface (existing and to come), as well as with the gas hydrate resources mapped and assessed as part of the GARAH project.

Although mapping the marine gas hydrate distribution along the European continental margin is ongoing (see GARAH Delivery Report 3.3 for the present status), an awareness for potential geohazards of marine gas hydrates remains critical, especially with the potential for destructive tsunamigenic events. In addition, as evidence mounts for sustained global warming, there is increased concern that widespread disintegration of marine gas hydrates may lead to excess methane emissions and enhanced global warming. It is well known that the gas hydrate stability zone is sensitive to relatively small pressure and temperature perturbations, potentially driven by sea level changes and increased bottom water temperatures. In the Arctic region these feedback mechanisms have already been observed. Similarily, marine gas hydrates along parts of the European continental shelf pose a long-term environmental hazard and climate risk.

2 ALTERNATIVE USAGE

2.1 Objectives

There are several technological options to repurpose the offshore infrastructure and subsurface knowledge previously utilised for oil and gas extraction. Here, we present a catalogue of alternative, multiple or sequential use technologies for subsequent sustainable and climate mitigating developments of oil and gas fields and associated infrastructure. We use a case-based approach and focus on most recent developments and projects that are on-going or planned for the North Sea, or, where not possible, comparable onshore geological settings. Our examples employ the current scientific literature as well as project-based data and news reporting.

2.2 Alternative use catalogue

The catalogue groups the different alternative use objectives (e.g. CO_2-storage) and subcategorizes these by their potential geological subsurface targets / reservoirs. We classified these different options according to the technological readiness level (TRL) scheme for the Horizon 2020 program (Table 2-1). Our TRL classification attempts to take the general applicability to the challenging shallow marine offshore environment and the state-of-art technological developments into account. Individual site-specific conditions and challenges, however, are not considered herein. For each of these usage options we discuss case studies and provide relevant GIS feature sets.

Table 2-1. Technology readiness levels (TRL) definitions used. From h2020-wp1415-annex-g-trl_en.pdf (europa.eu).

- TRL 1 – basic principles observed
- TRL 2 – technology concept formulated
- TRL 3 – experimental proof of concept
- TRL 4 – technology validated in lab
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7 – system prototype demonstration in operational environment
- TRL 8 – system complete and qualified
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Table 2-2 Alternative use catalogue for the North Sea subsurface.

Alternative use	Where	TRL	Cases/projects in North Sea	Related GIS features
CO_2 storage				
	Abandoned/ depleted HC reservoirs	TRL 6	Pilots planned, storage license awarded in NL	HC fields
	Saline Aquifers	TRL 8	Active storage sites and pilots planned (e.g. Sleipner). Licensing ongoing in NK, UK.	CO2Stop storage locations
	Temporal storage	TRL 1	No active projects	
	In combination with EOR	TRL 4-5	No active projects	HC fields
	As gas hydrates	TRL 1	No active projects, too shallow	Hydrate stability area
H_2 Storage				
	Abandoned/ depleted HC fields	TRL 1	No active projects	
	Saline Aquifers	TRL 2	Project defined	
	Salt caverns	TRL 5	None offshore.Test site UK onshore (Teeside)	Salt structures
Underground Natural Gas Storage				
	Abandoned/ depleted HC fields	TRL 9	Assessed for suitability in NL. Licenses agreed offshore UK, working example Rough Field offshore, closed 2017.	Hydrocarbon fields
	Salt caverns	TRL 6	None offshore. Working onshore worldwide and licensed onshore in Lancashire.	Salt structures
Other Energy storage				
	Compressed air – salt caverns	TRL 5	None offshore, UK examining it	Salt structures
	Mixed gas storage (H_2/CH_4 or CO_2)	TRL 5	Onshore France – mixed gas	Salt structures
Geothermal energy				
	Enhanced geothermal systems	TRL 4	None offshore	
	Regular geothermal systems	TRL 4	None offshore	
Reuse of facilities				
	Pipelines for $C0_2$ and Mix gas (CH_4/H_2) transport	TRL 8	Several cases and new plans for tests	Infrastructure, Pipelines
	Platforms as Injection sites in storage operations	TRL 6	Projects ongoing – Greensand in Dk	Infrastructure
	Platform parts as artificial reefs	TRL 9	“Rigs-to-Reefs” In the North Sea	Infrastructure

Alternative use	Where	TRL	Cases/projects in North Sea	Related GIS features
	Platform as foundation for wind farms	TRL 4	No projects identified in North Sea	Infrastructure
Other surface area restrictions – Energy related				
	Wind parks	TRL 9	Multiple active projects	Wind parks license areas
	Energi islands	TRL 2	Projects in UK (Dogger Bank 130 km offshore UK) and Dk (80 km offshore Jutland)	

2.3 Case studies

2.3.1 *CO_2 Storage*

Carbon Capture Storage (CCS) and with the option to utilize CO_2 (CCUS) is recognised as a key negative emissions technique in achieving the 2050 net-zero emission goals of the EU-COM and world-wide. The North Sea subsurface has ample potential for storage of CO_2 (Figure 2-1 and 2-2), making it relevant not only to store negative emissions from neighbouring countries, but also to act as a storage hub for the whole European community. The development of large-scale CO_2 storage facilities in the countries bordering the North Sea is well underway (see, for example, IOGP, 2019). By planning for large-scale CCS and repurposing existing oil and gas infrastructure, the unit costs of transportation and storage are more likely to be competitive.

Norway

Norway is world leader in developing commercial offshore CCS projects. CCS facilities are already operating at the Sleipner Field (since 1996) and Snøhvit field (since 2008) in the North Sea and the arctic Barents Sea, respectively. The Norwegian Petroleum Directorate (NPD) publishes extensively on the vast potential for CCS, including an atlas of CO_2 storage in the Norwegian North Sea (Halland et al., 2013) and is involved in various cross-border projects such as CO_2Stop (https://ec.europa.eu/energy/studies_main/final_studiesassessment-co2-storage-potential-europe-co2stop_en).

In the North Sea, CO_2 injection into the saline Utsira Sandstone of the Sleipner Field has occurred at a rate of up to one million tonnes per year since 1996. The CO_2 comes from and is removed from the natural gas stream produced from deeper stratigraphic reservoirs from the Sleipner Field. The nearby Gudrun and Utgard fields were connected to the Sleipner facility in 2014 and 2019, with associated CO_2 being seperated and injected into the Utsira. Monitoring of the Sleipner CCS-project has been ongoing since its inception in 1996 using a variety of techniques from direct well measurements to 4D seismic, as summarised in Furre et al., (2017). World-wide this resembles a unique monitoring data-set of CO_2-injection and storage. The data from the Sleipner project is publicly available through the CO_2 DataShare portal (https://co2datashare.org/dataset).

Northern Lights is a key European joint venture project to demonstrate upscaling of CCS operations in the North Sea. Situated on the Norwegian Shelf, recently in 2020, the first exploration well has been drilled here. The Northern Lights facility will permantly store CO_2 captured from onshore industrial plants in the Lower Jurassic Johansen Formation near to the Troll field (https://northernlightsccs.com/).

Denmark

CCS is part of the Danish government's climate mitigation action plan to reach its CO_2 emission reduction targets. The Danish potential for CO_2 and energy storage has been mapped out be GEUS and assessed to exceed a capacity 22 Gt CO_2. (Hjelm et al. 2020, see Figure 2-1). Currently efforts are being made to examine several CO_2 storage options in detail, both on and offshore and within depleted oil fields.

A recent road map from the Danish state innovation fund outlined the perspectives specifically on four different storage options:

1. offshore storage in hydrocarbon depleted sandstone fields,
2. offshore storage in hydrocarbon depleted chalk fields,
3. offshore storage in saline aquifers,
4. near-shore and onshore storage in saline aquifers, such as existing gas storage sites.

(https://innovationsfonden.dk/sites/default/files/2021-08/Appendix%202%20_%201112-00004A%20-%20Mission%20CCUS%20%E2%80%93%20a%20roadmap%20for%20Carbon%20Capture%2C%20Utilisation%20and%20Storage.pdf)

Each option has its individual maturation timeframe and advantages. Offshore storage in depleted oil and gas reservoirs builds on decades of technology development. Furthermore, infrastructure is in place, whereby the surface is connected to the subsurface. By taking advantage of the high initial Technology Readiness Level (TRL>2), existing infrastructure and reservoir knowledge, this option provides a fast path to CO_2 storage in Denmark. Offshore storage in depleted chalk fields has today a lower TRL level than sandstone reservoirs, but chalk is ubiquitous in the Danish underground and this type of reservoir could be developed based on our current knowledge of the reservoir as outlines by Bech and Frykman (2003) and more recently by Bonto et al. (2021). Offshore storage in saline aquifers provides a very large storage potential of several Gt CO_2 (Figure 2-1). The location of CO_2 storage sites near-shore or on land will aid integration with Power-to-X and other utilities and could thus provide the most optimal storage option in the long term.

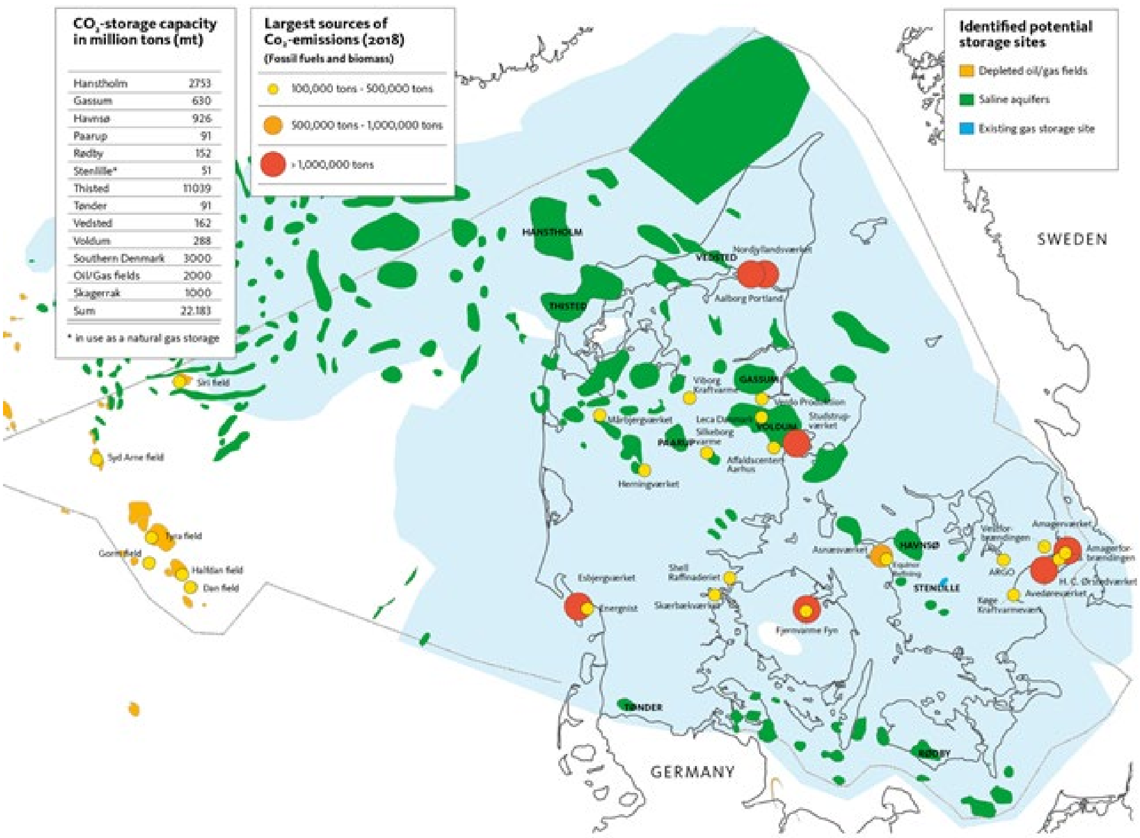

Figure 2-1 Mapped potential CO_2-storage sites in Denmark and Southern Norway. Modified from Hjelm et al. (2020).

Case studies of Danish projects aiming to store CO_2 in depleted oil fields include the Project Greensand (https://projectgreensand.com/) and the Bifrost project ([TotalEnergies og DUC indgår partnerskab for CO2-transport og lagring | TotalEnergies in Denmark]). The Greensand project will repurpose the depleted Nini West oil field and the Bifrost project will convert the depleted Harald Field into storage sites. The topside facilities are planned to be reused. which otherwise would have to be decommissioned within a foreseeale furture . Transport of CO_2 by vessel is envisioned in project Greensand as the Nini Field is not connected to pipelines; the Bifrost project will investigate the possibility to reuse all or parts of the infrastructure that the Harald field is connected to. is connected to.

