Geological Analysis and Resource Assessment of selected Hydrocarbon systems

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ABSTRACT

This report provides a brief update of the activities carried out so far in the GARAH work programme, with a focus on work packages 2.2 and 2.3, which look at conventional and unconventional hydrocarbons, respectively. This part of the GARAH work programme first aimed to assess data availability related to conventional oil and gas resources in the North Sea study area. This exercise was completed in 2019, with each survey providing national compilations of existing assessments, play types and exploration histories. The second part of this work package is to assess cross-border resources with a play-based focus. Our approach here is not only to compare existing reporting on resource assessments, but also to elucidate and compare methodologies. We are taking a play-based approach to collate information on conventional petroleum systems across the North Sea, and compare exploration data to see if further insight can be made regarding particular plays and regions of exploration interest. We are also compiling information on alternative use of the subsurface in the North Sea for activities such as hydrogen storage and geothermal potential, where this information is available.

EXTENDED ABSTRACT

The Geological Analysis and Resource Assessment of selected Hydrocarbon systems (GARAH) work package 2 (WP2) overall aim is to assess and evaluate hydrocarbon resources across borders in the North Sea.

This report provides a brief update of the activities carried out so far, with a focus on work packages 2.2 and 2.3, which look at conventional and unconventional hydrocarbons, respectively. This part of the GARAH work programme first aimed to assess data availability related to conventional oil and gas resources in the North Sea study area. This exercise was completed in 2019, with each survey providing a compilation of existing HC resource assessments, play types and exploration histories. The second part of the work package is to assess cross-border resources with a play-based focus. Our approach here is not only to compare existing reporting on resource assessments, but also to elucidate and compare methodologies. We are taking a play-based approach to collate information on conventional petroleum systems across the North Sea and compare exploration data to see if further insight can be made regarding particular plays and regions of exploration interest. We are also compiling information on alternative use of the subsurface in the North Sea for activities such as hydrogen storage and geothermal potential, where this information is available.

Future work will focus on reconciling cross-border issues in order to create harmonised datasets across the study area. The main focus will be on the final compilation and harmonisation of the play maps created for each country to date, and using these to define any further areas of interest (for example, regional trends in chalk or HPHT reservoirs). The intention is also to link quantitative information on resources with individual plays where possible and to incorporate further information on seal and migration as metadata, if feasable incorporated into the GIS. As part of work package 2.6, GIS layers for alternate use will also be developed, harmonised and provided in the GIS deliverable.

Future work on the unconventional work package 2.3 will focus on the assessment of the *yet-to-find* resource associated with the unconventional plays. The assessment will be based on a Monte Carlo simulation and focus on the thirteen shale plays reflecting four main stratigraphical levels (Carboniferous, Triassic, Lower and Upper Jurassic) that have been identified to potentially hold unconventional HC resources in the North Sea area.

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1 INTRODUCTION

The Geological Analysis and Resource Assessment of selected Hydrocarbon systems (GARAH) work package 2 overall aim is to assess and evaluate hydrocarbon resources across borders in the North Sea.

This report provides a brief update of the activities carried out so far, with a focus on work packages 2.2 and 2.3, which look at conventional and unconventional hydrocarbons (HC), respectively. Section 2 of the report outlines the current state of the offshore conventional assessment for each country and provides details on the play-based assessments conducted. Section 3 outlines activities related to shale oil and gas in the North Sea and details the screening process and assessments for unconventional HC by country. Section 4 describes the upcoming final tasks of the GARAH project WP2.

2 OVERVIEW OF THE CONVENTIONAL ASSESSMENTS, PETROLEUM SYSTEMS AND PLAYS

This part of the GARAH work programme first aimed to assess data availability related to conventional oil and gas resources in the North Sea study area. This exercise was completed in 2019, with each country providing a compilation of existing assessments, play types and exploration histories. The second part of the work package is to assess cross-border resources with a play-based focus, and our approach here is not only to compare existing reporting on resource assessment, but also to elucidate and compare methodologies. We are taking a play-based approach to collate information on conventional petroleum systems across the North Sea, and compare exploration data to see if further insight can be made regarding particular plays and regions of exploration interest. We are also compiling information on alternative use of the subsurface in the North Sea for activities such as hydrogen storage and geothermal potential.

2.1 State-of-the-art of conventional hydrocarbons in the North Sea offshore.

For each country, a brief overview of the current situation with regard to oil and gas exploration and production is provided, for example: current licensing activities; planned or recent exploration activities; relinquishments; production forecasts; government priorities and policy. Also, relevant overview publications and websites are listed. The original material for this section was compiled in 2018/19 and has been briefly updated for 2020 and 2021.

2.1.1 Denmark

Between 1993 and 2017, Denmark was one of the largest oil exporting countries in Europe having gained this position from its share in the highly prolific Danish Central Graben whereas the area outside the Central Graben has a little and highly uncertain resource.

In December 2020 Denmark introduced a cut-off date of 2050 for oil and gas extraction in the North Sea and cancelled all future licensing rounds. Hence no licences were awarded as part of the 8th rounds that was cancelled in 2020. It is expected that near field exploration will be possible and also that a plan for development of stranded discoveries will be made within the Danish part of the North Sea. However, the revised legislation is not in-place at the time of preparation of this report.

Relevant websites and publications

https://ens.dk/sites/ens.dk/files/OlieGas/ressourcer_og_prognoser_20180829_rev_en.pdf
https://en.kefm.dk/news/news-archive/2020/dec/denmark-introduces-cutoff-date-of-2050-for-oil-and-gas-extraction-in-the-north-sea-cancels-all-future-licensing-rounds
https://ens.dk/en/our-responsibilities/oil-gas/reports-oil-and-gas-activities

2.1.2 Germany

In Germany there are currenty five active licenses (as of 31.12.2017).

The last exploration well in the German North Sea was drilled in 2010 (L-1-2). All other wells (~40) drilled since 2009 are production wells or near-field (<5 km) new pool test wells. So far ~100 wild cat wells have been drilled in the German North Sea and one oil field (Mittelplate) and one gas field (A6-A) are in production. Additionally, approximately 100 development wells have been drilled.

In Germany no public license rounds are conducted. Companies can apply for licenses at the respective mining authority, which is the State Authority for Mining, Energy and Geology of Lower Saxony (LBEG) for the North Sea.

The search for economically meaningful natural resources like for example hydrocarbon, coal, lignite, potash and rock salt and their mining are subjected to the regulations of the Federal Mining Law in Germany (BBergG).

Relevant publications and websites:
www.gpdn.de
http://nibis.lbeg.de/cardomap3/#
Annual reports on Crude Oil and Natural Gas in Germany:
http://www.lbeg.niedersachsen.de/erdoel-erdgas-jahresbericht/jahresbericht-erdoel-und-erdgas-in-der-bundesrepublik-deutschland-936.html#english

2.1.3 The Netherlands

As of 1 January 2019 there are 486 discovered gas fields in the Dutch on- and offshore area. Of these discoveries 282 are in the continental shelf/offshore area, with 142 in production, 67 not (yet) developed and 73 (permanently) on hold. Since 2018 4 new fields were added to the discoveries, one new find and 3 previously discovered but deemed not prospective.

The natural gas resources as of 1 January 2019 are estimated at 245.9 billion Nm3, with 102.8 billion Nm3 on the continental shelf area. Compared to 2018 the resource estimate for the Groningen gas field was reduced by 471 billion Nm3 which is mostly related to the decision of the Dutch government to stop the production of gas from Groningen by 2022 and reducing the contribution of Groningen gas to the gas resources from 563 billion Nm3 to 73 billion Nm3 with 18.8 billion Nm3 actually produced gas in 2018. The small fields onshore contain 70.1 billion Nm3 of natural gas, the offshore fields are estimated to have 102.8 billion Nm3.

Current licensing policy: Although onshore production licenses from fields in production, or fields about to be developed, continue (with the exception of Groningen), no new exploration licenses are being granted for onshore. Offshore licensing applications remain steady, 2018 saw the application of one production license application and one exploration license application for a total area of roughly 11 license blocks (20*20 km each).

Production forecast for natural gas, including reserves, contingent and prospective is ~15.5 billion Nm3 Geq for 2019, resulting in a total expected production of 285 billion Nm3 until 2043. Groningen natural gas production is controlled by political mandate and is being rapidly reduced from a high of 57 billion Nm3 in 2012 down to zero probably as early as 2022.

The long term average exploration drilling rate is ~7 per year offshore, 3 per year onshore. However recent changes in public acceptance of onshore drilling and a low gas price has decreased this to 4 and 1, respectively.

Additional measures through additional financial tax relief for offshore developments have been announced by the Minister of Economic Affairs and Climate. A modest upturn in developments may occur once this will implemented in the Mining law in combination with and expected increase in natural gas prices.

Due to overall high NOx emissions exceeding current permitted levels, drilling activities close to natural reserves are currently being reduced or on hold. The drilling plans must be updated to comply with EU limits for NOx emission.

A yearly updated overview of the natural resources and geothermal energy in the Netherlands is published on https://www.nlog.nl/en/annual-reports

2.1.4 Norway

This introduction is based on the Resource Evaluation report issued in 2018 (NPD 2018).

Two types of licensing rounds with equal status are conducted on the NCS – numbered, and awards in predefined areas (APA). 5 APA rounds have taken place annually since 1999, while the numbered rounds in less-explored exploration areas are generally staged every other year. These regular rounds contribute to important predictability for the industry. The first licensing round in 1965 was clearly the most extensive in terms of acreage on offer. While the first four rounds were confined to the North Sea, parts of the Norwegian and Barents Sea were opened for exploration from the fifth round held in 1980-82.

Introduced in 2003, the APA scheme is intended to ensure efficient exploration of mature areas and to prove time-critical resources close to planned and existing infrastructure. It is important that acreage awarded gets explored quickly and efficiently so that existing infrastructure can be utilised in the best possible way and small discoveries are phased in swiftly if spare capacity is available. As new areas become mature, the APA coverage has been expanded on the basis of established criteria.

The 24th round was announced on 21 June 2017 with a deadline of 30 November 2017 for applications. It included 102 full or partial blocks – nine in the Norwegian Sea and 93 in the Barents Sea. 12 Production Licences Offered to 11 Companies in the 24th Licensing Round in June 2019. In the Norwegian part of the Central

Graben APA are reworded on a yearly basis. The deadline to apply for APA 2019 is 27th of August 2019 and awards are expected during the first quarter of 2020. The results of the APA 2018 was 83 production licences on the Norwegian Shelf that was the largest number ever awarded in one licensing round. Of the 83 production licences, 37 are in the North Sea, 32 in the Norwegian Sea and 14 in the Barents Sea. Eighteen of the licences are additional acreage to existing production licences. Map of current licenses: http://gis.npd.no/factmaps/html_21/

2.1.5 United Kingdom

Offshore oil and gas exploration in the UK sector of the North Sea has been ongoing since the 1960's. The oil and gas industry is regulated by the Oil and Gas Authority (OGA), part of the UK Government Department for Business, Energy, and Industrial Strategy (BEIS). The OGA regulates, promotes and influences the oil and gas industry in order to maximise economic recovery of oil and gas from the UK. The OGA carried out a significat review of strategy which was published in February 2021 here:

https://www.ogauthority.co.uk/news-publications/publications/2021/the-oga-strategy/

The OGA 2021 overview was published in March 2021 here:
https://www.ogauthority.co.uk/news-publications/publications/2021/oga-overview-2021/

The most recent OGA report on UK oil and gas reserves and resources was published in 2020 and can be found here:
https://www.ogauthority.co.uk/media/6681/uk_oil-gas-rr_2020.pdf

Oil and gas production from the UK North Sea peaked in 1999, and the OGA reports 42.3 billion barrels of oil equivalent (boe) total hydrocarbons produced since 1975 (updated October 2018 and March 2020). Of this, 39 bn boe of hydrocarbons have been produced from the North Sea area - 92% of total production (OGA, 2018). Up to date production information can be found and queried here:
http://data-ogauthority.opendata.arcgis.com/pages/production

Production is expected to decrease to between 0.2 and 0.4 mboe per year by 2050.