Netherlands

CO_2 underground storage is part of the strategy to achieve a CO_2 neutral industry in the Netherlands. Several research projects have focused on the development of the essential technology and infrastructure to implement large-scale CCUS in the Netherlands (e.g., CATO and CATO-2, 2004 - 2008 and 2010 – 2014, https://www.co2-cato.org/).

Currently, several national and international follow-up studies are focused on specific issues faced by the industry and providing support for a rapid and cost-effective implementation of the technology. The recently completed national and EU-funded ALIGN-CCUS project (https://www.alignccus.eu/) investigated multiple aspects needed for a successful implementation of the technology like the capture, transport and storage of CO_2 but also societal issues, re-use of infrastructure and economic considerations. Six industrial regions in five different European countries were selected as case studies, including the Port of Rotterdam in the Netherlands, with the aim to store captured CO_2 in a depleted gas field in the Dutch offshore area of the North Sea, as well as re-use existing oil and gas infrastructure.

The Porthos project (https://www.porthosco2.nl/en/) is the current follow-up project aimed at the actual implementation of the technology in the Port of Rotterdam area. The main focus of this project is on the technical development of the transport and storage infrastructure, the assessment of the environmental impact and necessary permits and to set up agreements with CO_2 suppliers and the Dutch Government. The storage license for the P18-4 was granted in 2013, others are currently reviewed (www.nlog.nl).

In the Netherlands CO_2 storage is currently only considered in depleted hydrocarbon fields. Earlier studies have also assessed the storage potential of saline formations, based on their extent, thickness, average porosity and compartmentalization (Kramers et al. 2007 and Neele et al. 2012, see summary in Wildenborg and Loeve, 2020). However, the development of these formations is less advanced and mostly hampered by the presence of still actively producing oil and gas fields in the same formations.

Germany

In the context of the “Geopotenzial Deutsche Nordsee” project (GPDN - https://www.gpdn.de – in German), potential stratigraphic storage intervals in the German North Sea area were mapped. The storage potential for CO_2 within these intervals were assessed in a case study area in the southern central North Sea sector (see https://www.gpdn.de/media/1450 - in German).

UK

The United Kingdom has been assessing the potential for carbon capture and storage on-and-offshore since the early 2000s, and announced its intention to deploy working CCS in the UK (with international collaboration) at scale in its 2017 Clean Growth Strategy (BEIS, 2017). UK government, academic, and research institutions are active in a number of projects relating to CO_2 storage potential in the North Sea and beyond, including CO_2Stop, the UK Carbon Capture and Storage Research Centre (UKCCSRC) and the Scottish Carbon Capture and Storage partnership (SCCS). Most recently, the CO_2Stored project has identified potential for greater than 70 billion tonnes of carbon storage offshore the UK (http://www.co2stored.co.uk/), in both saline aquifers and in depleted fields. The BGS is also a partner in the AlignCCUS project (https://www.alignccus.eu/)., and in the EU-funded CO2GeoNEt (http://www.co2geonet.com/home/).

Licensing and regulation of offshore CO_2 storage is controlled in the UK by the Oil and Gas Authority (OGA), except where in the territorial waters of Scotland, where the Scottish government oversees licensing processes. As of October 2021, the OGA has granted 3 licences for CO_2 appraisal and storage, and one license transfer. Of these, the Pale Blue Dot Energy-Acorn CCS Project, Harbour Energy-V Net Zero project, and National Grid/BP/Equinor – Northern Endurance Partnership are within the GARAH AOI in the North Sea, as shown in Figure 2--2.

On the 19th of October, 2021, as part of its net zero strategy, the UK government announced that the East Coast Cluster project, located in the Humber/Teeside area, will form one of two carbon storage clusters with CO_2 to be extracted from onshore industry and stored in depleted oil and gas fields offshore as part of the Northern Endurance project. The Acorn project is designated a ‘reserve cluster’ if the initial projects are discontinued.

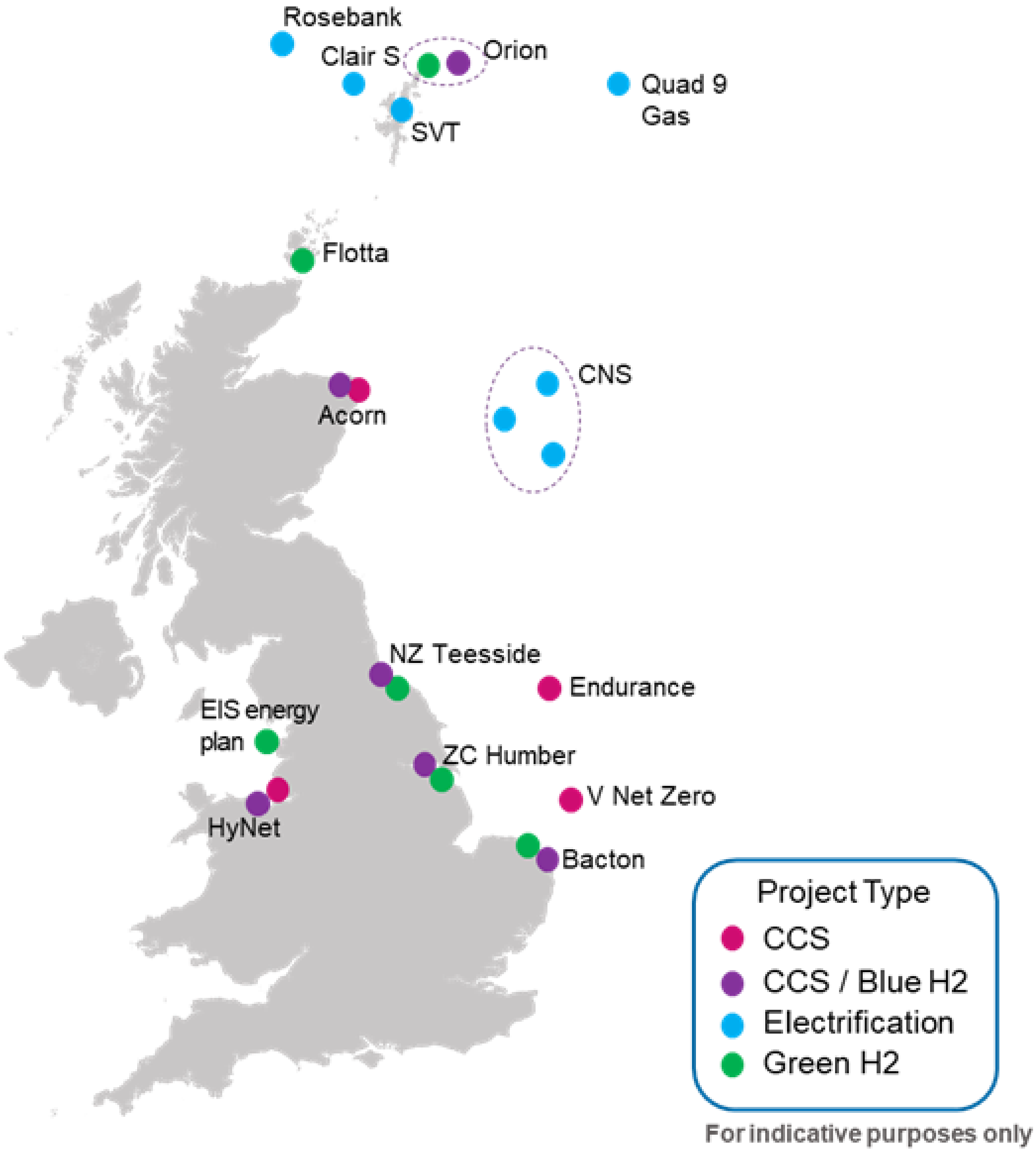

Figure 2-2 Location of CCS projects (in pink) licensed by the OGA. Figure from https://www.ogauthority.co.uk/the-move-to-net-zero/carbon-capture-and-storage/ accesssed on the 22nd October 2021.

CO_2 storage in combination with EOR

In Denmark no current project plans to store CO_2 as agent for enhanced oil recovery (EOR), although the feasibility for this use has been recently summarised by Bonton et al. (2021). Olsen (2011) reports that in Danish chalk the Tor Formation chalk produced 70% original oil in place (OOIP) during the water-flooding and an additional 23% OOIP during the CO_2-flooding. In contrast, Ekofisk chalk produced 41% OOIP during the water-flooding and additionally 52% OOIP during the CO_2-flooding, suggesting EOR techniques, if deployed, may significantly increase recovery and also store CO_2. In other parts of the world the technology is already proven and in use in various settings, with most of the active projects located onshore in the US (Novak-Mavar et al., 2021).

Trapping of CO_2 in subsurface (onshore, offshore and deep offshore cases) as mixed gas hydrates

Deep saline aquifers are the most important potential geological reservoirs for CO_2 storage under supercritical conditions (i.e. a pressure higher than 7.4 MPa and a temperature higher than 31 °C). Because the density of supercritical CO_2 is lower than that of pore water (both seawater and brine), the storage efficiency depends on the sealing capacity of the overlying tight formations (the so-called “cap rock”) with respect to a non-aqueous buoyant fluid (CO_2 and associated impurities). Another storage option (the so-called “deep offshore” option) is the trapping of CO_2 in deep sea sediments at lower temperature and higher pressure than the standard options, the onshore and offshore geological storage options. In those conditions, CO_2 may be liquid and denser than seawater. In that case, the injected liquid CO_2 may be gravitationally trapped in the deep sea sediments, either in the liquid state or in the solid state as gas hydrates. This deep offshore option is currently much less investigated in the literature, even though it may offer certain advantages in terms of capacity and long-term containment of CO_2 and associated impurities as shown in the case of the French and Spanish Exclusive Economic Zones (see GARAH Delivery Report D3.3 Chapter 5).

*2.3.2 **Hydrogen Storage***

The EUCOM and several EU member states have set forth national hydrogen strategies on the path to net-zero emissions. Hydrogen is regarded as key renewable fuel in the future with a multitude of applications. Hydrogen storage could prove to be a key technology to ensure future electric grid stability (e.g. McPherson et al., 2018). Reliable hydrogen-storage facilities are essential for this energy transition and in the long term to replace natural gas storage.

Current research is mostly focused on advancing technologies for the generation of green hydrogen (H_2 generated from renewable energy only), with a potential transition from blue hydrogen (H_2 generation from fossil fuels, integrated with CCS), highlighting the need for integrated subsurface concepts and regulations (see also https://www.iea.org/reports/hydrogen).

In the offshore North Sea area, research is currently identifying hydrogen storage capacities in depleted gas fields and salt caverns, with storage in salt caverns already being a proven technology in the onshore and near offshore and storage in depleted gas fields curreny in the pilot phase (e.g., Austria https://www.underground-sun-storage.at/). Storage of H_2 in saline aquifers has so far only been discussed on a conceptual basis (Heinemann et al. 2021). An overview report from Guidehouse Inc. for Gas Infrastructure Europe (GIE) was published this year giving assessments for expected European H_2 demand and respective infrastructure requirements (https://www.gie.eu/wp-content/uploads/filr/3517/Picturing%20the%20value%20of%20gas%20storage%20to%20the%20European%20hydrogen%20system_FINAL_140621.pdf).

Denmark

H_2 storage in salt caverns has been practiced since the 1970s in Europe but has not yet been carried out in depleted hydrocarbon fields or aquifers. Technical developments are needed to validate these two H_2 storage options. In Denmark GEUS is involved in the EU co-funded Horizon 2020 project "Hydrogen Storage In European Subsurface" (HyStorIES).

HyStorIES will provide developments applicable to a wide range of possible future H_2 storage sites by:

- The addition of H_2-storage relevant characteristics in reservoir databases at European scale.
- Reservoir and geochemical modelling for cases representative of European subsurface, and tests of this representativeness by comparing it with results obtained from real storage sites models.
- An extensive sampling and microbiological laboratory experiment programme to cover the variety of possible storage conditions.

The HyStorIES project will also provide insights on underground hydrogen storage for decision makers in government and industry by modelling of the European energy system by: defining the demand for H_2 storage; developing techno-economic feasibility studies for future H_2 storage options in depleted HC fields or saline aquifers; developing high-level cost estimates for development of geological storage options within a given area; ranking sites based on techno-economic criteria developed within the project; and by providing environmental and societal impact studies. Several case studies will enable consideration with respect to the implementation of potential H_2 storage projects, particularly by considering their economic interest. This results are planned toprovide substantial insight into the suitability for implementing hydrogen storage across EU and enable the proposition to an implementation plan. The HyStorIES project was initiated January 2021 and is expected to be finalised by the end of 2022.

Onshore Denmark, the project Green Hydrogen Hub Denmark plans to establish one of the World's largest green hydrogen production plants in combination with an underground hydrogen storage in a salt deposit in the area between Hobro and Viborg. The ambition is to establish a complete Power-to-X (PtX) value chain by 2025 comprising of an electrolysis plant, a subsurface hydrogen storage and a Compressed-Air-Energy-Storage (CAES), involving several industrial hydrogen consumers. The current consortium has applied to the European Innovation Fund 2020 call for funding of the primary development aspects. [New, large-scale hydrogen hub to support Denmark's green transition | Energinet]

France

There is up to now no industrial site of hydrogen underground storage in France, however there are two ongoing demonstration projects:

Etrez gas storage of Storengy (subsidiary of Engie): Installed in the town of Etrez for more than 40 years, it is one of the first underground gas storage in salt cavities in Europe. The capacity of the cavity is of the order of 300,000 m^3. It has 25 cavities in a layer of salt 650 meters thick at a depth varying from 1,250 to 1,900 m. In 2010, this capacity was close to one billion cubic meters of natural gas. Since mid-2010, work has been carried out for the rehabilitation and renovation of the Etrez site. The project is to carry out a first French pilot of hydrogen underground storage in a small cavity (previously filled by brine).

Caresse gas storage of HDF (Hydrogène de France): These salt cavities in the south-west of France (previously owned by Total) were in 1966 the first gas storage site in France. They were recently abandoned and the project of HDF is to re-use these cavities for green hydrogen storage.

Netherlands

In the Netherlands, H_2 has been identified as one of the key players in the energy transition, including the use of longer-term energy storage option as well as though the generation of blue hydrogen (Dutch Climate Agreement, 2019). Funding and research at the moment is mostly directed towards hydrogen generation technologies, but several projects have started to identify possible storage locations for H_2, mainly in salt caverns in the onshore. In 2019 Juez-Larré et al. published a first assessment of underground storage potential, focussing on natural gas, hydrogen and compressed air storage capacity in the on and offshore (Juez-Larré et al. 2019)

Hystock (https://www.hystock.nl/ - in Dutch)

Onshore salt cavern temporary storage project, a project of the Dutch national gas infrastructure and transportation company Gasunie at the location Zuidwendig, which is also the operator of the natural gas storage site at the same location. The aim is to enlarge the current setup by another 4 caverns that will be used for H_2 storage as well as the re-use of one existing natural gas storage cavern for H_2. Currently first tests are being performed on the influence of H_2 on the infrastructure, the materials and the salt cavern.

Hy3 (https://hy3.eu/)
Collaboration between FZ Jülich, TNO and DENA, focussing on three main fields of research: Hydrogen demand, Hydrogen Transport & Storage and Hydrogen production from Offshore Wind. The cross-border project started early 2020 and is funded by the Dutch and German government.

NortH2 (https://www.north2.eu/en/)
Consortium of Energy companies in the Netherlands in collaboration with Germany to further the generation, storage and transport of H_2 and to prepare the infrastructure for targeted delivery to industry and heavy transport and later for domestic use. At the time of reporting no potential storage sites have been announced.

Blue hydrogen initiatives – H_2 generation and subsurface storage of CO_2
(e.g., Porthos: https://www.porthosco2.nl/en/, H2Gateway: https://portofdenhelder.nl/files/documents/Poort%20naar%20een%20CO2-vrije%20waterstofeconomie%20-%20H2%20Gateway.pdf and Athos: https://athosccus.nl/project-en/)
Several projects in the Netherlands aim at the use of blue hydrogen, H_2 generation from fossil fuels combined with CO_2 storage in the offshore area. In all of these cases the subsurface use is limited to the storage of CO_2. The most notable projects include the Porthos project of the Port of Rotterdam and the H2Gateway project of the Port of Den Helder, several municipalities as well as energy companies. The Athos project, a collaboration between TATA steel and the Port of Amsterdam has recently been stopped due to TATA steel anouncing their switch to the direct reduced iron technology (DRI), circumventing the generation of CO_2 and therefore eliminating the need for CCS (https://www.tatasteeleurope.com/corporate/news/tata-steel-opts-for-hydrogen-route-at-its-ijmuiden-steelworks).

Germany
In its "National Hydrogen Strategy", the German government formulates comprehensive goals for the energy transition including H_2. In terms of future energy supply security underground storage of hydrogen is regarded as one option. Germany already has extensive experience with on-shore underground natural gas storage, which can support overcoming the technological and geological subsurface challenges in developing a subsurface H_2-storage infrastructure. In general, there are two main underground storage options for H_2: (1) porous media such as aquifers or depleted gas reservoirs and (2)

underground caverns in salt or rock. The current situation for Germany is described in Warnecke and Röhling (2021).

UK

Natural gas has been stored succesfully onshore in both natural and engineered salt caverns in the UK since the 1950's; the associated technology is well-established. Hydrogen (and other gasses) has also been stored onshore in the UK since 1965 at the Sabic-operated facility in Teeside, which reports a million cubic metres of stored H_2 in three salt caverns at a depth of 350 to 390 m below surface (Panfilov, 2016).

The UK was invovled in the ESTMAP project, running from 2015 to 2016, with a total of 18 onshore storage caverns defined, largely in Permian and Triassic halite. More recently, the government and the Oil and Gas Authority have identified H_2 production and storage as a critical part of the energy transition (OGA, 2021); of most relevance to the GARAH project is the potential for offshore green hydrogen production and storage (see, for example, https://www.ogauthority.co.uk/media/6059/hydrogen-ppt-final.pdf).

The Hydrogen East project was formed in 2020 to assess new hydrogen markets in the east of England, with the OGA providing further funding in December 2020 to analyse potential demand. The Bacton area project includes the potential to reuse offshore oil and gas infrastructure for the production/transportation of green and blue hydrogen, and for H_2 storage, as well as associated CO_2 storage (see https://hydrogeneast.uk/bacton-energy-hub/).

The BGS is a third party in the Hystories Project, which began in 2021 (see description under Denmark above).

2.3.3 ***Underground natural gas storage***

Natural gas storage is a well developed technology using either depleted gas fields, salinie aquifers or salt caverns. In most cases these storage locations are located onshore or near-onshore with onshore surface facilities. This type of seasonal or even shorter tem storage usually requires a direct link with the transport grid, making offshore storage locations less relevant. A daily overview of all European natural gas storage volumes can be found on the website of the GIE (https://agsi.gie.eu/#/).

Germany

Germany onshore natural gas storage capacity ranks fourth largest in the world. Storage is realized in several depleted hydrocarbon fields that are re-used for natural gas storage as well as in salt caverns (https://erdgasspeicher.de/, Annual report on Crude Oil and Natural Gas in Germany 2020, LBEG - https://www.lbeg.niedersachsen.de/download/169420/Erdoel_und_Erdgas_in_der_Bundesrepublik_Deutschland_2020.pdf).

Netherlands

Multiple facilities in depleted gas fields already exist onshore, however, offshore, there are no natural gas storage facilites in operation or planned. The first active onshore storage locations in depleted natural gas are located in depleted natural gas fields Norg and Grijpskerk, that were put into operation in 1997. As of now there are five storage facilities for natural gas currently active in the Netherlands, 4 in depleted gas fields and 1 in salt caverns (www.nlog.nl).

UK

The UK has multiple sites for onshore natural gas storage (in salt caverns and porous media) but none as yet in the offshore. Planning is underway for a proposed gas storage site which extends to the nearshore in salt caverns in County Antrim, Northern Ireland (see https://www.islandmageeenergy.com/). Any offshore gas storage is regulated and licensed by the Oil and Gas Authority (OGA).

Denmark

In Denmark both saline aquifer (the Triassic Gassum Formation) and salt caverns are used as temporal storage of natural gas. No offshore sites are in use.

2.3.4 Other Energy Storage

In addition to the previously mentioned storage technologies, other types of energy storage could be of interest for the offshore North Sea area, most notably Compressed Air Energy Storage (CAES).

CAES uses electricity during off-peak times to compress air and store it either in underground caverns or in storage tanks. During high energy demand times, the compressed air is released to a combuster in a gas turbine to generate electricity.

A recent EU project published an updated compilation of developed and future potential storage capacity and facilities focused on Underground Natural Gas Storage (UGS), Hydrogen Storage, Compressed Air Energy Storage (CAES), Underground Thermal Energy Storage and Pumped Hydro Storage (PHS) (https://www.estmap.eu/home.html). The result of the data collection shows that CAES in Europe is currently very underrepresented with just 4 sites. The majority of the energy storage in Europe consists of UGS and PHS.

As a transition technology, mixed gas storage is a working concept, combining natural gas and hydrogen (usually in a 90/10 ratio) to achieve a better energy output and lower CO_2 emissions. The French onshore storage facility in Beyne is an example of this technology.

Netherlands

A general assessment of the underground energy storage potential including CAES for the Netherlands was published in 2019 (Juez-Larré et al. 2019). Also in the context of the LSES project (Large-Scale Energy Storage in Salt Cavern and Depleted fields, Final report 2020 - http://publications.tno.nl/publication/34637700/8sBxDu/TNO-2020-R12006.pdf) the possibilities of CAES in the Netherlands, potential business cases as well as a risk catalogue for the technology was developed.

Germany

One of the two commercial CAES systems in operation is located in Huntorf, Germany. The facility was commissioned in 1978 and has a capacity of 321 MW from two salt caverns (https://www.uniper.energy/de/kraftwerk-wilhelmshaven).

UK

No working subsurface CAES systems are in operation in the UK, although a number of schemes are proposed as summarised in King et al., (2021). The potential for CAES in halite deposits in the UK was recently reviewed by Evans et al., (2021), with total UK storage capacity calcualted ot exceed UK electricity demand of ~300 TWh as part of the UK Engineering and Physical Sciences (EPSRC) research council IMAGES (Integrated, Market-fit and Affordable Grid-scale Energy Storage) project.

*2.3.5 **Geothermal energy***

Geothermal energy uses the inherent heat from the subsurface for heating or power generating purposes. The source can be either water produced from a saline aquifer or water pumped into the hot substrate and reproduced. The potential use for geothermal energy is highly dependent on the type of substrate, the permeability and the temperature and can be subdivided into electricity production (T > 150 °C), direct use (T between 50 - 150 °C) and heating and cooling (T between 5 - 30 °C, using heat pumps). Direct use as well as heating and cooling are closely dependent on the availability of a market and a transport grid that, both usually are absent in the offshore. Furthermore, using Enhanced Geothermal Systems (EGS) off-shore might be geotechnical option. In the UK and Norwegian HPHT province, for instance, the required temperatures for EGS are achieved and existing infrastructure could be used (Lockett, 2018 -

https://www.offshore-mag.com/pipelines/article/16762144/geothermal-power-an-alternate-role-for-redundant-north-sea-platforms).

2.3.6 Repurposing of facilities

Oil and gas production offshore facilities (platforms, pipes, wells and other infrastructure) represent a massive investment that, if re-used in connection with the green transition and alternative use of the North Sea, may provide net-zero activities with a head-start. The topic has therefore attracted considerable interest and has also been a topic for a recently held (in 2019) Consultation that the UK government held (Carbon capture, usage and storage (CCUS) projects: re-use of oil and gas assets - GOV.UK (www.gov.uk)). The outcome of this study was a comprehensive list of projects and studies around the North Sea. Below we present an update on the most recent plans for re-use to compliment the Consultation list.

Denmark

Decommissions of the Danish infrastructure has not yet been initiated but as several fields are near depleted this is expected to be commenced soon. One example of plans of postponing abandonment and to re-use the infrastructure is the Project Greensands plans to re-use the top facility in the Nini West field as an CO_2 Injector site for its proposed Nini West Storage Site (https://projectgreensand.com/). A study to investigate the possible re-use of the pipe-line infrastructure as CO_2 export to depleted North Sea hydrcarbon fields has just recently been announced in connection with Bifrost project that seeks to converts the Harald depleted oil field operated by TotalEnergies into a CO_2 storage site.

Germany

In Germany, Wintershall Dea has recently anounceded a project togther with the OTH Regensburg University of Applied Sciences on how existing natural gas pipelines in the southern North Sea can be used for future CO2 transport (Wintershall, university to study North Sea pipelines for CO2 | Oil & Gas Journal (ogj.com)). According to the press release, technical feasibility will be tested, and certification will follow.