The OGA has generally run two licensing rounds every few years: one for mature areas; and one for frontier areas. The 31st round closed in November 2018, attracting 36 applications covering 164 blocks in frontier areas. A supplementary 31st licensing round, focusing on the Greater Buchan Area in the Outer Moray Firth, was opened on the 31st January 2019 and closed on on the 2nd May 2019. The 32nd licensing round closed on the 12th of November 2019 and in September

2020, the OGA offered 113 license areas over 260 blocks/part-blocks to 65 companies in mature areas.

New licensing rounds are currently (May 2021) paused while the OGA works with the UK government on a review of future licensing and the UK commitement to net zero carbon by 2050.

Up to date information on licensing rounds can be found here:
https://www.ogauthority.co.uk/licensing-consents/licensing-rounds/offshore-licensing-rounds/#tabs

The most recent summary of oil and gas reserves for the UK, published by the OGA in 2020, estimates proven and probable UKCS reserves at end 2019 as 5.2bn boe (barel of oil equivalent), with 240mn boe added in 2019. The UKCS contingent resource level of discovered but undeveloped resources is given as 7.4 bn boe, comprising appoximately 70% oil and 30% gas. Total mapped prospects and leads are estimated at 4.1 bn boe; and further statistical play analyses provided an additional risked mean prospective resource of 11.2 bn boe outside of mapped leads and prospects. The total of the discovered reserves and resources and prospective resources put the OGA estimate of remaining recoverable reserves for the UKCS at 10 to 20 bn boe, unchanged from the 2018 estimate.

Out of a mean 11.2 billion boe play-level prospective resources calculated by OGA in 2020, 3.7 boe are from the northern (0.9), central (1.5), southern (0.8) and mid-North Sea High (0.5) areas relevant to this study.

The full 2020 report is available here:

https://www.ogauthority.co.uk/media/6681/uk_oil-gas-rr_2020.pdf

2.2 Conventional hydrocarbon plays in the North Sea Basin

2.2.1 Play definition methods

This study defines a hydrocarbon play as an area where the geological factors that are a prerequisite for the generation and trapping of hydrocarbons coexist. Each play type is described and named after known productive reservoir intervals, but more hypothetical intervals are also described. Where possible, details of exploration (including fields and discoveries) may be incorporated, as well as each play element and trap type.

At the start of the project a questionnaire was designed to get an overview of the current state of knowledge on the hydrocarbon system of the participating countries. In the context of that questionnaire the following parameters were defined for the hydrocarbon play definition (Table 2-1). These parameters and their respective definitions are also used for the plays in the final GIS mapping.

Table 2-1 List of parameters for the conventional play description and their definitions

Parameter	Field Options	Definition
ID	Number	A consecutive number for the play type
Play type name	Text	Name of the play type, this can refer to e.g., the reservoir or structural unit or other
Play type status	Defined list	The status of the play type, the different options are mentioned below
	Mature	A mature play type is well known and explored and has been proven in many successful discoveries, it usually has limited potential for new discoveries
	Proven	A proven play type is known to work and has seen a few discoveries. There is still good potential for new discoveries
	New	A new play type has one discovery and is therefore known to work but its potential is still uncertain
	Con-ceptual	A conceptual play type has no discovery and it potential is unknown
Play type structural element	Defined list	A general description of the structural element type the play is mainly located in.
	Basin	
	Platform	
	High	
	Unspecified	
Play location	Text	The name of the structural element, the play is mainly located in. This can be very general like Southern North Sea or very specific like Northern Dutch Central Graben
Trap type	Defined list	A general description of the overall type of traps in the play type.
	Structural	
	Stratigra-phic	
	Both	
	Unknown	
Reservoir name	Text	The name of the main reservoir associated with the play type, probably the main lithostratigraphic name of the reservoir
Age (Age)	Defined list, see reference	The age of the source according to ICS 2018. If possible on age level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Age (Epoch)	Defined list, see reference	The age of the source according to ICS 2018. If possible on epoch level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL:

		http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Lithology	Defined list	A general subdivision based on overall lithology of the reservoir.
	Carbonate sedimen-tary rock	http://resource.geolba.ac.at/lithology/162
	Clastic sedimen-tary rock	http://resource.geolba.ac.at/lithology/161
	Igneous material	http://resource.geolba.ac.at/lithology/1
	Metamor-phic rock	http://resource.geolba.ac.at/lithology/98
	Mixed	
Lithology comments	Text	Anything else that needs to be specifically mentioned wwith respect to the lithology of the reservoir
Hydrocar-bon type	Defined list	The type of hydrocarbons that are mainly accumulated in this play type
	Oil	
	Gas	
	Conden-sate	
	Oil and Gas	
	Unknown	
Source name	Text	The name of the main source rock associated with the play type, probably the main lithostratigraphic name of the source rock
Source age (Age)	Defined list, see reference	The age of the source according to ICS 2018. If possible on age level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Source age (Epoch)	Defined list, see reference	The age of the source according to ICS 2018. If possible on epoch level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Source type	Defined list	The type of organic matter of the source rock according to standard van Krevelen/Rock-Eval classifications
	Type I	
	Type II	
	Type III	
	Type II/III	
Source type comments	Text	Anything else that needs to be mentioned over the source rock

Main seal	Text	The name of the main seal associated with the play type, probably the main lithostratigraphic name of the seal formation
Seal age (Age)	Defined list, see reference	The age of the source according to ICS 2018. If possible on age level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Seal age (Epoch)	Defined list, see reference	The age of the source according to ICS 2018. If possible on epoch level (Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013; updated) The ICS International Chronostratigraphic Chart. Episodes 36: 199-204. URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf)
Seal lithology	Defined list	A general subdivision based on overall lithology of the seal. The options are listed below
	Chemical sedimen-tary rock	http://resource.geolba.ac.at/lithology/165
	Carbonate sedimen-tary rock	http://resource.geolba.ac.at/lithology/162
	Clastic sedimen-tary rock	http://resource.geolba.ac.at/lithology/161
Seal Comments	Text	Anything else that needs to be mentioned over the seal

Plays for all countries have now been compiled (Figure 2-1) and the work package is focusing on harmonising information across borders to produce coherent play maps by reservoir and age.

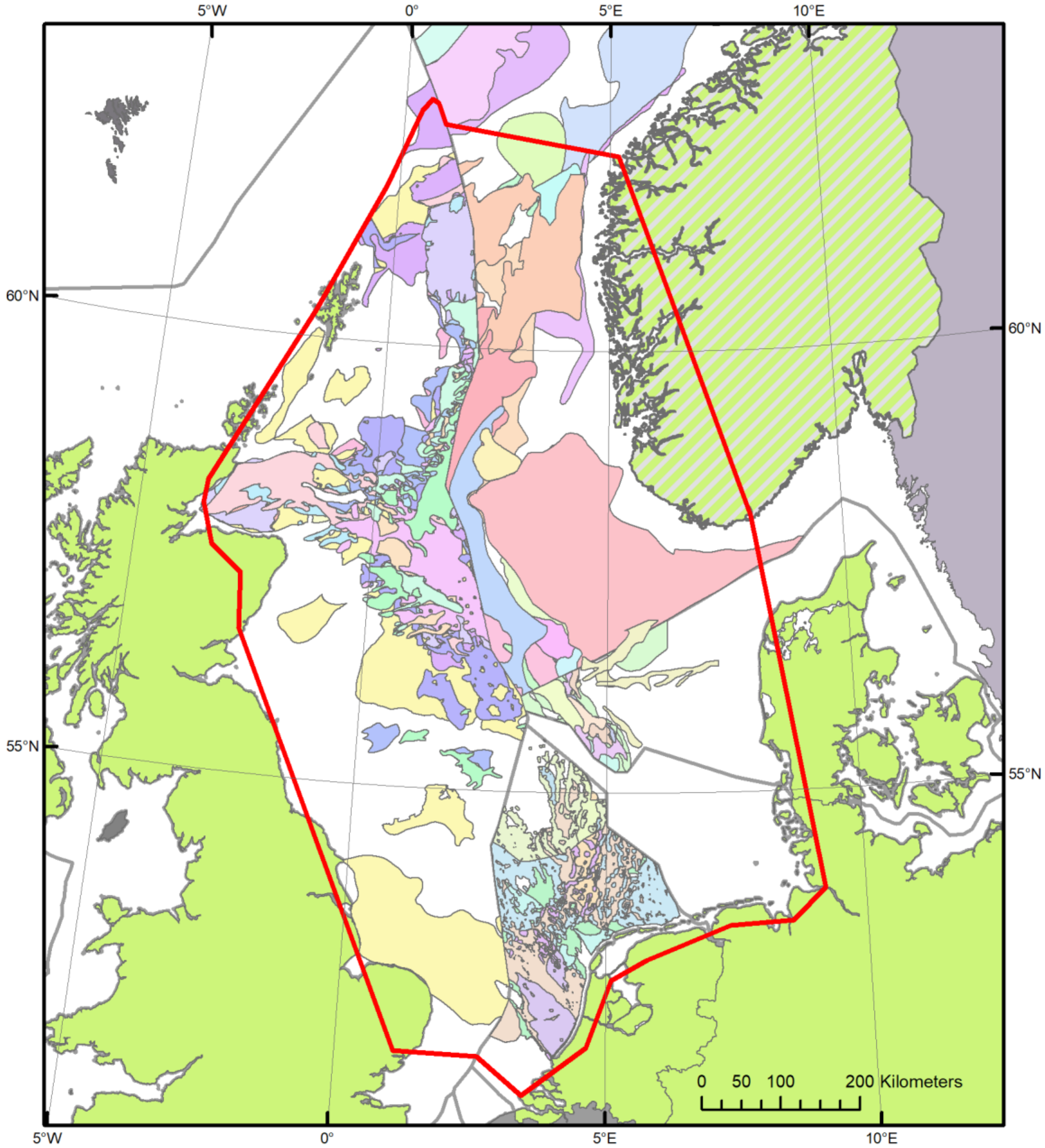

Figure 2-1 Example showing all play outlines in conventional GARAH GIS to be harmonised.

2.2.2 Summary of Play Types

Information on the main play types per country's North Sea sector are described below. Plays are listed based on: play type status (proven, conceptual etc.); reservoir (Age or Epoch and lithology); hydrocarbon present (i.e. heavy oil, dry gas etc); main source(s) (including age and kerogen types); main seal (including age and lithology); trap type (structural or stratigraphic). A general geographic location (e.g. Viking Graben, Broad Fourteens Basin) is also included in the deliverables.

For each country, a short summary is given, which play types have been most successful, which are relatively underexplored, and which are most promising for future exploration, as well as relevant references.

2.2.2.1 Denmark

The play maps and descriptions of plays in Denmark are mainly based on the report Schovsbo et al. (2020b). In this report a play is defined as a geographical area where the geological factors that are a prerequisite for generation and trapping hydrocarbons can occur simultaneously. The plays in Schovsbo et al. (2020b) include 12 plays. Here 6 additional plays are described and marked with "new". These additional plays are more hypothetical and has yet been proven.

The main petroleum source rock in Denmark is the Upper Jurassic – lowermost Cretaceous marine Farsund Formation. The Middle Jurassic coaly units of the Bryne and Lulu Formations constitute a secondary source, whereas unknown contribution may come from other source rocks including the Upper Jurassic Lola Formation, the Lower Jurassic Fjerritslev Formation, Permian shales and Carboniferous coals.

In Denmark 18 conventional play types are described and named after known productive reservoir intervals, but also more hypothetical intervals are described.

The plays include:

1. Mid Jurassic sandstone gas / condensate play
2. Upper Jurassic Kimmeridgian shallow marine sandstone oil play (Heno Formation)
3. Upper Jurassic Volgian shallow water marine sandstone oil / gas play (Outer Rough sandstone)
4. Intra Farsund Formation sandstone oil / gas play (Kimmeridge - lower Volgian)
5. Upper Farsund Formation sandstone oil play (between Volgian - Ryazanian)
6. Lower Cretaceous Chalk oil / gas play (Tuxen and Sola Formations)
7. Upper Cretaceous Chalk oil / gas play (Hidra and Kraka Formations)
8. Upper Cretaceous Chalk oil / gas play (Tor and Ekofisk Formations)
9. Palaeogene sandstone oil / gas play in the Siri Canyon
10. Paleogene sandstone on the Ringkøbing Fyn High (new)

11. Neogene sandstone on the Ringkøbing Fyn high (new)
12. Miocene diatomite in the Lark Fm (new)
13. Rotliegend Sandstone (pre-Jurassic)
14. Zechstein Carbonate (pre-Jurassic)
15. Jurassic Sandstone on Ringkøbing Fyn high (new)
16. Triassic sandstone (pre-Jurassic)
17. Ekofisk - Tor Fm on the Ringkøbing Fyn High (new)
18. Palaeogene-Neogene Sandstone – biogenic (new)

Plays no. 2 - 9 depend on the same well-established Upper Jurassic – lowermost Cretaceous Farsund Formation, while plays no. 13-16 depend on deep-lying source rocks of Carboniferous; of which quality and distribution are very uncertain in the Danish Central Graben.

2.2.2.2 Germany

The plays in the German North Sea include Paleozoic, Mesozoic and Cenozoic source rocks.

<u>Paleozoic source rocks</u>

Lower Carboniferous coals (type III kerogen) are present in the northwestern part of the German North Sea ("Duck's Bill") (Kombrink et al., 2010). The coal bearing strata were deposited in a fluvial-lacustrine environment of the Yoredale delta the Dinantian. Potential reservoir rocks are Permian and Jurassic sandstones. Zechstein salt and Mesozoic claystones pose potential seals. The only German offshore gas field, A6/B4 is potentially charged by this source rock. It produces gas and condensate from Upper Jurassic and Zechstein sediments.

Upper Carboniferous (Westphalian) coals (type III kerogen) are the main source rock for gas onshore Germany and of the neighbouring Netherlands (onshore and offshore). Westphalian source rocks are present in the southern and southwestern German North Sea (Kombrink et al., 2010). In the H and L block in the area, some gas fields were discovered (H15-SE, L1-Alpha, and L2-D1). However, the fields are not in production. The most probable reservoir rock for Westphalian gas (like ~ 80 % of the fields in the area), is the Permian Rotliegend sandstone.

<u>Mesozoic source rocks</u>

The Lower Jurassic Posidonia Shale Formation (type I – II kerogen) is the most important source rock for oil onshore Germany. In the German North Sea, the Posidonia Shale Formation is the source rock of Mittelplate, the only German offshore oil field. The oil is produced from Middle Jurassic sandstones, which pinch out on the flank of a Zechstein salt dome (Pletsch et al., 2010). Remnants of the Posidonia Shale Formation are also assumed in the German Central Graben, but are not confirmed by wells. Other potential source rocks in the area of the German Central Graben are Jurassic claystones or coals (Mueller et al., 2020). Potential reservoir rocks are Middle Jurassic sandstones or carbonates from the Upper Cretaceous Chalk group.

Cenozoic source rocks

In the area of the German Central Graben, there are several shallow gas accumulations that are analogue to producing shallow gas fields offshore The Netherlands (Mueller et al., 2018). The gas is located in unconsolidated Plio-Pleistocene sediments and is trapped in anticlines above Permian Zechstein salt domes. The source of the gas is still part of a discussion. A microbial origin from Tertiary clay and/or a thermogenic origin from Jurassic claystones or coals are under consideration (ten Veen et al., 2013; Verweij et al., 2018; Mueller et al., 2020).

2.2.2.3 The Netherlands

The play maps for the Netherlands are based on the present-day outlines of the mapped reservoir units according to the distribution maps published on www.nlog.nl from the DGM-deep V3 offshore models. They are merged on stratigraphic interval combined with the present-day occurrences of the respective source rock units, including a possible charge range of 10 km.

Paleozoic source rocks

The most important natural gas play in the Dutch offshore area is the Westphalian sourced Paleozoic play. The Westphalian coal measures are the principal source rock, which, in combination with the good reservoir sandstones of the Rotliegend and the excellent sealing capacity of the Upper Permian Zechstein evaporites form the play for most of the natural gas accumulations. Westphalian coal sourced natural gas is also found in less quantities in clastic and carbonate reservoirs ranging from Upper Carboniferous to Cretaceous age.

Lower Carboniferous play

The Lower Carboniferous play is considered a conceptual play. Based on cross-border studies in the northern part of the Dutch offshore, the German Entenschnabel and the UK offshore region it is known that the Lower Carboniferous sediments contain considerable amounts of coal. So far no discovery in the Dutch offshore region was explicitly attributed to this source but its source potential is currently under review and can be considered the most promising new play.

Mesozoic source rocks

The most important oil play in the Dutch offshore is the Toarcian Posidonia shale play. The main reservoirs of this play are either the Jurassic-Cretaceous Delfland and Vlieland Sandstones or Triassic reservoirs in the Broad-Fourteens and West Netherlands Basin or the Upper Jurassic to Lower Cretaceous sandstones and Upper Cretaceous Chalk Group reservoirs in the Dutch Central Graben.

Current studies suggest that the theoretical source potential of the Upper Jurassic in the north of the Dutch offshore is immature for oil generation.

Cenozoic source rocks

Several discoveries in the northern part of the Dutch offshore were made in Neogene sediments at depth between 500 and 1000m. The source of these shallow gas fields is still unknown, current studies suggest a mostly biogenic source (Verweij et al. 2018).

Doornenbal et al. (2019) have recently published a paper summarizing the exploration history and play systems of the North Sea area. Previous summaries have been published by, e.g., Breunese et al. (2010) and de Jager and Geluk (2007).

2.2.2.4 Norway

A total of 24 plays have been defined by the NPD for the Norwegian part of the North Sea area (see attached spreadsheet). Of these four and unconfirmed. The most successful in terms of resource volumes are the Cretaceous Chalk and Jurassic Sandstones reservoirs sources from the Upper Jurassic shales. The most promising in term of future development is the Upper Triassic to Lower Jurassic Sandstones plays sourced from Jurassic source rocks.

The 24 NPD defined play types are listed in the Appendix. For each play a map polygon is associated. These polygons are available in Esri format to the GARAH project and have been incorporated in the overview.

2.2.2.5 United Kingdom

Figure 2-2 and Figure 2-3 summarise the UK play types in the Central and Northern, and Southern North Sea, with a total of 48 general plays identified. In the southern North Sea, pre-rift gas-dominated petroleum systems/plays have been most successful. In the central and northern North Sea, Palaeocene/Eocene reservoirs sourced by Upper Jurassic/Lower Cretaceous Kimmeridge Clay Formation shales, have found most success.

To enable correlation of these plays with neighbouring countries, plays in the UK were grouped into 17 play types defined by stratigraphical age and depositional environment of the reservoir formations. This grouping is illustrated in Figure 2-2 and Figure 2-3.

In the Northern and Central North Sea, hydrocarbons are found in pre-rift tilted fault block traps of Carboniferous to Middle Jurassic age, syn-rift structural and combination traps of Upper Jurassic and Lower Cretaceous age, and post-rift stratigraphic traps of Upper Cretaceous to Eocene age. Shallow gas accumulations in post-Eocene strata have also been identified as a conceptual play.

Play types include:

1. Post-Eocene plays: Shallow/biogenic gas (conceptual)
2. Eocene T60-T98 plays: localised basinal fan sandstones
3. Paleo-Eocene T45-T50 plays: progradational shelf/deltaic sandstones
4. Paleocene T20-T40 plays: extensive basinal fan sandstones
5. Upper Cretaceous plays: Reworked chalk in structural traps
6. Lower Cretaceous plays: Slope apron/basin floor fan sandstones
7. Upper Jurassic shelfal plays: Shallow marine/shelf sandstones
8. Upper Jurassic basinal plays: Deep marine basinal fan sandstones
9. Middle Jurassic plays: Fluvial-deltaic sandstones
10. Triassic-Lower Jurassic plays: Fluvial-deltaic-shelf sandstones
11. Permian Zechstein play: Intra-Zechstein carbonate reservoirs
12. Palaeozoic plays: Carboniferous and Devonian sandstones

In the Southern North Sea, the majority of gas discoveries have been found in Permian and Carboniferous sandstones that subcrop beneath thick Zechstein evaporites. The Zechstein forms an important seal in the basin, and discoveries in younger (Triassic) strata are largely restricted to the basin margins where Zechstein evaporites transition into clastic facies, or to the crests of some salt anticlines where the underlying Zechstein seal has been breached. Additional potential may exist in Lower Carboniferous (Dinantian) carbonates charged by onlapping Carboniferous shales, however this play remains conceptual and the distribution of potential reservoirs is largely unmapped.

1. Triassic sandstones play (Bunter)
2. Upper Permian carbonates play (Zechstein)

3. Lower Permian aeolian sandstones play (Rotliegend)
4. Carboniferous fluvial-deltaic sandstones play
5. Lower Carboniferous (Dinantian) carbonates play

In 2014, the Oil and Gas Authority (OGA) recognised unexplored potential in Palaeozoic petroleum systems (and plays) in the UK and launched a joint BGS/industry/government research project to investigate the potential for Palaeozoic plays: of interest to this work were the studies on Carboniferous and Devonian petroleum systems carried out on the mid North Sea High (Monaghan, 2016a) and Orcadian Basin (Monaghan, 2016b).

The OGA has also recently released details of 300+ undeveloped discoveries/clusters in UK waters, which can be explored using this tool:
https://data-ogauthority.opendata.arcgis.com/pages/statistics

High pressure, high temperature (HPHT) plays in the central North Sea are the largest discoveries in the area for the last decade, and comprise around 15 BBoe hydrocarbons in place, with 32 undeveloped opportunities. The Glengorm discovery well was drilled in 2019 and found gas and condensate in a high quality Upper Jurassic reservoir (OGA Overview 2020). Other underexplored plays of interest are Triassic Sandstones (Morris and England, 2018) and Cretaceous chalks in the central North Sea.