Netherlands

In the Netherlands several projects are looking into possibilities to re-use the existing infrastructure as hubs for wind energy or as locations for the generation of green hydrogen (https://poshydon.com/en/home-en/). The CO_2 storage project Porthos is also built around the re-use of the K18 production platform as well as the re-use of the former hydrocarbon wells as CO_2 injectors.

Other plan for re-use

A new project looking into the feasibility of converting the rig-legs into biostructures (“rigs-to-reefs” see Picken et al., 2003). In the North Sea the Merces project in the UK (Welcome to Merces | Merces (merces-project.eu) reprent one initiative to study the ecological aspect of this use. A larger EU foundered study examines the impact from an understanding of the deep water ecosystems (Home - atlas - a transatlantic assessment and deep-water ecosystem-based spatial management plan for Europe (eu-atlas.org)).

*2.3.7 **Other surface area restrictions***

Other surface area restrictions to the use of the North Sea subsurface include windmill parks, “Energy Islands” and nature conservation areas. Recent projects include the “Energy Islands” that are planned in the North Sea - The “Dogger bank hub” to be located 130 km of the East coast of England and aim at supplying UK and EU with renewable power and the Danish plans to construct an Energy Island some 80 kilometres west of the peninsula Jutland (for example, the. Politisk aftale bringer energiøen i Nordsøen tættere på realisering | Klima-, Energi- og Forsyningsministeriet (ritzau.dk) in Danish).

In the Netherlands, the IJVERGAS project addresses the feasibility of hydrogen generation on an artificial, multifunctional island off the coast in the Ijmuiden Ver area. The study focusses on the techno-economical as well as non-technical aspects that are required in the development of such a project.
https://publications.tno.nl/publication/34637961/8YWFzT/topsector-2020-ijvergas.pdf

2.4 Discussion

The results here show a rapid growing body of projects and pilots throughout the North Sea aimed to solve the growing need for subsurface storage possibilities and the narrow “window of opportunities” for reuse of infrastructure. Understanding the current and potential paths is, however, paramount to support the green transition now and should feed into planning and policy making (particularly licensing of areas) by EU member states. In addition, our mapping of options and remaining knowledge gaps can inform any academic research or programs of exploration sponsored by member states.

Current strategies and roadmaps

Within the GeoERA project “GeoConnect3d”, an overview of the current state-of-the-art of subsurface planning and management, and avenues for improvements was compiled (Konieczyńska et al., 2020). The report gives a comprehensive summary of the current state of legislation, strategies and roadmaps for the participating EU countries and the EU legislation with respect to subsurface use. One of the main conclusions was the need for a harmonized database of subsurface use and subsurface data and coherent legislation, covering all types of emerging technologies.

Two of the GARAH participating Geological Surveys (TNO and BGR) were also included in the GeoConnect3d project. The main focus here was on the onshore but the conclusions also apply to the results of this project. Even within the well-established field of the oil and gas industry, differences in legislation and data handling across borders can cause planning and harmonization issues (see e.g. GARAH Delivery Report 2.3). The increased interest in the surface and subsurface potential of the North Sea from multiple countries and many different types of technologies will require a more streamlined strategy, integrating all potential technologies, as well as coherent legislation. An example of a first approach on such a strategy could be the STRONG (Structuurvisie Ondergrond, https://open.overheid.nl/repository/ronl-da2bbe33-1384-4f85-9912-1b3d389e091e/1/pdf/bijlage-1-structuurvisie-ondergrond.pdf, in Dutch) assessment of the Netherlands.

A harmonised legal basis assuring that CO_2 can be stored in the underground throughout the North Sea area (nearshore, offshore). Currently countries such as Denmark does not allow for CO_2 storage while it is allowed to inject CO_2 for enhanced oil recovery whereas countries like Norway allow CCS. A legal basis assuring that CO_2 can be transported across borders with the North Sea (London Convention) for the purpose of storage or use.

Fortunately, the process of compiling and harmonizing transnational geological data is in progress. EGDI (EuroGeoSurveys’ European Geological Data Infrastructure) has created and is still maintaining a central access point for transnational geological spatial data, http://www.europe-geology.eu/. The EGDI portal so far contains data that originate from about 30 different projects. Data from 15 GeoERA projects are or will be included in EGDI portal. Furthermore, GeoERA maintains a map viewer (https://geusegdi01.geus.dk/egdi/?mapname=geoera#baslay=baseMapGEUS) for all GeoERA projects. However, while compiling this report, it became evident that a large amount of information gathered outside of the GeoERA program is found in individual and country-specific databases and reports. A better integration of these project results into this unified database would be beneficial for future projects.

Technology improvements

Another important aspect of attention should be the identification of current barriers and hurdles for alternative use technologies that impede the technological advancement and application in the offshore. In the field of CCS for example, published strategies in Denmark will take the technology from its current state of TRL4 and into a full demonstration project by 2025.

Similar European-scale strategies should also be envisioned for the other alternative use strategies to streamline development and to make use of so called ‘play-based portfolio approaches’ (van Wees et al. 2020). The recently published Roadmap for the Global Energy Sector (IEA, 2021) outlines a scenario to achieve worldwide net-zero emissions by 2050, including a review of the current energy mix and the necessary behavioural and political developments and technolgy needs to achieve that goal. The report focusses mostly on surface infrastructure, industry and societal developments, however, based on this scenario the required demand on the subsurface should also be assessed and relevant strategies developed.

Preferred case vs. time constraints

At the moment, the TRL of a technique/technology, as well as the state of legislation for its use, often define the type of alternative use applied in certain subsurface areas. However, subsurface geology and conditions are not uniformly distributed, and certain technologies might only be applicable in specific geological settings. As the energy transition cannot rely on only one or a limited number of alternatives, the available subsurface should be assessed on a European level, making ideal use of the available geological settings. This again shows the need for a pan-European approach to long-term planning and collaboration to ensure the stability of the energy supply.

On the other hand, there are also time constraints. The need for fast alternative energy options and reduction of CO_2 emissions result in the preferential application of technologies that can further be developed. Furthermore, the ongoing abandonment of conventional oil and gas fields as well as the decommissioning of infrastructure sets a time limit on new technologies that can re-use these.

So far, most energy storage projects are developed in the onshore, due to the close distance of the power grid and end-user. This is certainly most important for short- and shorter-term storage types. However, the offshore is currently only considered for the long-term storage of CO_2. Part of the overall strategy decisions should be the identification of technologies that could be applied to the offshore sector without large additional investments, thereby making best use of the available subsurface area and appropriate geology.

Public perception

Stakeholder reactions can significantly affect plans for re-use or alternative use of the subsurface, as both risk and benefit understanding shapes perception which again is shaped by the cultural and sociodemographic context. As the only operational alternative use case offshore, in the past 10 years, several planned onshore CCS projects were cancelled as seen in the Netherlands, Germany and Denmark. One high-profile project is the Dutch Barendrecht project, cancelled in 2011 after massive stakeholder resistance (Brunsting et al., 2011; Terwel et al., 2012).

A lack of acceptance in the civil society can be a real game-stopper for CO_2 storage and work must therefore be done to identify and map out issues and concerns and the societal readiness level to determine how to engage stakeholders – both supporters as opponents in order to widen the knowledge level and to understand/mitigate potential concerns. Some areas, such as the North Sea, may have an initial higher societal readiness level than onshore storage sites due to a common NIMBY (not in my backyard) attitude of populations. Many learnings and issues are already identified, and mitigations measures presented in numerous academic studies (see Seigo et al., 2014 for a review) and should be considered/addressed accordingly – additionally, local issues must be collated, understood and dealt with together with stakeholders. Obtaining social license for CCS is a change journey and should be approached accordingly.

3 HAZARDS

3.1 WP2 – North Sea Mature Fields

3.1.1 *Legal Framework*

The potential risks and environmental impacts associated with subsurface use for energy applications in the North Sea are managed under the Convention for the Protection of the Marine Environment of the North-East Atlantic or OSPAR Convention (OSPAR Commission: Protecting and conserving the North-East Atlantic and its resources), which is the current legislative instrument regulating international cooperation on environmental protection.

3.1.2 *Hazard catalogue*

The hazards catalogue focussess on the potential risks and environmental impacts associated with subsurface use for energy applications, for example, if any of the plays examined in GARAH introduces new hazards or changes the general risk level. We followed a case based approach with examples of risks and hazards chosen from the scientific literature, published reports and datasets, and country-specific legislation. In Chapter 3.2 we also discuss hazards associated with gas hydrates, and and hazards associated with the alternative use of the subsurface and hydrocarbon infrastructure in the North Sea.

Table 3-1. Catalogue of oil and gas related hazards.

	Hazard	**Hazard status**	**Examples**	**Related GIS Features**
HC Play specific				
Conventional and unconventional plays	Induced seismicity	Existing - but risk generally low in offshore area	Onshore UK, NL	HIKE Fault database and report, field map
High Pressure / High Temperature Reservoirs	Uncontrolled flow / leakage / blow-out	Existing production-related	Ocean Odyssey 1988	
Unconventional plays Fracturing out of formation	Unconventional plays – generically related to the resource / technique	Conceptual in offshore area	Shallow onshore condictiones - migration along existing faults	
Conventional and unconventional plays	Fault leakage of hydrocarbons	Existing, natural	Fluid escape structures; seafloor instability; oil slicks; methane escape	
Conventional and unconventional plays	Fluid migration (Shallow Gas related)	Existing natural and production-related	Fluid escape structures on sea floor; Vagn-1 well; 22/4a- 4	Pockmarks map from Emodnet, brightspots

	Hazard	Hazard status	Examples	Related GIS Features
Conventional and unconventional plays	Fluid composition (e.g. H_2S or radioactive substances - scale formation)	Existing	Rd and U in scale in Uncoventional and conventional; H_2S in Central and Viking Grabens; Magnus oilfield; Zechstein SNS deposits; Lacq	
Infrastructure structure specific				
Production and end of life / decommisioning	Leakage during production and production stream. Flaring.	Existing	OGA Technology Insight (2020). OGA Strategy (2021) states flaring to be kept to minimum.	Infrastructure
Infrastructure	Leaks from pipes / infrastructure	Existing		Infrastructure
Wells	Leaking wells – after abandoning	Existing but risk expected to increase due to abandoning, regulated, see overview by OSPAR	Vielstädte et al. 2015, 2017, Wilpshaar et al. 2020, BGR paper	Wells (emodnet)
Alternative use of subsurface				
Storage in abandoned HC fields	Leaking from seal or from wells	New in North Sea		HC fields
CO_2/H_2 Storage saline aquifers	Leaking from seal or from wells	CO_2: existing; H_2: new in North Sea	Sleipner in NK	
Geothermal energy	Leaking from seal or from wells			
Energy storage	Leaking from seal or from wells	New in offshore areas		

3.1.3 *Hazard case studies*

This chapter gives an overview the identified hazards exemplified by selected case studies, to show potential effects and possible mitigation procedures. The list was compiled from scientific publications, reports, databases and reputable new sources. Relevant citations and links are given in the text for further information.

3.1.3.1 HC Play specific

Induced seismicity

Induced seismicity is usually caused by a change in the stress state along a fault related to either an increase in pressure caused by the injection of a fluid, or a decrease in pressure during reservoir depletion by fluid production (e.g., Candela et al., 2019). Anthropic influence on earthquake triggering or seismicity has been widely studied and several authors produced overviews of the likely cases of triggering (e.g., Gupta, 2002; McGarr et al., 2013; Foulger et al., 2018), covering a range of magnitudes between 1.0 and 7.9. Due to the shallow depths of induced seismic events (usually between 2 and 4 km) even smaller events (~3.5) can have an effect on the surface.

Groningen – onshore The Netherlands

One well-known and researched example on the effects of induced seismic is the Groningen Gas field in the north of the Netherlands. Over the last decade a large set or research papers and conclusion reports have been published on the geology, as well as the societal and environmental effects, of the large-scale gas production in this onshore area. Most public reports on the topic are available on the webportal of the operator of the field (https://www.nam.nl/feiten-en-cijfers/onderzoeksrapporten.html#iframe=L3JlcG9ydHMvb3ZlcnZpZXcvZ3JvbmluZ2VuLw – reports partly in Dutch and English), as well as an interactive map showing the location of all registered earthquakes in the area since 1986, measured ground subsidence, andthe location of production wells.