Phase	Play	Play units
Post-rift	**Post-Eocene plays**: Shallow/biogenic gas in combination/stratigraphic traps	Quaternary Pliocene Oligo-Miocene
Post-rift	**T60-T98 Eocene plays**: Small localised submarine fans Incl. Alba/Tay/Frigg	Alba Tay Frigg
Post-rift	**T45-T50 Paleo-Eocene play**: Progradational shelfal/deltaic sands and small, localised basinal fans in 4-way compaction drapes Incl. Balder/Sele/Dornoch/Beauly	Balder Ninian Sele Teal-Heimdal
Post-rift	**T40 Forties play**: Aggradational fan	Forties
Post-rift	**Paleocene T20-T30 plays**: Extensive submarine fan systems Incl. Balmoral/Andrew/Heimdal/Maureen	Mey Maureen
Post-rift	**Upper Cretaceous play**: Reworked chalk in structural traps.	Chalk
Post-rift	**Lower Cretaceous plays**: End syn-rift and early post-rift deposition of deep-water slope apron/basin floor fans in stratigraphic/combination traps	Kopervik DevilsHole-Scapa Lower_Cretaceous
Syn-rift	**Upper Jurassic plays**: 1. Shallow marine/shelf sandstones around basin margin (Fulmar, Hugin, Piper) 2. Deep-marine submarine fan sandstones (Magnus, Brae)	Fulmar Piper Alness Brae-Kimmeridge Kimmeridge Heather Magnus
Pre-rift	**Middle Jurassic plays**: Fluvial-deltaic sandstones in tilted fault block traps, often in eroded footwall highs. Dominated by northward prograding Brent delta system	Beatrice Pentland Fladen-Hugin Brent-Emerald Beryl
Pre-rift	**Triassic-Lower Jurassics**: Subcrop/tilted fault block traps below BJU/BCU; anticlinal structures at BCU above inter-salt pods, and complex faulted/tilted closures due to pod rotation/gravity sliding Distribution salt-controlled in CNS. Charge via juxtaposition against UJ source rocks	Dunrobin Nansen Statfjord Cormorant Skagerrak
Pre-rift	**Paleozoic plays**: Zechstein carbonates, L. Permian sandstones, and fractured Devono-Carboniferous sandstones Fault-bounded traps in footwall highs along basin margin/intra-basin highs Charge via faults from downthrown Upper Jurassic source rocks	Hopeman Zechstein-Halibut Rotliegend Carboniferous Devonian Devonian Carbonates Basement

Figure 2-2: UK plays identified in the Central and Northern North Sea.

Play	Play units
Triassic sandstones play: Anticlinal closures above breached or poor Zechstein seal	Bunter-Hewett
Permian carbonates play: Fractured Z1-Z4 carbonates in structural traps	Zechstein
Permian sandstones play: Aeolian sandstones in fault block or pinch-out traps	Rotliegend
Carboniferous sandstone plays: Fluvial-deltaic sandstones in Variscan folds or fault traps along intra-basin highs	Westph_Red_Beds Westph_Coal_Measures Namurian
Dinantian carbonates play:	Dinantian

Figure 2-3 UK plays in the Southern North Sea

The play maps have been compiled from published maps of reservoir distribution and depositional environment (OGA and Lloyds Registry, 2019, Kubala *et al*. 2003). Each play type is defined by the limit of the merged reservoir facies for the component plays. Reservoir maps are overlaid with source maturity and migration limits (Millenium Atlas, 2002), known hydrocarbon occurrences, and other relevant structures (e.g. salt piercements) in order to identify the prospective areas of the play.

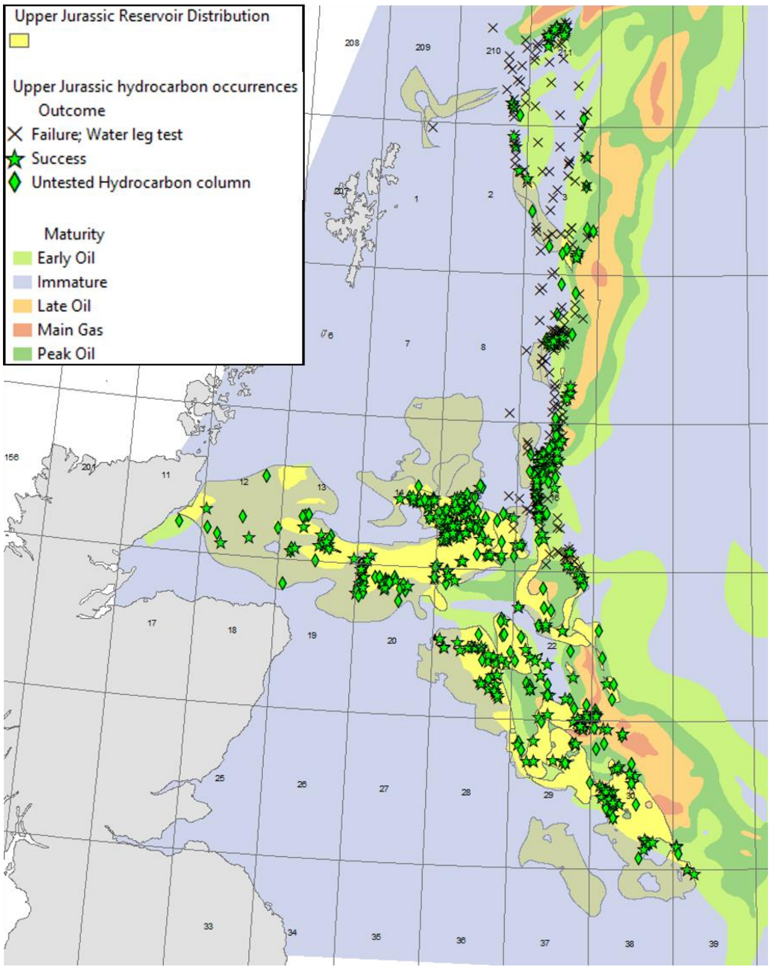

Figure 2-4 Example play map for the Upper Jurassic shelfal play, UK Sector. Contains information provided by the OGA.

2.2.3 Table based on GIS

The tables with the plays identified in the GARAH project for the participating countries are shown in the Appendix and summarised as shown in

Table 2-2. More detailed descriptions of the plays will be given in a final report.

Table 2-2 List of fields and the field descrition from the homogenized play definition GIS file

Field	Field Description
FID	An automatically assigned consecutive number for each element in the file
Shape	Polygon
Id	A unique ID assigned to each play
Name	The name of the play
Status	The status of the play, options are mature, proven, new and conceptual
Struct	The type of structural element in which the play is located, options are, basin, platform, high or unspecified
Locn	The names of the respective structural elements
Trap	Most common trap type in the play, options are structural, stratigraphic or both
Res1	The name of the main reservoir in the play
Age	The age of the main reservoir on age level
Epoch	The age of the main reservoir on epoch level
Lith	The lithology of the main reservoir, options are carbonate sedimentary rock, clastic sedimentary rock, igneous material, metamorphic rock or mixed
Lith_com	Comments on the lithology
HC_type	Main hydrocarbon type in the play, options are oil, gas, condensate, oil and gas or unknown
HC_type 2	Other possible hydrocarbon type in the play, options are oil, gas, condensate, oil and gas or unknown
Src	Name of the main source rock formation of the play
Src_age	The age of the main source on age level
Src_epoc	The age of the main source on epoch level
Src_typ	The type of organic matter according to the Rock-Eval classifications, options are type I, type II, type III or type II/III
Src_com	Comments on the source rock
Seal1	The name of the main seal of the play
Seal_age	The age of the main seal on age level
Seal_epo	The age of the main seal on epoch level
Seal_lith	The lithology of the main seal, options are chemical sedimentary rock, carbonate sedimentary rock or clastic sedimentary rock
Comm	Comments on the seal
Cntry	The country in which the play is located
Res2	Other reservoir formations associated with the play
Res3	Other reservoir formations associated with the play
Res4	Other reservoir formations associated with the play
Src2	Other source rock formations associated with the play
Src3	Other source rock formations associated with the play
Src4	Other source rock formations associated with the play
Seal2	Other seal formations associated with the play
Seal3	Other seal formations associated with the play
Seal4	Other seal formations associated with the play

3 UNCONVENTIONAL PETROLEUM SYSTEMS

3.1 Shale oil and gas Activities in the North Sea

Below follows a brief description of the unconventional exploration activities, if any, in the North Sea. A summary for all countries is presented in Table 3-1.

3.1.1 Denmark

Two main unconventional plays are recognised: the Jurassic Farsund play (Schovsbo et al., 2020b) and the Palaeozoic Alum Shale play (Schovsbo et al., 2014). The Farsund Formation is the main source rock in the Danish North Sea (Schovsbo et al., 2020a, b, Petersen and Hertle 2021). In the Farsund unconventional play no dedicated exploration well data exist, and the potential is unknown apart from a few test data made in 1982. Here the exploration well Jens-1 drilled a more than 10 m thick fractured zone of shales and dolomite stringers within the Farsund Formation. The well tested around 1200 barrels oil per day from a drill stem test. Later, an additional test was made in connection with a production well in the Lower Cretaceous Valdemar Field. The operator estimated a potential of $1.5 \cdot 10^9$ m^3 oil in-place (OIP) within the upper 700 m of the formation within an area of 50 km^2 (Andersen et al., 2015 in Schovsbo et al., 2020b). However, the test did not produce, and the project was abandoned with the conclusion that the production potential was very limited.

The Alum Shale play has been drilled onshore in 2015 with poor results form a oil and gas production point of view (Schovsbo and Jakobsen, 2019). The potential in the Alum Shale was assessed in a joint GEUS-USGS effort in 2013 (Gautier et al., 2013) and later in 2017 in the GEUS-TNO lead project EUOGA (Zijp et al., 2017). Although it is assumed that the Alum Shale extends offshore into the North Sea (Gautier et al., 2013) then there is practically no data coverage and the play status here is highly hypothetical.

In Denmark, newly implemented oil and gas legislation does not allow oil and gas production after 2050. New oil and gas exploration and development licences will not be issued except possibly near -field exploration and development of stranded discoveries.

3.1.2 Germany

In the German North Sea sector, no unconventional hydrocarbon exploration activities have been undertaken or are ongoing and no assessments of unconventional resources of the offshore areas have been made. The onshore unconventional shale resources were assessed in 2016 (BGR 2016).

3.1.3 UK

There are no current offshore shale gas exploration activities. One offshore licence was let for shale gas (2014) but no activity took place (https://www.bbc.co.uk/news/business-26157228). Onshore a total of 11 wells have been drilled with ~10 additional wells planned or permitted. One vertical well and one horizontal well (6 stages) have been hydraulically fractured. Onshore that is a moratorium in place for unconventional exploration pending assessment of environmental impacts.

Offshore unconventional plays in the UK North Sea have not been assessed so far. Cornford et al., (2014) presented a sweet spot analysis for a hybrid tight sand shale system within the Upper Jurassic Kimmeridge Shale Formation. Onshore assessment of the Carboniferous Bowland is presented by Andrews (2013) and for the Jurassic in southern England by Andrews (2014).