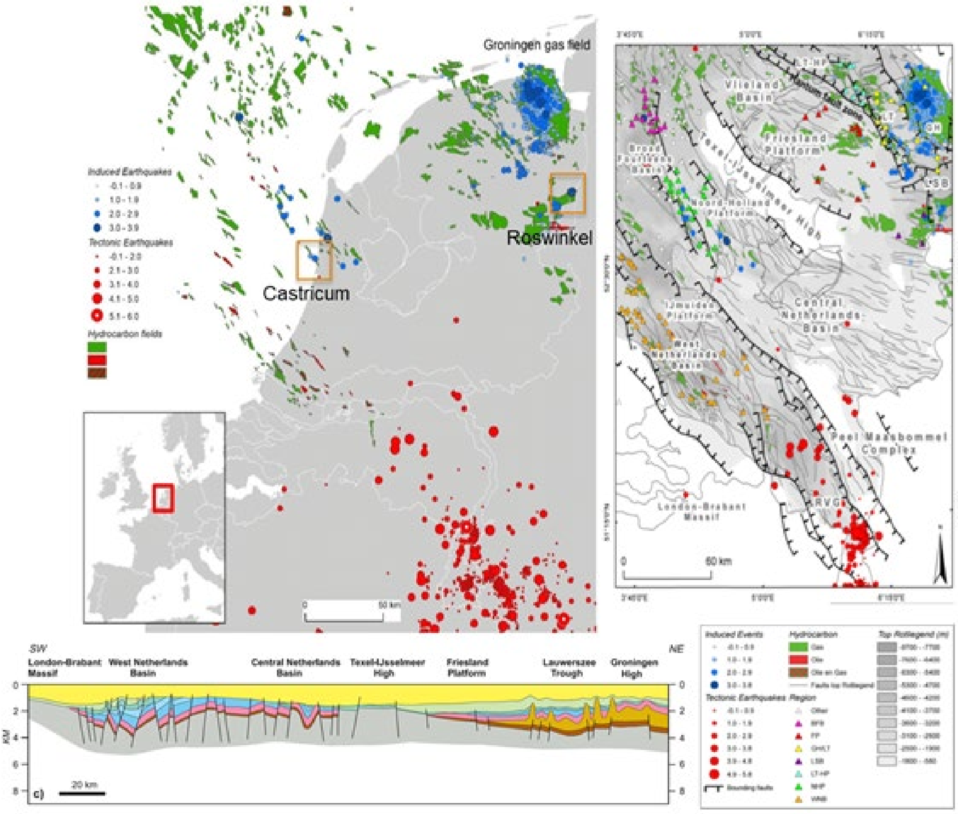

Figure 3-1 Natural and induced seismicity in the Netherlands, oil and gas production and major fault locations (From HIKE report D3.3).

In the context of the GeoEra HIKE project data on induced seismicity in the Netherlands was collected and linked to the fault database. A detailed description of several focus areas can be found in HIKE Report 3.2 and 3.3 Reports.

Lacq – onshore France

Lacq, southwestern France, is the largest gas exploitation field in France for more than a hundred years. Active seismicity related to the exploration/extraction was observed in the late 1960s and 1970s. Seismological and mechanical studies were progressively brought in the 1980s and 1990s (e.g. Segall et al., 1994). After the end of the commercial exploitation in 2013, several M~4 events continued (Aochi and Burnol, 2018), implying that the stress in the crust assocatiation with exploitation has not completely ceased. It is difficult to associate every earthquake to any particular faults, as the earthquakes are isolated at depth and the fault structure is also embedded around the reservoir depth (~5 km). None of the major tectonic faults mapped on the ground surface is activated. It is important to monitor the evolution of the seismicity and estimate the state of the residual stress in and around the reservoir.

Preston – onshore UK

Induced seismic event was linked to fluid injection during hydraulic fracturing and may as a result lead to felt, or even damaging, seismic activity. Delvoye and Edwards (2020) and Edwards et al. (2021) have presented a case study from the onshore UK, the Preston New Road site (Lancashire, UK). Here, numerous earthquakes of ML -0.8 to 2.9 were recorded over the period from October 15th 2018 to September 2019, corresponding to the period during which hydraulic fracturing (fracking) was carried out by the operator, Cuadrilla Resources.

In the North Sea, induced seismic eventsare also likely to be associated with the unconventionial plays (but not limited to these) as hydraulic fracturing is a prerequisite for production for this resource type (GARAH delivery Report 2.3). Long horizontal wells with multiscale fracturing have, however, been standard development in parts of the North Sea for decades (c.f. Lafond et al., 2010) and thus this is not a new technology to the North Sea. The case study from Preston new road site has, however, shown that subsurface stress field and state should be well-known and understood before this technology is deployed in order to limit seimic events.

Castor – offshore Spain

The Castor project is an example of both induced and triggered seismicity in an offshore environment due to the storage (injection) of natural gas in an old and abandoned Oil field exploited in the last 20th century (1970s-1980s). The Castor well is located offshore the Gulf of Valencia (Mediterranean Sea, Spain). The offshore gas injection in the oil trap modified the natural stress regime of surrounding faults and triggered earthquakes (Mw≥3.5, and up to 4.2, in magnitude) from September of 2013 to October of 2013. The ending of injection activities was followed by a quick decreasing of seismicity during November and December of 2013 .

Enhanced or deep geothermal systems
Induced seismicity can also occur in the context of deep geothermal energy, especially Enhanced Geothermal Systems (EGS) use. A detailed review of the occurrence and mechanisms of induced seismicity related to geothermal energy production was published by Buijze et al. (2020). They identified a list of main parameters influencing the risk for induced seismicity, however, emphasise that detailed assessments still needs to be site-specific.

High pressure and high temperature (HPHT) field developments
There are some variations in the country definitions of High Pressure, High Temperature (HPHT) field, but, in general, HPHT conditions are commonly defined as deep (> 4km), with operational pressures greater than 10,000 psi (690 bar) and temperatures exceeding 150 ^{o}C (300 ^{o}F). In the GARAH study area, HPHT developments are generally limited geographically to the deepest parts of the Central and Viking Grabens in the Danish, UK and Norwegian sectors, and some fields in the Moray Forth area of the UK sector.

The most significant hazards associated with HPHT reservoirs are uncontrolled or unplanned flow in wells and failure of blow-out preventers or similar equipment on associated infrastructure. The Ocean Odyssey Blowout, which occurred in 1988 while drilling the 22/30b-3 well, resulted in the death of one crew member and was caused by uncontrolled gas influx into the well, while drilling at depths of more than 4900 m in what is now the Shearwater Field in the UK sector. Most approaches to reducing risk in HPHT fields relate to drilling plans and engineering applications, but, of course, an understanding of the potential geological nature of the HPHT successions remains key in predicting and mitigating any potential hazards.

Fault leakage case studies
The risk of leaks through natural faults or induced fractures from hydraulic stimulation has been extensively studied for shale gas and oil reservoirs in North America. One of the most comprehensive studies has been conducted by U.S. Environmental Protection Agency (EPA, 2016). Additional case studies of fault leakage are presented in the GeoEra HIKE project (Delivery Report D3.4), including a study from Poland on improved reservoir seal assessment.

Shallow gas

Shallow gas generally refers to free gas trapped within the topmost 1000 m below the seafloor, often in unconsolidated sediments. In the southern North Sea, shallow gas is widespread (Müller et al., 2018; Römer et al., 2017; Schroot et al., 2005), www.gpdn.de). Besides being a potential natural gas resource, shallow gas also poses a risk during drilling operations for deeper targets due to unexpected gas kicks possibly leading to blow outs or instability of foundations. However, preventing shallow gas blow outs during drilling operations is standard practice in the offshore hydrocarbon industry, and associated mitigations and procedures are regulated by the responsible national authorities. In particular, shallow gas is often clearly visible as high amplitude anomalies in seismic data, and usually avoided when co-ordinating drilling programmes. In a number of recent projects these seismic amplitude anomalies were mapped (e.g., GPDN (https://www.gpdn.de/), Wilpshaar et al., 2020)

However, encountering shallow gas during drilling has led to a limited number of incidents in the North Sea. In 1977, shallow gas caused a blowout and subsequent fire during the drilling of the Vagn-1 well by Maersk in the Danish North Sea. In 1990, shallow gas from mid-Quaternary sands around 360 m below sea level caused a blowout during the drilling of the well 22/4a- 4 in 1990 by Mobil, resulting in the formation of a large seabed pockmark, and continued leakage of methane in the vicinity (von Deimling et al., 2007).

Mitigating the risk of encountering shallow gas during drilling largely relies on engineering solutions (for example, controlling well pressure during drilling/swabbing, and the installation of pressure-control equipment such as blowout protectors). Understanding the geological evolution of sequences containing shallow gas can also help mitigate risk, particularly where distribution is related to relatively recent local processes, as, for example, in the central North Sea, where shallow gas is being produced from the Aviat field in heterogenous glacially-influenced Quaternary sands (Rose et al., 2017); gas from the same horizon, but poorly understood and imaged in subsurface data, caused the blowout of the well 22/4a- 4 as mentioned above.

Gas Composition

Natural gas and oil can contain a number of other hazardous substances, for example, H_2S, that pose a serious risk to the infrastructure, health and environment. In the oil and gas industry and regulations these hazards and the relevant mitigation strategies have been identified in detail and are implemented as Hazards and Effects Management Processes (HEMP) in all producing companies (see e.g., Salter, 2005). However, identification and regulation of these substances can also be relevant in other technologies that use the subsurface. It should be noted that hydrocarbons need to be included in the list of potentially hazardous substances in the context of these technologies.

Water chemistry and reservoir chemistry

Produced water discharge into the sea poses an environmental risk due to the composition of the discharged fluid, for example, formation brine, oil, dissolved organic components, back produced and/or spend chemicals (c.f. Breyer et al., 2020; Sun et al., 2019). In addition to discharged minerals, precipitates (scale) may form in the wells and/or in the facility that may pose an additional risk due to the presence of naturally occurring radioactive material (NORM, Hylland and Eriksen, 2013). NORM active scales are not limited to oil and gas but may also develop in geothermal wells under certain geochemical conditions.

Discharge and disposal of produced water including NORM waste is stringently regulated in the North Sea within the OSPAR convention. Fundamentally new or additional risks from new or alternative activities were not identified here. Increased activities will, however, lead to an increase in waste fractions both solid and non-solid.

A detailed review of drilling fluid and formation water composition and respective hazards for deep geothermal energy systems in Germany was compiled by Plenefisch et al. (2015).

3.1.3.2 Infrastructure structure specific

Leakage from abandonend wells

Natural gas leakage from offshore abandoned wells in the North Sea has recently become a point of concern, especially since it might contribute to the atmospheric methane pool and thus to global warming. Natural gas leakage has been observed and studied at three plugged and abandoned wells at the Utsira High on the Norwegian continental shelf (Vielstädte et al. 2015, 2017). Probably the gas originates from shallow gas pockets in the vicinity of the wells migrates upwards along them. These findings have been extrapolated by the same research group to the whole number of wells in the UK Sector of the Central North Sea (Böttner, 2020). However, Wilpshaar et al. (2021) comment that for a reliable upscaling more and careful consideration of the geological subsurface, well details and plugging and decommissioning parameters need to be considered. Furthermore, a recent methane seep survey in the German North Sea sector did not find corroborating evidence for natural gas seepage near abandoned wells there (Römer et al., 2021). More research it appears is needed, to further identify and quantify natural gas leakages at abandoned wells in the North Sea.

3.1.3.3 Alternative use of subsurface

Potential alternative uses for the subsurface (apart from existing conventional hydrocarbon extraction) are envisaged to carry similar risk of hazard, largely because the techniques and infrastructure required are similar to that used in hydrocarbon extraction and production. However, in addition to the cases mentioned above, there are a number of studies that have set up specific risk and hazard identification and mitigation studies for alternative use technologies.

Deep geothermal

A review of the current view on risks related to deep geothermal exploration and production from the perspective of the Dutch State Supervision of Mines (SodM) was recently published by Jharap et al. (2020). This review is a summary of a more detailed report published by SodM in 2017 (https://www.sodm.nl/documenten/rapporten/2017/07/13/staat-van-de-sector-geothermie - in Dutch) and focusses on the technical and organisational risks while excluding project specific risks as well as risks that are generally not supervised by SodM. One of their main conclusions for geothermal projects is that the main technical risks are very similar to those identified within the oil and gas industry. An update of the report as well as review with respect to the progress in making geothermal energy more secure was published by SodM in 2021 (https://www.sodm.nl/documenten/publicaties/2021/09/30/evaluatie-aanbevelingen-staat-van-de-sector-geothermie).