3.1.4 Norway

Potential unconventional resources in Norway are limited to the offshore region due to geological conditions. Galluccio et al. (2019) presented a sweet spot analysis of the Upper Jurassic Mandal Formation (Farsund and Kimmeridge Clay equivalent). According to this study a sweet spot in this sequence is characterised by mature shales with numerous interbeds of dolomite stringers.

No unconventional hydrocarbon exploration activities are currently ongoing, and no assessment of the unconventional resources has been made.

3.1.5 The Netherlands

There is currently no offshore shale gas/oil exploration and also no resource assessments have been undertaken or are planned. Between 2013 and 2015 two industry sponsored research projects were carried out at TNO with the aim of characterising the shale gas reservoir properties of the Posidonia Shale Formation in the Dutch subsurface on- and offshore (Ten Veen et al., 2014; Nelskamp et al., 2015). In addition, several assessments have been published for the onshore area of the Netherlands, the latest in the context of the EUOGA project (Zijp et al., 2017). Onshore exploration has been on hold since 2010 in order to perform research into possible effects and risks of shale gas. The moratorium status has been extended a number of times, latest by a decision on 10th July 2015, extending the moratorium for 5 years without drilling activities for shale gas. There are currently no licenses for shale gas/oil exploration and no wells have been drilled for that purpose.

Table 3-1 Unconventional assessments and exploration status of the North Sea area.

Country	Remarks	Exploration onshore	Exploration offshore
Denmark		yes	yes
USGS 2013	Assessment Palaeozoic shales		
Schovsbo et al. 2014	Sweet Spot Characterisation Palaeozoic shales		
Andersen et al. 2015	Jurassic test data offshore		
Schovsbo & Jakobsen 2019	Cambrian test Data		
Galluccio et al. 2019	Sweet Spot Characterisation offshore, Jurassic		
Germany		no	no
BGR, 2016	Assessment onshore		
The Netherlands		yes	no
Bergen et al. 2013			
Muntendam-Bos, et al. 2009			
Ten Veen et al. 2014	Sweet Spot Characterisation onshore		
Nelskamp et al. 2015	Sweet Spot Characterisation offshore		
UK		yes	no
Cornford et al. 2014	Sweet Spot Characterisation offshore, Jurassic		
Andrews, 2013	Assessment Bowland Onshore		
Norway		no	no
www.NPD.no	Conventional play maps Norway		
Galluccio et al. 2019	Sweet Spot Characterisation offshore, Jurassic		
Regional Assessments			
Gautier 2005	Kimmeridge Clay total resource system offshore		
EUOGA, Ziip et al. 2017	Assessment and characterisation onshore		

3.2 Screening of the North Sea Basin for unconventional plays

As part of the GARAH project, screening for potential unconventional hydrocarbon resources was performed. The screening parameters used are presented in Tables 3-2 and 3-3 and reflect commonly accepted properties for identifying potential shale gas and oil layers based on the experience from US as well as European shale plays (EIA, 2011; 2013; Charpentier & Cook, 2010; Schovsbo et al., 2017; BGR, 2016).

Table 3-2 Screening criteria for thermogenic shale oil and gas layers.

Geological Properties:	Value/comment
TOC content and type	> 2%, Type I-II
Thermal maturity	>0.6% R_o, oil mature
Thickness	>20 m
Present day depth	< 5? km
Mineralogy	Brittle preferentially
Pressure regime	Normal to overpressure
Structural complexity	Low to moderate

Table 3-3 Screening criteria for biogenic shale gas layers.

Geological Properties:	Value/comment
TOC content and type	> 2%, Type I-II
Thermal maturity	<2% R_o, dry gas mature
Thickness	>20 m
Present day depth	< 2 km
Mineralogy	Brittle preferentially
Pressure regime	Normal to overpressure
Structural complexity	Low to moderate

3.3 Unconventional shale plays in the North Sea Basin

From the screening phase of the GARAH project 13 shales were identified (Table 3-4). The shales include the known source rock levels in the North Sea notably the Upper Jurassic to lowermost Cretaceous shales: Kimmeridge Clay Formation in the UK, the Farsund Formation in Denmark and Germany, and the Mandal Formation and Heather Formation in Norway. Also, the Lower Jurassic Posidonia shale in the Netherlands, Germany, Denmark (The Fjerritslev Formation) and UK. Apart from these Jurassic shales the Triassic Sleen Formation in Germany, the marine Carboniferous Bowland equivalent shales from UK and the Geverik Formation from the Netherland and the Cambrian-Ordovician Alum Shale from Denmark were identified. The latter shale and the Lower Jurassic Fjerritslev formation in Denmark are, however, poorly defined offshore and hypostatical and is not associated with a proven petroleum system or poorly mapped or both and therefore not all is considered relevant for assessing (Table 3-4).

Table 3-4 Result of the screening for shale oil and gas plays in the North Sea Basin.

Status, 29012021

CP index	Basin	Countries	Shale	Age	Maturity	Exploration	Area analysis	Status
3001	North Sea	Dk	Alum Shale	Cambrian - Ordovician	Gas	No -Explored Onshore (T1)	Not assessed	Hypothetical
3002	DK Central Graben	Dk	Bo Member, Farsund Formation	L Cretaceous	gas	Yes - preliminary	From 3D GeoERA model	Active petroleum system
3003	DK Central Graben	Dk	Farsund Fm (excl Bo member)	U Jurassic	Oil	no	From 3D GeoERA model	Active petroleum system
3004	DK Central Graben	DK	Posidonia Shale eq.	L Jurassic	gas	no	Not assessed	Hypothetical
3005	N Central Graben	N	Mandal Formation	U Jurassic _L Cretaceous	gas-oil	no	From Millennium Atlas polygons	Active petroleum system
3006	D Central Graben	D	Sleen Fm	Rhaet-Trias	Oil	No	Volume from 3D model	hypothetical
3007	D Central Graben	D	Posidonia Shale	L Jurassic	Oil	No -Explored Onshore (T25c)	From 3D GeoERA model	Active petroleum system
3007	D Mittelplate	D	Posidonia Shale	L Jurassic	Oil	No -Explored Onshore (T25c)	From 3D GeoERA model	Active petroleum system
3008	D Central Graben	D	Hot Shale - Bo Member eq.	L Cretaceous	Oil	No	From 3D GeoERA model	Active petroleum system
3009	NL Central Graben	NL	Geverik Member; Bowland Eqv.	Mississippian	Oil - gas (?)	No -Explored Onshore (T10a)	From 3D GeoERA model	
3010	NL Central Graben	NL	Posidonia Shale	L Jurassic	Oil	No -Explored Onshore (T25a)	From 3D GeoERA model	
3011	North Sea	UK	Bowland-Hodder Eqv.	M Carboniferous	Gas	No -Explored Onshore (T10b)	From BGS polygons	
3012	North Sea	UK	Lias; Posidonia Shale eq.	L Jurassic	oil-gas	No	From Millennium Atlas polygons	Active petroleum system
3013	North Sea	UK	Kimmeridge Clay	U Jurassic	oil-gas	No	From Millennium Atlas polygons	Active petroleum system

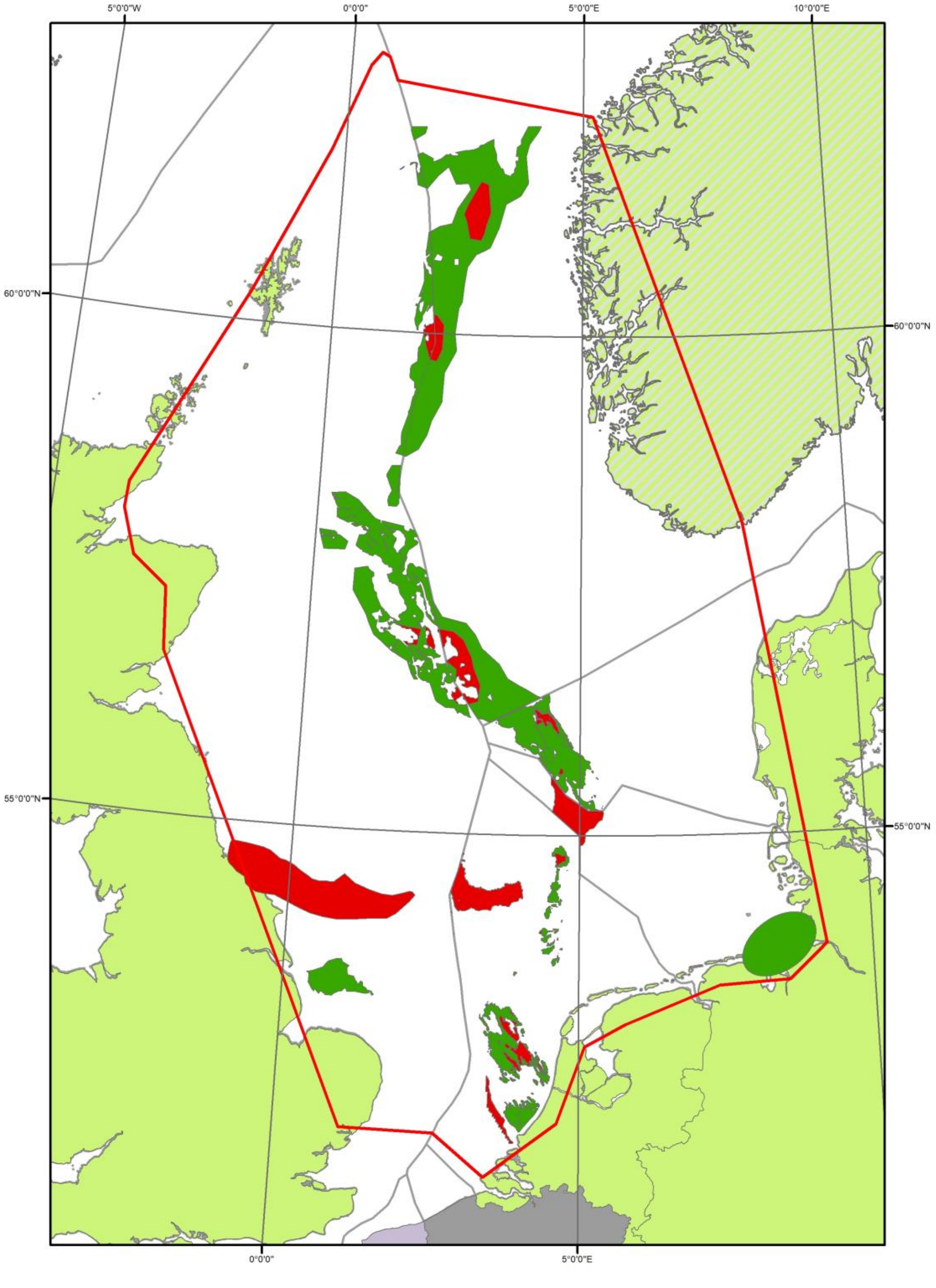

Figure 3-1 Occurrence of all 13 shales play outlines in unconventional GARAH GIS.

The Jurassic shales occur mostly in the Central Graben area apart from the Lower Jurassic in the Mittelplate Basin in Germany that occur separate and the older shales that typical occur outside of the Central graben (Figure 3-1).

Below follows a geological description of the identified shales and the basin development.