Underground Energy Storage

Within the context of the North Sea Energy project a Hazard Identification Study (HAZID) was conducted to identify the potential hazards of re-using HC infrastructure for H_2 storage (Koelewijn et al. 2019). The study details the potential hazards and foreseeable accident events related to the re-use of a typical gas production platform and identifies possible safeguard and mitigation strategies.

In the Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES) project, an inventory of risk and possible mitigation measures associated with Compressed Air Energy Storage and H_2 storage in depleted gas fields or salt caverns was compiled, based on a literature review and supplemented by expert knowledge. The identified risks are published in a risk catalogue that can be used as a starting point and checklist for new development projects (van der Valk et al., 2020). The two main subsurface risk components identified for CAES as well as H_2 Storage are the integrity of the storage reservoir and the well. In relation to these risk components, three potential hazards were listed: leakage of the stored fluid from the system; ground subsidence; and seismicity.

High temperature aquifer thermal energy storage (HT-ATES) is a new form of Underground Thermal Energy Storage (UTES) technology that uses aquifers for the storage of heat as a form of energy. In the context of the HEATSTORE project (High Temperature Underground Thermal Energy Storage - https://www.heatstore.eu/index.html), an inventory was compiled for risks associated with technical, economic, environmental, commercial, organisational, political and social issues (TEECOPS) and linked to potential mitigation measures (van Unen et al., 2020). As a test case, the inventory tool was tested on the HT-ATES demonstration case in Middenmeer, the Netherlands.

CCS

Studies investigating risks associated with carbon capture and storage (CCS) in the North Sea are largely concerned with escape of CO_2 to surface, and therefore relate to the integrity of the overburden for any particular CO_2 reservoir. Unlike many hydrocarbons, CO_2 is not in itself hazardous/toxic, but, if released in very large quantities, it can pose a danger by displacing oxygen, especially as it is heaver than air. In the context of CCS and potential risks associated with leakage post-storage, a suffificently large release via well or pipeline could pose a major hazard (see see Harper, 2011).

3.1.4 Discussion

In the following chapter we discuss the risk and safety aspects related to the identified hazards and technologies and comment on their impact on carbon abatement policy. Identified synergies and competitions between technologies will be discussed in Chapter 4.

Risks and safety and carbon abatement policy

Overall, hazards occurring during oil and gas exploration and production in the North Sea basin are already comprehensively regulated, either on country or EU-level (see OSPAR, section 3.1.1 for more detailed information). However, through the introduction of new technologies or resources, such as Unconventional Hydrocarbon exploration or Hydrogen Storage, new hazards could be introduced that are currently not yet accounted for in the current legislation.

Most of the current risk and hazard inventories focus on only a single or a small number of complementary technologies. One aspect of the energy transition, however, is the need for a variety of technologies, several of them using the subsurface, as well as attempting to re-use existing infrastructure in various ways and to create synergies. Such a combination of re-use or alternative use might introduce new risks and hazards, currently not recognized in the brief inventories below.

On the other hand, several technologies for risk mitigation are currently being developed and adapted, e.g. 4D- seismic monitoring applied to CO_2 storage sites, which has been ongoing since the 1990's (Ringrose et al., 2021). The added focus on additional stratigraphic intervals, classically not included in conventional hydrocarbon studies, provides a much more detailed view of the subsurface, allowing for better risk assessments and the development of new risk mitigation strategies.

Mapping of areas with potential hazards
One of the initial ideas of the GARAH project was to link GIS database features to corresponding hazards (c.f. Table 3-1) and thereby map areas where these hazards might be encountered. However, during the course of the GARAH project it became evident that the level of detail of the available information was not sufficient to provide this in a basin-wide context. Many of these hazards are local, and strongly dependent on reservoir-scale aspects (e.g., induced seismicity – see discussion in Buijze et al., 2020). Where possible, we have referenced relevant GIS layers in the list of hazards. However, this is not a comprehensive overview and should only be regarded as a first pass in identifying potential hazards.

3.2 WP3 – Hydrate-related Geohazards

3.2.1 Objective

Marine gas hydrates are crystalline solids forming ice-like marine deposits composed of water molecules surrounding light hydrocarbon gases such as methane (the most common), ethane, propane or CO_2, in cage-like lattices. Marine gas hydrate is considered an important geohazard feature. Depressurization due to drops in sea level and warming of bottom water is the natural main scenario where hydrate dissociation can take place, driving large-scale natural gas release with potentially profound impacts, generating landslides, pockmarks, collapses, seafloor explosions and gas release. However, under stable pressure/temperature conditions inside the gas hydrate stability zone (GHSZ), human activity on deep-water infrastructure such as wellheads, pipelines, production facilities, seabed anchors, cable touchdown areas on the seabed and catenaries in the water column can modify these pressure-temperature conditions of shallow sediments.

This project presents for the first time on the whole of the European margins and adjacent areas, a geohazard assessment (susceptibility analysis) of the presence of marine gas hydrates. It also assesses the main knowledge gaps of hydrate-related information with a pan-European scope and analyses their impact on the uncertainty of susceptibility inference.

3.2.2 *Hazard catalogue*

Table 3-2. Gas Hydrate related hazards

	Hazard	**Hazard status**	**Examples**	**Related GIS Features**
Fluid-related feature				
Fluid leakage and gas flares	Blowout – ground motion	Active - Latent	NW Norweigian margin - Gulf of Cadiz - Mediterranean Sea – Barents Sea and Irish margin	Pockmark
Mud volcano field	Blowout - burial	Active - Latent	Gulf of Cadiz - Mediterranean Sea – Barents Sea and Black Sea	Mud volcanoe
BSR presence	Possible Blowout – collapses – ground motion	Uncertain – in need of research	Greenland – Svalvard – Barents Sea	BSR
Ground motion related hazards				
Pockmarks and collapses	Ground motion	Active - latent	NW Norweigian margin - Gulf of Cadiz - Mediterranean Sea – Barents Sea and Irish margin	Pockmark - collapses
Submarine Landslides	Ground motion - tsunami	Dormant Active - latent	Storegga Slide ~8k BP Gulf of Cadiz	Landslide Landslide
Alternative use of subsurface				
CO_2 storage Hydrates	liquid CO_2 leaking from seafloor or from wells	New in very deep offshore areas	French and Spanish EEZ y Bay of Biscay	

3.2.3 *Hazard case studies*

Susceptibility assessment of seafloor areas affected by hydrate dissociation

The presence of gas hydrates in marine sediments is a geohazard that has not yet been evaluated in the whole of the European continental margins. This study, analyses the geological hazard by means of the susceptibility assessment. The term ‘‘susceptibility’’ is employed here to define the likelihood of occurrence of hydrates in the sediment column, and subsequently the likelihood of them being affected by dissociation processes resulting from natural or human induced activities (liquefaction, explosions, collapse, crater-like depressions or submarine landslides).

For the susceptibility assessment, several factors were taken into account:

- marine gas hydrate evidence,
- seismic indicators,
- seabed fluid flow structures
- thickness of the GHSZ.

Each geological and geophysical item of evidence and indicator was weighted according to the confidence/certainty of finding hydrates at the site. The maximum weight (weight = 1) was given to recovered samples of gas hydrates or evidence of hydrate dissociation, such as degassing or liquation structures in gravity cores. Seismic indicators of the presence of gas hydrates or hydrocarbon seabed fluid flow in the vicinity of the GHSZ were weighted with a lower value (weight between 0.8 and 0.9).

Regarding the theoretical GHSZ, the seafloor was weighted in three categories: (i) sea-floor areas outside the theoretical GHSZ were excluded as not likely to be affected by hydrate dissociation processes; (ii) any location inside the GHSZ was selected as theoretically likely to suffer dissociation processes, and (iii). A strip at the up-dip limit of the GHSZ (50 m in thickness) was a critical area for these dissociation processes.

The susceptibility assessment was performed by map algebra, taking into account the control maps of density of hydrate evidence and indicators and the weighted map of the GHSZ on the seafloor (Fig. 3-2).

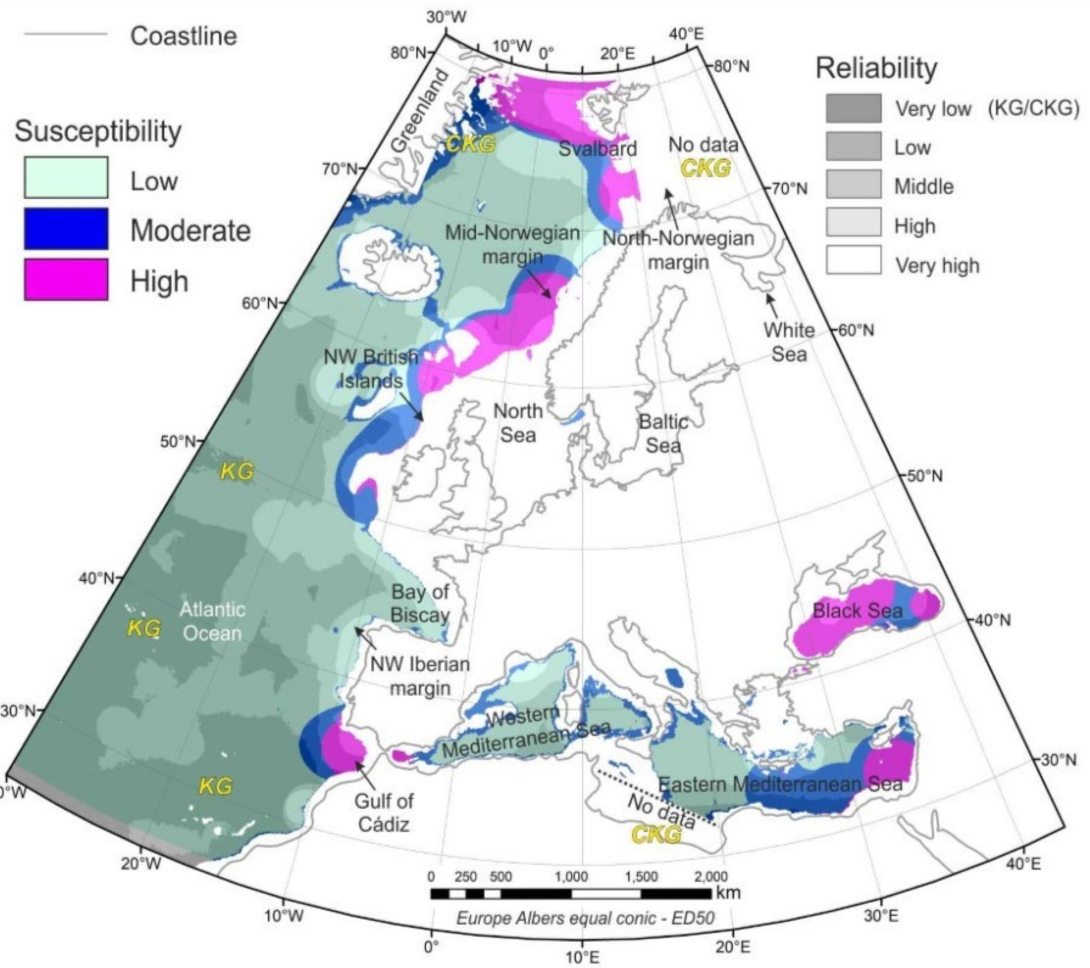

Fig. 3-2 Susceptibility assessment of gas hydrate presence on the European continental margins and reliability of this prediction. KG, knowledge gap; CKG, critical knowledge gap.

3.2.4 Discussion

Uncertainty assessment of the susceptibility assessment

In order to assess the reliability of the susceptibility inference, a qualitative value of uncertainty (very high, high, middle, low and very low) was established as a function of the data density taken into account in the susceptibility calculation (Fig. 3-2). The reliability (u) is thus equal to the sum of the density maps of geothermal gradient (ρ_{gr}), seafloor temperature (ρ_{st}) and hydrate evidence and indicators (ρ_{hy}):

$$u = \rho_{gr} + \rho_{st} + \rho_{hy}$$

Density maps are based on density kernel algorithm of ArcGIS®. Pixel value, number of hydrate evidences and indicators per 100,000 km^2. Parameters:

population field, none; cell size, 5000; radius, 178,415 meters; areal units, square kilometres; method, geodesic.

Five levels of reliability were established. The reliability is considered “very low” with values from 0 to 36 data per 100,000 km^2, approximately less than ca. 1 datum per 50 km in mean; and “low”, “middle”, “high” and “very high” from 36 to 144, from 144 to 648, from 648 to 3,149, and from 3,149 to 15,218 data per 100,000 km2, respectively. These levels were defined by the geometrical segmentation of *u*-value, except “very low” and “low”, which were defined by expert criteria. Very low reliability areas were catalogued as global knowledge gaps (KG in Figure 3-2) that are critical (CKG) in the vicinity of the up-dip limit of the GHSZ and hydrocarbon seabed fluid flow structures.

Areas located in the proximity of the continental shelf and intensively surveyed by oceanographic cruises show the most reliable results in the susceptibility assessment. By contrast, areas distant from the coastline (e.g. the mid-Atlantic Ocean) and areas that are inaccessible because of the presence of icebergs (e.g. east Greenland) or political issues (e.g. north of Libya) have very high uncertainty.

Owing to the methodology applied, the susceptibility map shows low values in areas that have knowledge gaps or are poorly surveyed. These areas may have two interpretations: (i) the catalogue is incomplete, these areas have been poorly surveyed, no records have been recovered but hydrates may exist and subsequently a high susceptibility may be potentially latent; and (ii) there are no data because there is no evidence or indicators of hydrates. These knowledge gaps could be especially critical at the up-dip limit of the GHSZ. Particularly, on the east Greenland shelf, the Irish margin, the western Iberian margin and the western Mediterranean Sea, no hydrates have been recovered but hydrocarbon seabed fluid flow structures and seismic indicators (e.g. on the Irish margin) have been observed.

High susceptibility values are located in areas with a high density of evidence and indicators. The majority of gas hydrate evidence stored in the database was recovered in focused seabed fluid flow structures such as mud volcanoes or pockmarks. This is especially significant on the southern European margins in the Gulf of Cádiz and the eastern Mediterranean and Black seas. In these cases, gas hydrates are circumscribed to the feeder systems of the hydrocarbon fluid migration structures, which, subject to certain exceptions, do not exceed 0.1 to 1 km and 4 km in diameter for pockmarks and mud volcanoes, respectively. In these areas, there is therefore no continuous spatial variation in the presence of hydrates. Gas hydrates appear with a located distribution (nugget effect?) and focused inside the hydrocarbon fluid flow structures where fluid migration is mainly controlled by faults. However, the presence of hydrocarbon fluid flow structures shows a continuous spatial variation in fluid leakage areas. In these areas, the density map shows areas where hydrate-bearing fluid flow structures are more probable and, subsequently, the likelihood of the seafloor suffering gas hydrate dissociation processes as a result of natural or human activities could also be high. Finally, although the susceptibility could be high in mud volcano fields, for instance, the real risk or magnitude of dissociation processes will be low because of the typology or internal structure of hydrates inside the sediment. In mud volcanoes, hydrates constitute small (millimetres or centimetres) crystals or aggregates and their real volume is low.

Moderate susceptibility values seem to be controlled by the GHSZ and in particular by the optimal theoretical environmental conditions for hydrate presence on the continental shelves of the Arctic region and Mediterranean Sea. In our opinion, the presence of moderate values on the eastern continental shelf of Greenland and their absence on the western Norwegian shelf is directly related to the presence of cooler bottom water masses on the eastern continental shelf of Greenland and the subsequent influence on the theoretical GHSZ. Although no hydrates have been recovered in the Mediterranean Sea, owing to the particular seafloor temperature/pressure conditions (bathymetry) on the continental slope, this area has a slightly elevated likelihood of occurrence of hydrate dissociation processes in the hypothetical presence of hydrocarbon gases in the sediment column.

Presence of gas hydrates as a hazard for other uses of the sea floor

In these areas of high susceptibility, alternative seafloor uses such as the CO_2 storage, mining and seafloor infrastructures such as wellheads, pipelines, production facilities, seabed anchors such as opensea windfarms, cable touchdown areas on the seabed and catenaries in the water column (where drilling, digging ditches or drainage operations take place) are affected by potential hydrate geo-hazards. With these alternative uses of the seafloor, gas hydrate dissociation may occur if the equilibrium temperature and pressure condition of the deposit is disturbed. In this cases, high volumentric changes, degasing and dewatering processes occur with the subsequent blowout or liquefactions of the sediment. In addition, when hydrates are drilled, overpressured free gas trap below GHSZ or vigorous shallow water flows in overpressured sands can erode the structural integrity of the well, and lead to buckling and failure of the casing.

Nevertheless, such seafloor hazardous areas can be safely drilled using existing industry protocols geohazards associated with gas hydrate and free gas. In this way, these protocols should be taken into account in areas classified as high susceptibility in the Black Sea, eastern Greenland, Svalvard, Norweginan margin and Barents Sea where extensive areas of gas hydrates and Bottom Sea Reflectors (BSR) have been detected. In the rest of European margins, gas hydrates have been found localized in seabed fluid flow structures (mainly mudvolcanoes), thus, above mentioned alternative uses should avoid these seabed fluid flow structures.

Gas hydrates and global warming

As evidence mounts for sustained global warming during the last half of the 20th century and the two first decades of the 21st century, there is increased awareness of the relative importance of methane emitted at these focused fluid flow systems to greenhouse warming. Among the large CH_4 carbon reservoirs that naturally interact with the ocean-atmosphere system and thus global climate, gas hydrates have special relevance. The pressure/temperature conditions of the gas hydrate stability and the global distribution of gas hydrate make it susceptible to the key perturbations associated with global warming, namely relative changes in pressure (sea level and tides) and increases in ocean temperatures. This is especially observed in several sites in the Arctic region.

In the East Siberian Arctic (both shelf and litoral areas), the Holocene warming of the overlying seawater has triggered the defrosting of the underlying subsea permafrost. A large volume of free natural gas (majority come from gas hydrates dissociation) trapped below the permafrost is migrating to the atmosphere. In a future projection, the quantity of CH_4 that can be emited to the atmosphere if the marine gas hydrate (nowdays stable) below the permafrost is massively dissociated is critical and remain elusive and controversial for the scientific community.

In the Svalbard and western Barents Sea margins, pressure changes associated with isostatic rebound during deglaciation, the elastic response of the crust as the ice load was removed, appear to play a key role in gas hydrate dissociation and rapid sediment accumulations such as glacigenic sediment pulses can have a significant effect on gas hydrate dynamics. Short-term marine tides or seasonal temperature variations may have an impact of the stability of the gas hydrates in subseabed sediments in the Arctic Ocean (Ferré et al., 2020). Long-term ocean warming could affect further the stability of hydrate reservoirs detected in the Artic region. Numerical models predict that continued dissociation of gas hydrates due to current trends in bottom water temperature increase will occur between 375 and 425 m water depth and that these will have an impact on pore pressure build-up in marine sediments. A key question is the fate of this released methane in the water column: how much methane will reach the atmosphere and what will be the impact on the global methane budget?

These Arctic areas have been selected as high susceptiblity and of interest for future scientific projects of the impact of global warming on the methane budget.

4 INTERACTIONS BETWEEN UNDERGROUND USES (SYNERGIES, COMPETITIONS) - PERSPECTIVES

Almost all current roadmaps foresee a need for a very diverse energy landscape in the near future to be able to ensure the energy supply while moving towards a net-zero emissions policy. Supporting the transition to a low-carbon future is one of the main objectives of GARAH project. Most of the technologies that are using the subsurface can benefit (financially or technologically) from synergies or re-use of infrastructure and knowledge from other technologies. At the same time, however, several of these technologies are also utilizing similar structures or subsurface environments, which will result in competing interests as well as potential additional hazards. This chapter presents these potential synergies as well as competitions or conflict of interest for the described technologies.

In addition, a low-carbon or a carbon-neutral future need not mean to step away completely from the use of hydrocarbons. It may be that a net-zero future could be envisaged with hydrocarbon use coupled with CCUS. The integrated use of hydrocarbons and electricity generation from renewable energy such as wind, wave or tidal energy could also be a way to ensure the energy supply. In such a scenario, the continued use of hydrocarbons could be possible as long as a net-zero carbon model could be maintained.

4.1 Competing interest to the subsurface

A conflict of interest can arise when different techniques or resources are applied to the same structures and stratigraphic intervals in the subsurface. To illustrate this potential conflict of interest, the main stratigraphic intervals currently investigated in the North Sea area for the different technologies are compiled in Figures 4-1 and 4-2. The figures highlight that many competing uses (e.g., HC production, CCS, geothermal energy, waste water injection, water production) are envisogend for the same permeable clastic or carbonate intervals A good understanding of the underlying controls on distribution and geological properties with respect to licensing should mitigate some of the potential interactions by allowing good estimation of potential resources, hazards, and conflicting use.

Techniques which make use of salt caverns for various types of fluid and energy storage may also create potential conflict of interest. (c.f. Table 4-3). While the impact of storage in salt caverns on the surrounding strata is less pronounced than for overlapping porous media, the potential space available for storage caverns is limited. Currently the effects of re-using existing natural gas storage locations for other energy storage are investigated in the Hystock project .

A very recent example of this conflict of interest is provided by the awarding of rights by the Crown Estate in the UK sector for both windfarm sites and carbon storage offshore the Yorkshire coast (The Guardian, 2021). The carbon capture project (East Coast Cluster) was recently (October 2021) awarded fast-track status by the UK government (see Section 2.3.1) while the windfarm site was bought in 2015. Concern has been raised that the foundations of the wind turbines would negatively affect subsea seismic detectors used to monitor the CO_2 storage.

Within the context of the ESTMAP project, maps were produced showing areas with potential conflict of interest between Natura2000 and energy storage locations as well as CCS and energy storage locations (https://www.estmap.eu/downloads/ESTMAP-D3.04-v2016.12.14-Datacollection-report-public.pdf)

Figure 4-3 presents a synthesis of the interactions between underground uses according to a previous Dutch study (NLOG, 2015) that has been extended and modified in a BRGM report (Le Guenan and Gravaud, 2016). A color code is used to signify synergy or competition. We make a distinction between proven competitions (in orange) and possible competitions (in yellow). The letters specify the type of competition or synergy in play.

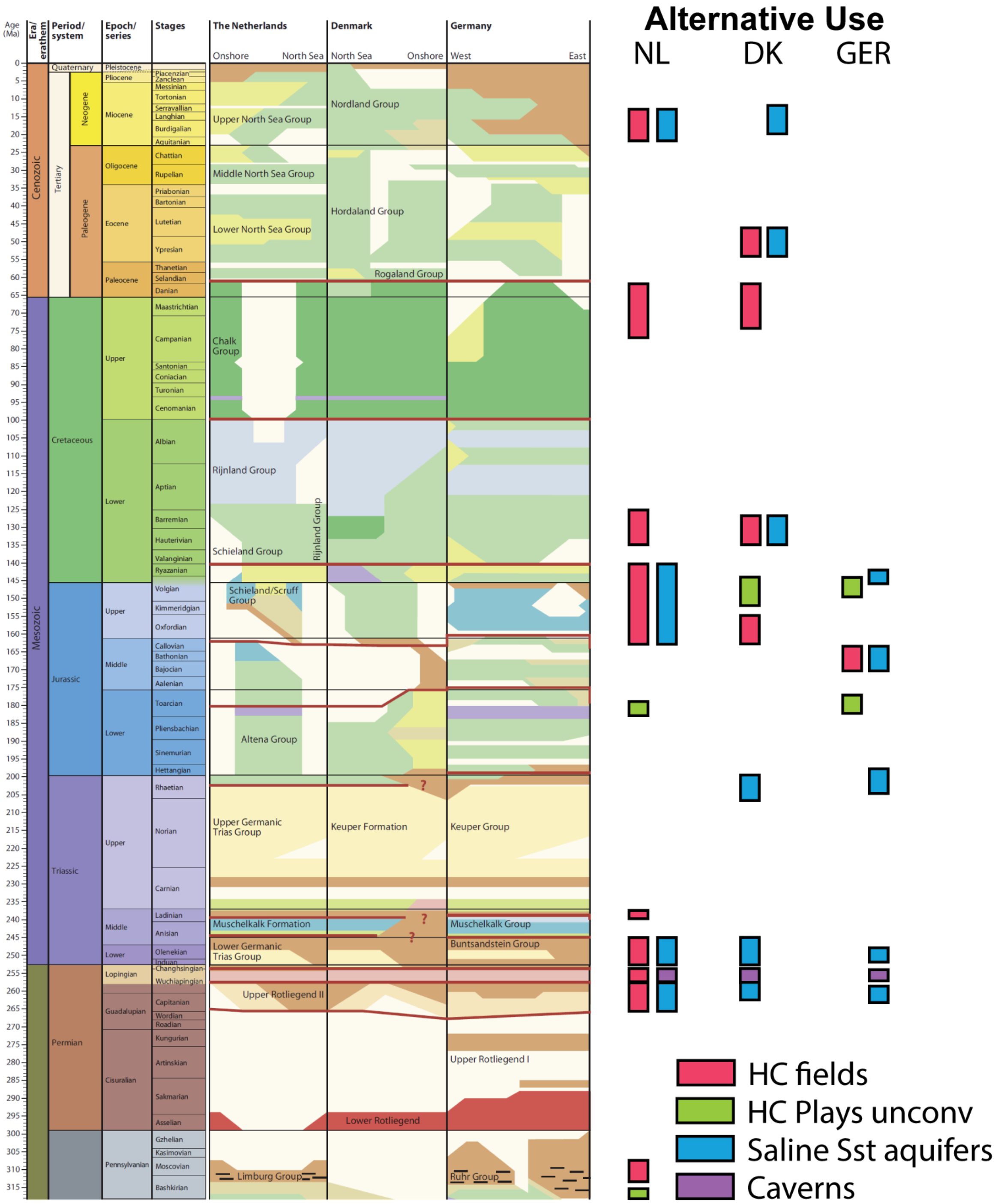

Figure 4-1 Simplified summary of stratigraphic use and potential use of the subsurface within the GARAH North Sea area. Note that the conventional plays are not shown for simplicity. Stratigraphical chart modified after Doornenbal et al. (2010).