3.3.1 Denmark

In Denmark the Farsund Formation has been divided into an oil play represented by the Bo Member of the formation and a gas/oil play represented by the deeper parts of the formation (Figure 3-2 and 3-3). For calculating the area of the Bo Formation, we use the depth and maturity of the topmost Farsund Formation and for the deeper gas/oil play we use the depth of the mid-base Farsund Formation.

In the Bo Member the oil mature area that is within the 1-5 km depth range is 3772 km^2 whereas the gas mature area is insignificant (18 km^2) (Table 3-5). In the deeper regions of the Farsund Formation the oil and gas mature area slightly decreases (2564 km^2 and 280 km^2 respectively, Table 3-5).

Table 3-5 Oil and gas mature areas in the Danish part of the Central Graben.

Bo Member (CP 3002)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Area oil mature	3772	189	3583		3961	km^2	2a
Area gas mature	18	1	17		19	km^2	2a
Thickness			15	35	50	m	
Deep Farsund (CP 3003)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Area oil mature	2564	128	2436		2692	km^2	2a
Area gas mature	280	14	266		294	km^2	2a
Thickness			20	100	100	m	

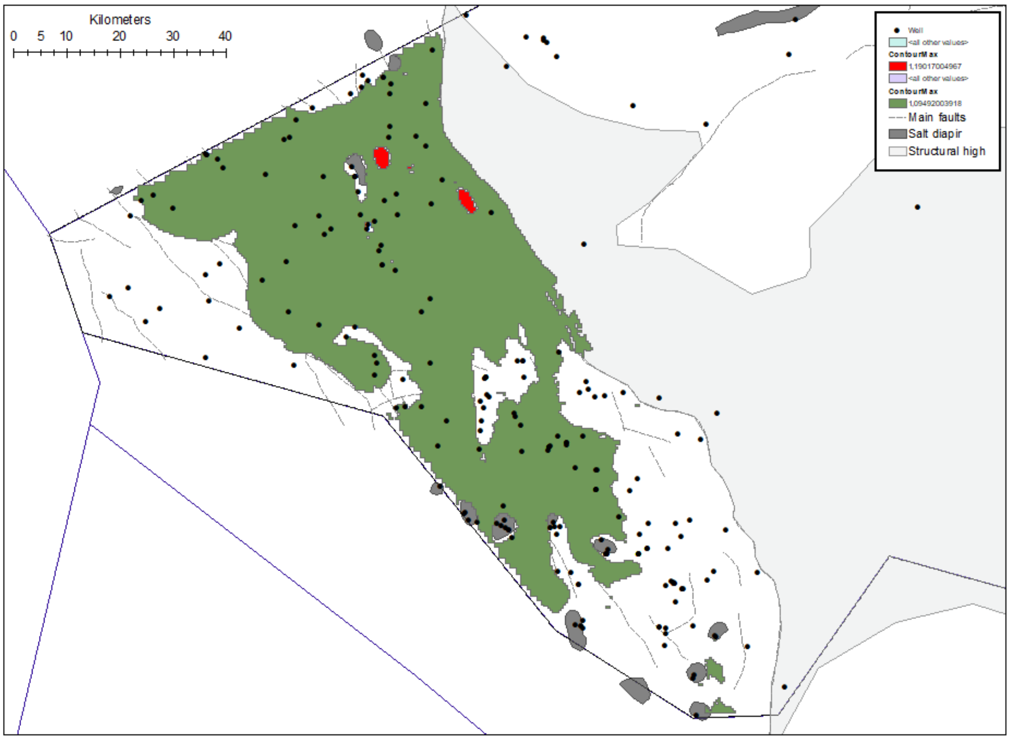

Figure 3-2 The Bo Member of the Farsund Formation oil mature area in the Danish Central Graben (CP 3002) between 1 – 5 km present day.

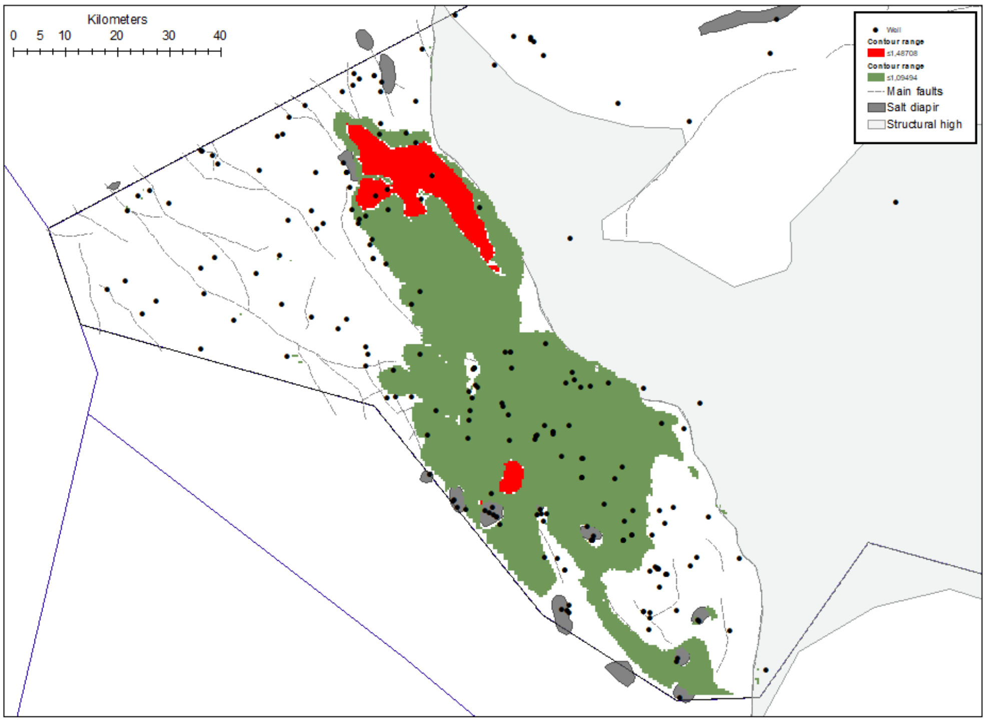

Figure 3-3 The oil and gas mature areas of the Upper Jurassic Farsund Formation (CP 3003) in the Danish Central Graben between 1 – 5 km present day.

3.3.2 Germany

The oil and gas mature area on the Triassic Sleen Formation (Figure 3-4) that is within 1 – 5 km depth is 500 and 250 km^2 respectively (Table 3-6). In the Central Graben the Posidonia shale is only developed as oil play with a mature area of about 900 km^2. In the Mittelplate area the Posidonia is developed as both a gas and oil play with 197 and 470 km^2 respectively. Like Denmark the upper part of the Farsund formation is developed as an oil play with around 650 km^2 being mature (Table 3-6).

Table 3-6 Area of gas and oil mature plays in the German part of the North Sea Basin.-

Sleen Formation (CP 3006)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	500	250	375		625	km^2	5b
Gas mature area	250	125	188		313	km^2	5b
Thickness (net)			5	20	30	m	
Posidonia Shale (CP 3007)							
Present day 1 – 5 km							
For Mittelplate AU:							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	900	135	833		968	km^2	3b
Gas mature area	–					km^2	
Thickness (net)			20	35	50	m	
For Entenschnabel AU:							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area			29	250	470	km^2	5b
Gas mature area			6	102	197	km^2	5b
Thickness (net)			20	35	50	m	
Hot Shale (CP 3008)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	650	325	488		813	km^2	5b
Gas mature area	–					km^2	5b
Thickness (net)			5	15	30	m	

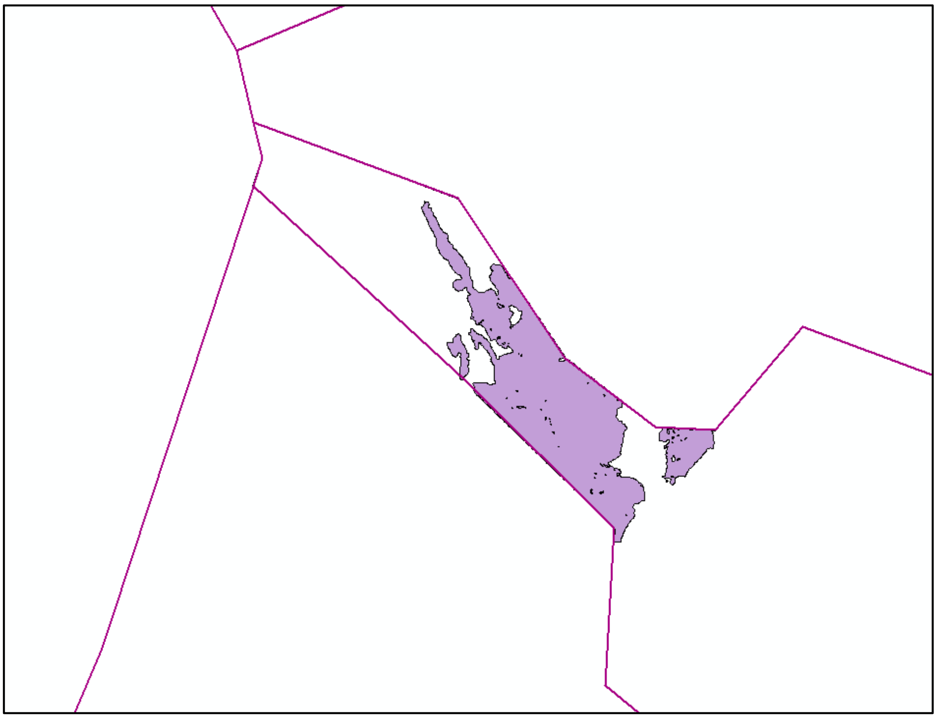

Figure 3-4 Extent of the potential Upper Triassic Rhaetian source rock (CP 3006) in the German part of the southern Central Graben.

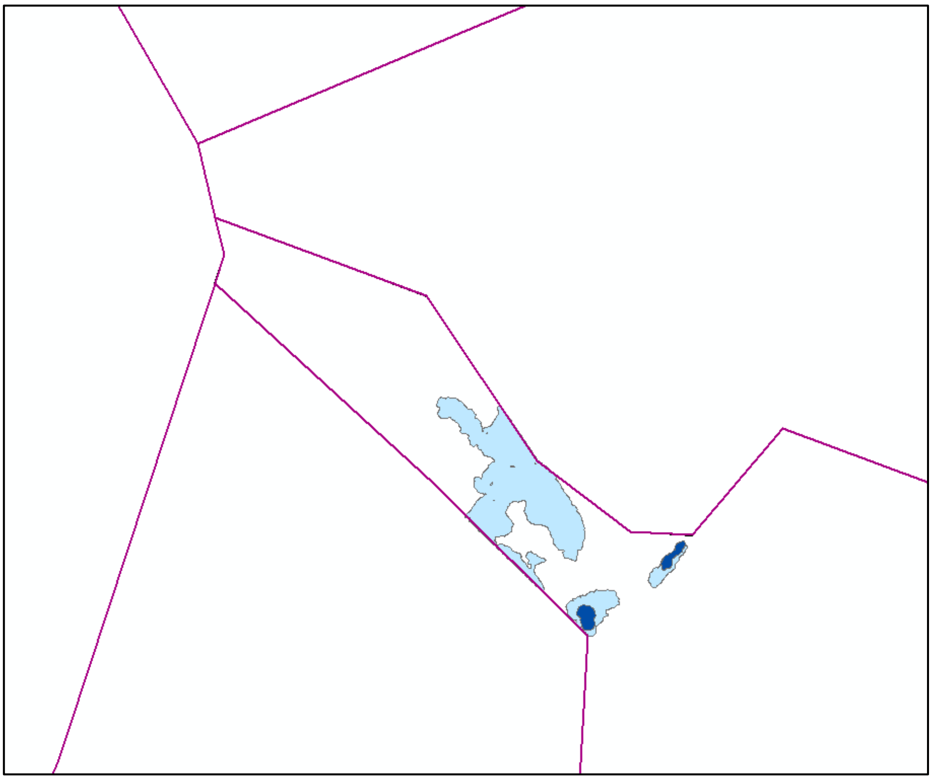

Figure 3-5 Minimum (dark blue) and maximum (light blue) extent of the Posidonia source rock facies in the German part of the southern Central Graben (CP 3007).