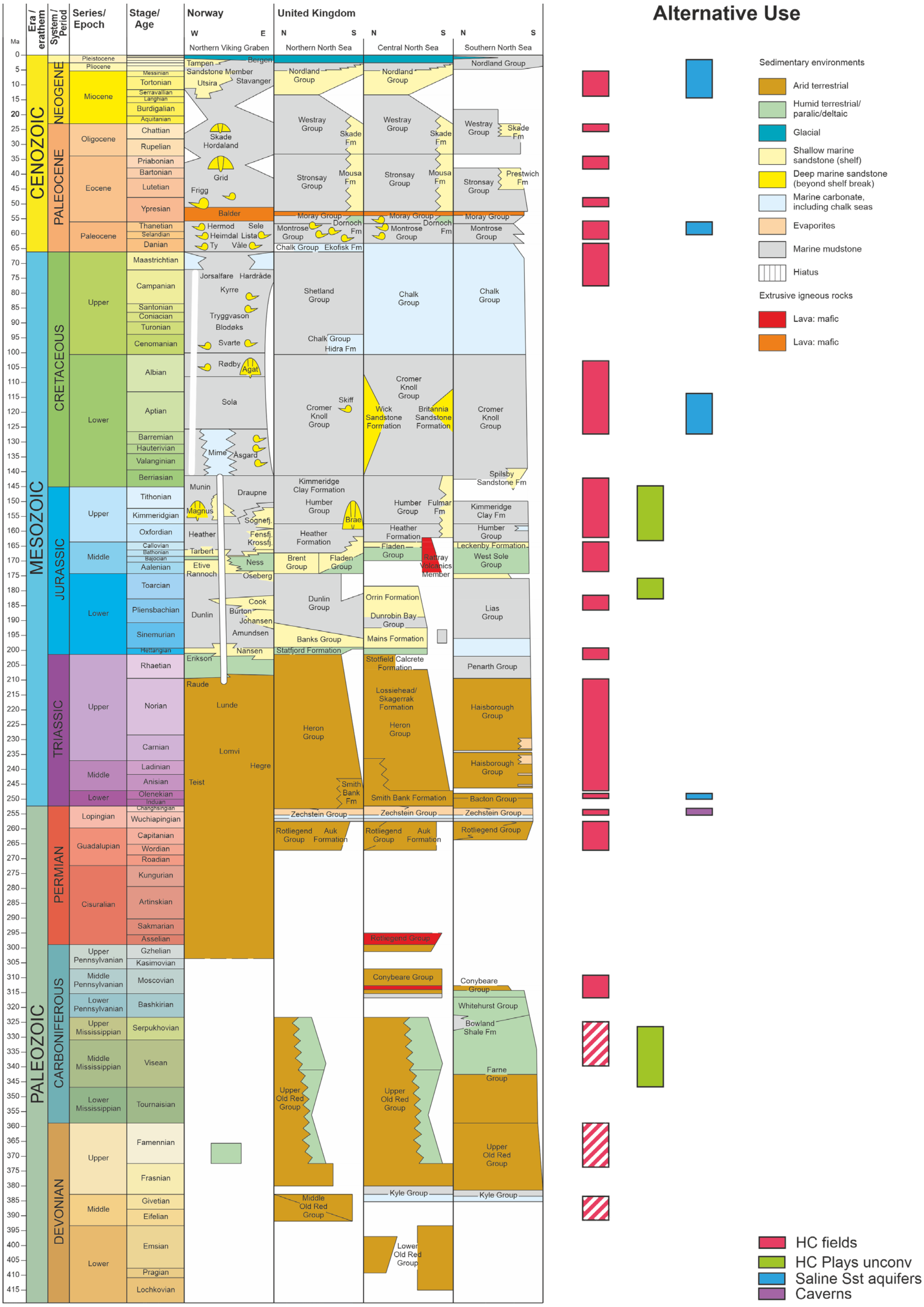

Figure 4-2 Simplified summary of stratigraphy and potential use of the subsurface with the UK and Norwegian parts of the GARAH North Sea area. Aadapted from Figure 11.18 of Hopper et al., (2014).

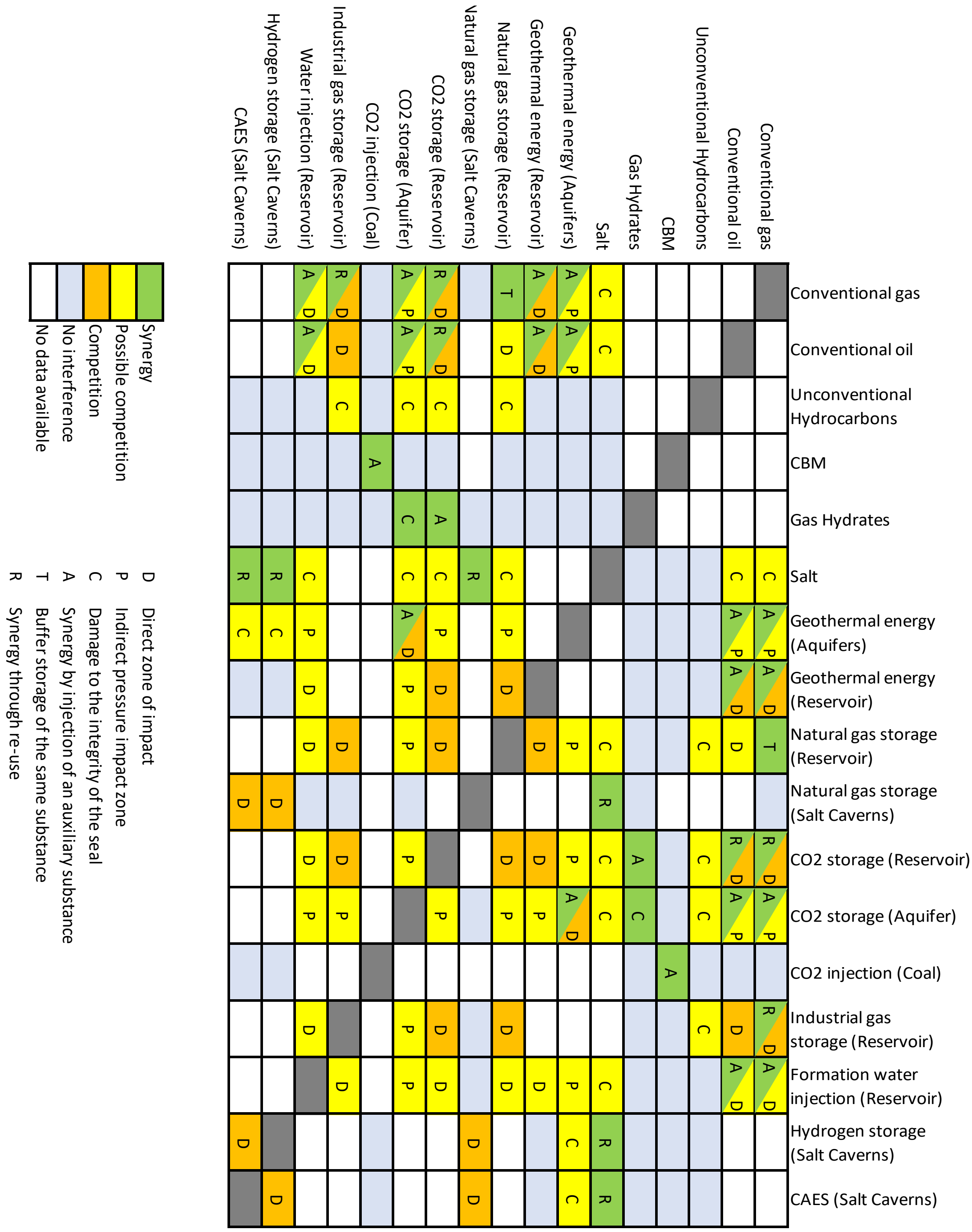

Figure 4-3 Overview of potential synergies and competitions in subsurface use between different technologies (modified from Le Guenan and Gravaud, 2016).

4.2 Synergies

Fostering synergies between different technologies is currently becoming more and more important to ensure a most cost- and energy efficient application. The most advanced synergy as of now is the re-use of caverns from salt solution mining for natural gas storage, which has been ongoing since the 1960s. Furthermore, CO_2 storage using saline aquifers, or depleted gas fields is already fairly well advanced, in combination with the re-use of hydrocarbon production infrastructure such as facilities and pipelines (Konieczyńska et al., 2020).

A critical factor for alternative use of the subsurface, particularly in the North Sea, is the vast amount of data gathered for conventional hydrocarbon exploration and production. These data are key for assessing the potential for new storage facilities, both in understanding the properties of depleted oil and gas fields, and to catalogue drilled 'dry' structures that may be re-used, for example, for CCS.

Other more conceptual examples of synergies are: the generation of "green hydrogen" using wind energy on so called Energy Islands; the production of "blue hydrogen" in combination with natural gas and CO_2 storage; and dual hydrocarbon-geothermal energy systems (van der Molen et al., 2020). The North Sea Energy program is currently compiling an atlas highlighting these potential synergy options for the offshore area (north-sea-energy.eu).

The synergy between geothermal energy and CO_2 storage in aquifer has been developed in the French project called "CO2-DISSOLVED" (https://co2-dissolved.brgm.fr/). The basic idea is to dissolve CO_2 in the cold water before the injection in the geothermal doublet. This concept is only suitable for low-CO_2 industrial emitters due to the limited solubility of CO_2 in brines.

5 CONCLUSIONS AND FINAL REMARKS

The summary of technologies that use the subsurface for energy generation and storage, as well as the list of associated hazards compiled in this report, can be used for planning policy-making (particularly for licensing of areas for exploration), and commercial exploration strategies by EU Member States. The compilation presented in this report can highlight remaining knowledge and technology gaps, which may inform further academic research, or programs of exploration/assessment sponsored by member states.

Our main conclusions are:

Multiple use of the subsurface

- Need a unified cross-border subsurface use strategy to maximise benefit from synergies and limit “bottle-neck” competitions
- Identification of Europe-wide best usage options to maximize the benefit of the subsurface, also given the time constraints on ageing infrastructure
- Make best use of already available information and infrastructure of the subsurface and use EU-wide play-based portfolio approaches to get the most benefits out of investments. This is already partially in use for research but should also apply to industry projects – data sharing policy
- Need for a clear EU-wide policy and rules to avoid cross-border conflicts (identify options for designated area use without full disclosure)
- Initiative for more offshore options in current energy storage plans to include additional space

Hazards

- Additional hazards can potentially be introduced by new/alternative use technologies
- Current technological developments provide better hazard mitigation through data-rich monitoring technologies
- Gas hydrates pose an additional hazard to other types of sea floor uses. The characterization of the gas hydrate susceptibility identifies areas where this has to be included in the project planning.
- Climate change can lead to gas hydrate dissociation, current projects are trying to estimate the global impact and boundary conditions.

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