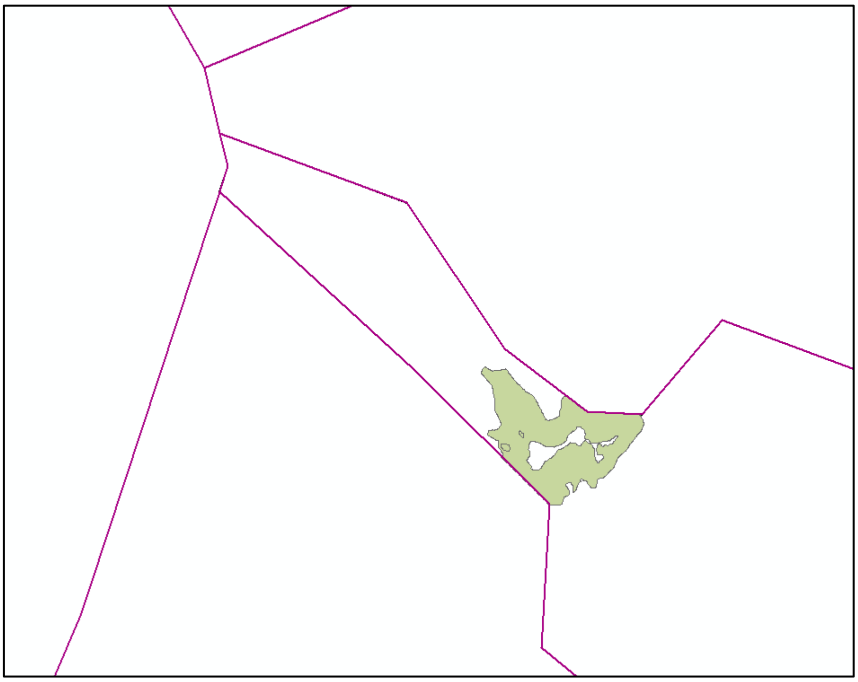

Figure 3-6 Extent of the Hot Shale (Bo Member in the Farsund Formation, CP 3008) in the German part of the Central Graben.

3.3.3 UK

In the UK the Carboniferous play extend offshore from the west coast (Figure 3-7) and has a gas mature area of 7814 km^2; no oil mature area has been identified (Table 3-7). The Lower Jurassic Lias Group that meet the depth and thickness criteria are present in the Cleveland Basin of the Southern North Sea (blue outline on Figure 3-7). For assessment on the maturity both vitrinite reflectance (VR) and T_{max} data are available for numerous wells, sampled at various depths within the Lias Group. Based on the mean VR value for each well the area where VR ≥ 0.6 has been identified (green outline on Figure 3-7). The thicknesses from wells indicate that the Posidonia shale range between 24 – 53 m (Table 3-7). In the Lias the oil mature area is estimated to be 1630 km^2; no gas mature area has been identified that lies within the depth 1 – 5 km.

In the Kimmeridge Clay Formation the oil and gas mature areas are 11763 km^2 and 699 km^2 respectively (the hashed areas in Figure 3-9). Uncertainties (minimum and maximum) on the mapped area is estimated assuming a standard deviation of 7.5% of the mean areas. The area has been calculated from the outline of the oil and gas mature areas respectively (Figure 3-9) and the mean values for depth are taken from the raster histogram that was clipped to the oil mature area. Net thickness of the Kimmeridge Clay Formation is taken from well penetrations within the oil mature area and do not include Upper Jurassic sandstones.

Table 3-7 Area of oil and gas mature unconventional plays in the UK part of the North Sea.

Upper Bowland Shale (CP 3011)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	–						
Gas mature area	7814	781	5087		10541	km^2	4a
Thickness (net)			17	39	110	m	
Lias Group, Posidonia Eqv. (CP 3012)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	1630	122	1346		1914	km^2	3a
Gas mature area	–						
Thickness (net)			24	43	57	m	
Kimmeridge Clay (CP 3013)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	11763	882	9710		13815	km^2	3a
Gas mature area	699	52	577		821	km^2	3a
Thickness (net)			1	126	1123	m	

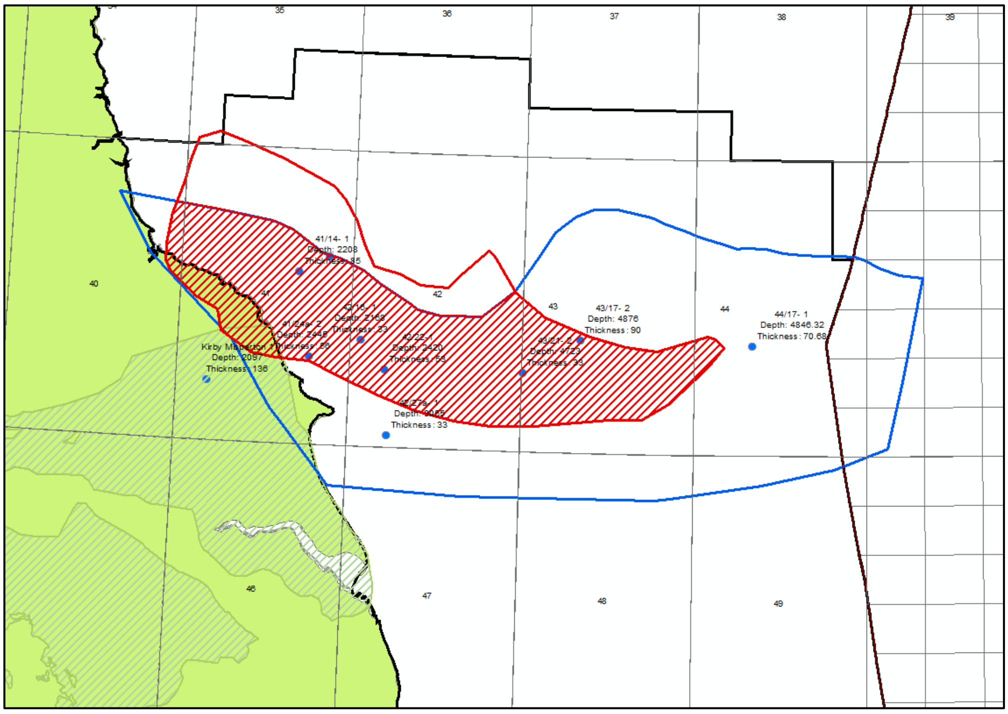

Figure 3-7 Part of the Upper Bowland shale play (CP 3011) that has been assessed. Blue line outlines the Cleveland E basinal facies. Red line outlines the extent of the gas mature area.

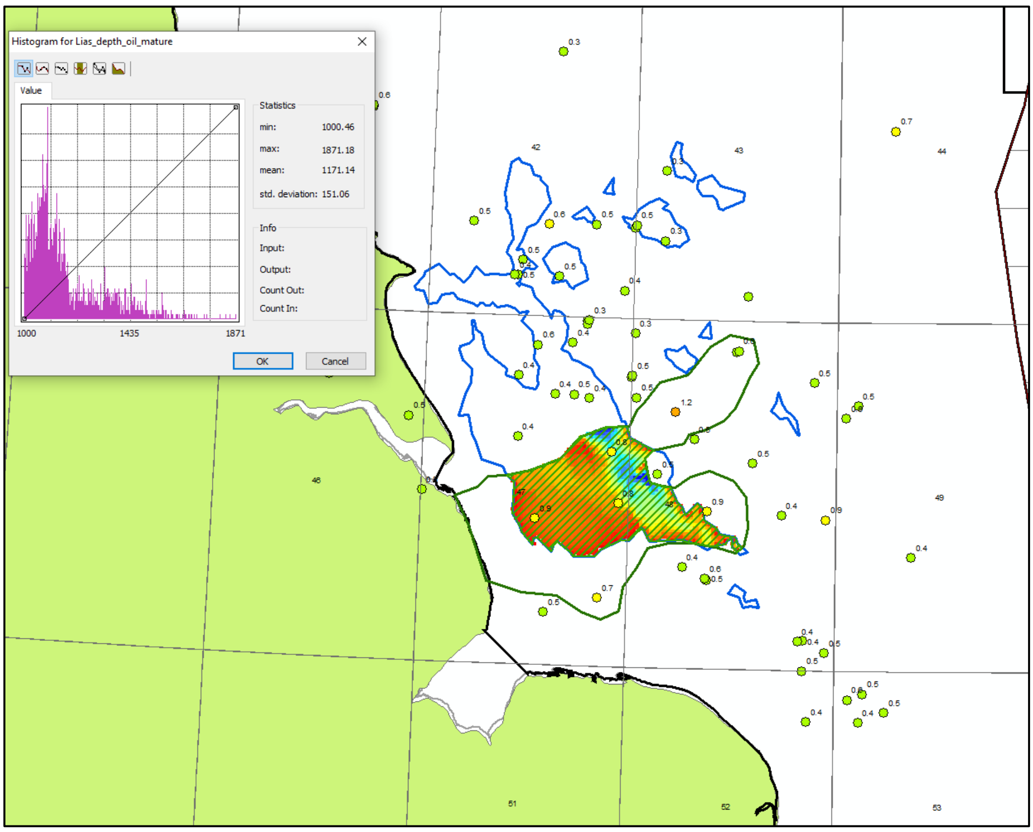

Figure 3-8 Distribution of the Lower Jurassic Posidonia Equivalent shale play (CP 3012) in the UK part of the North Sea Basin (Cleveland Basin).

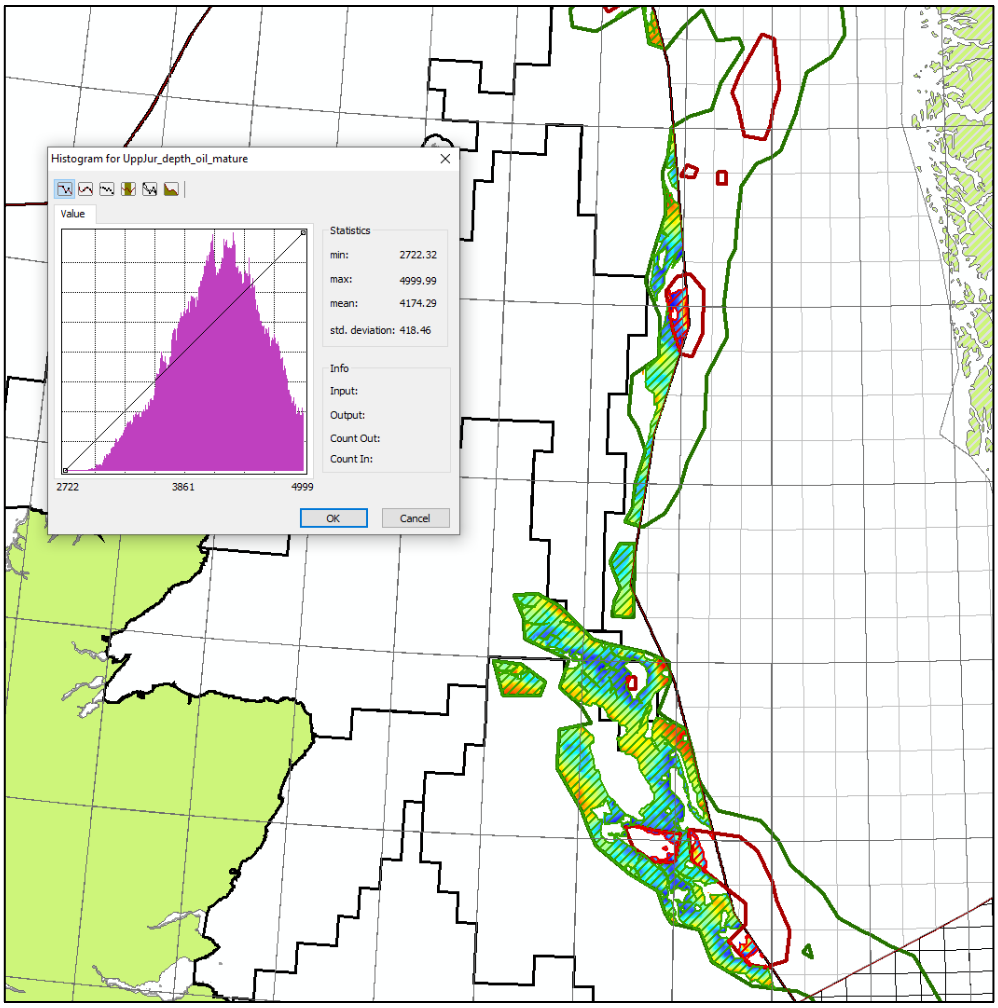

Figure 3-9 Upper Jurassic Kimmeridge clay play (CP 3013) in the UK part of the North Sea. The hashed areas show where the Kimmeridge Clay Fm meets the depth (1 – 5 km) and the maturity criteria (VR ≥ 0.6 %R_o).

3.3.4 Norway

In Norway the Upper Jurassic play in the Mandal Formation (CP 3005) occusr in the Central Graben and in the Viking Graben within the North Sea Basin (Figure 3-10). The Oil mature area is 17219 km^2 and the gas mature area is 3007 km^2 (Table 3-8). The thicknesses from wells indicate that the prospective parts range between 20 – 1153 m similar as for the Kimmeridge Clay Formation (Table 3-8).

Uncertainties (minimum and maximum) on the mapped area are estimated assuming a standard deviation of 7.5% of the mean areas. The area has been calculated from the outline of the oil and gas mature areas respectively and the mean values for depth are taken from the raster histogram that was clipped to the oil mature area.

Table 3-8 Area of oil and gas mature unconventional							

plays in the Norwegian part of the North Sea. Mandal Formation (CP 3005)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Oil mature area	17219	1291	9710		13815	km^2	3a
Gas mature area	3007	226	577		821	km^2	3a
Thickness (net)			20	126	1123	m	

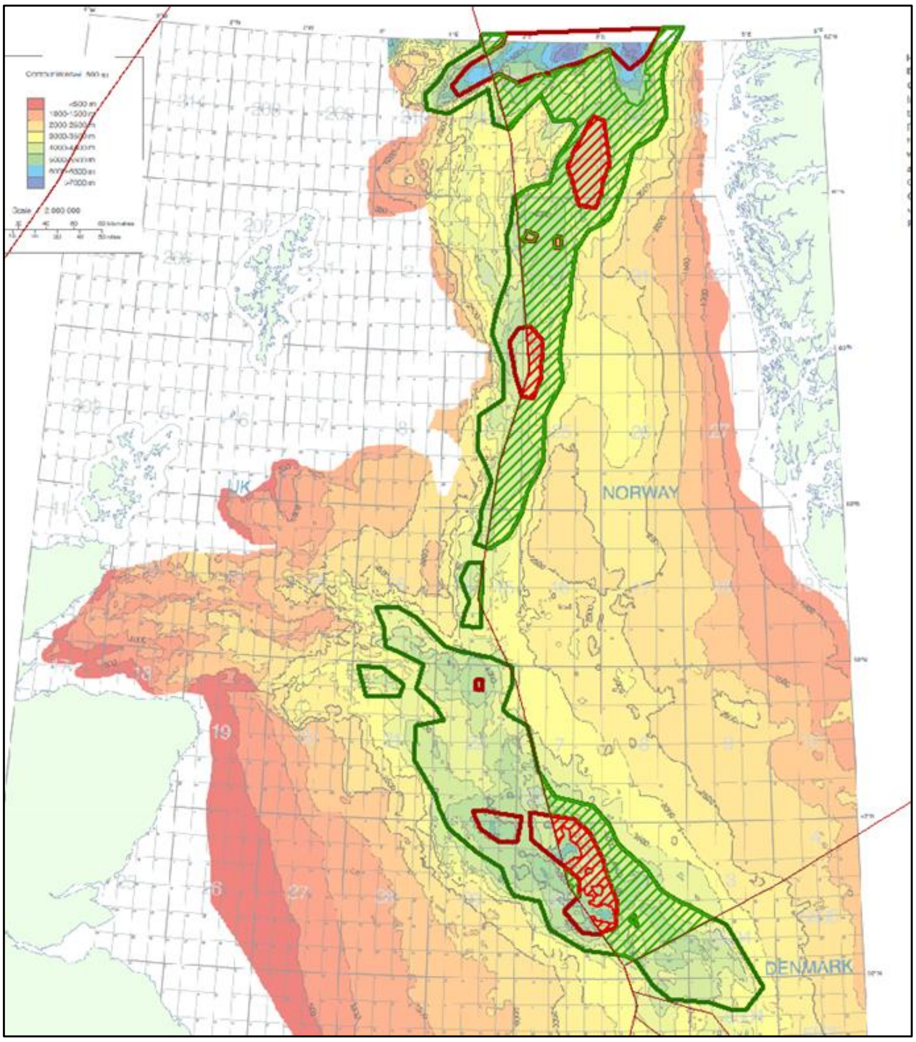

Figure 3-10 Upper Jurassic Mandal Formation play (CP 3005) in the Norwegian and the Kimmeridge Clay Play in the UK part of the North Sea. The hashed areas show where the Formations meets the depth criteria (1 – 5 km) and maturity criteria (VR ≥ 0.6 $\%R_o$). Analysed from the Millennium Atlas.

3.3.5 *The Netherlands*

In the Netherlands the Carboniferous play in the Geverik Member (CP 3009) has a gas mature area of 2416 km^2 no oil mature area has been identified (Figure 3-11, Table 3-9). The Lower Jurassic Posidonia Shale Formation (CP 3010) that meet the depth and thickness criteria are also present in the Dutch part of the North Sea Basin (outlined on Figure 3-12). The oil mature area is 3505 km^2 and the gas mature areas is 842 km^2 (Table 3-9). The thicknesses from wells indicate that the Posidonia shale range between 26 – 58 m. In the Geverik Member the thickness range between 40-80 m (Table 3-9).

Table 3-9 Area of oil and gas mature unconventional plays in the NL part of the North Sea.

Geverik Member (CP 3009)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Area oil mature	–					km^2	
Area gas mature	2416	121	9710		13815	km^2	3a
Thickness			40	50	80	m	
Posidonia Shale Formation (CP 3010)							
Present day 1 – 5 km							
	Mean	Std	Min	Likeliest	Max	Unit	Class
Area oil mature	3505	263	9710		13815	km^2	3a
Area gas mature	842	63				km^2	3a
Thickness			26	41	58	m	

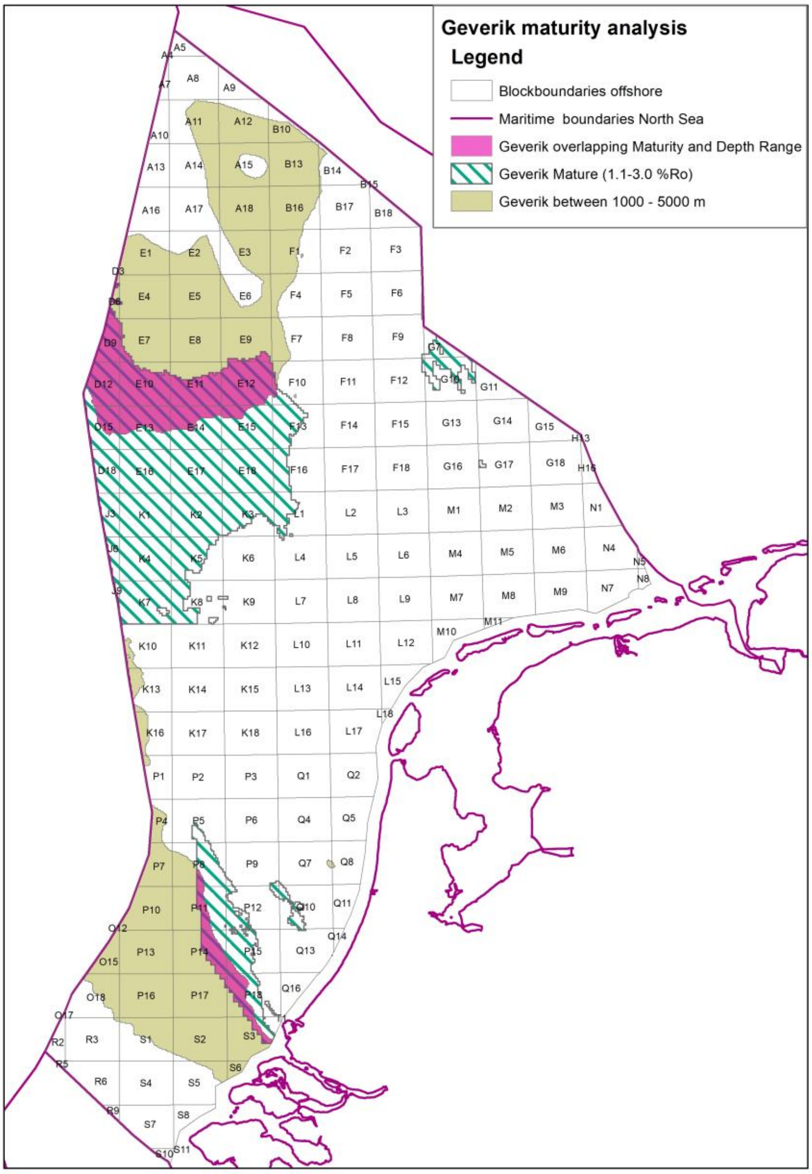

Figure 3.11 Mature area of the Lower Carboniferous Geverik Member of the Epen Formation with a depth cut-off of 5 km in the Dutch offshore area.

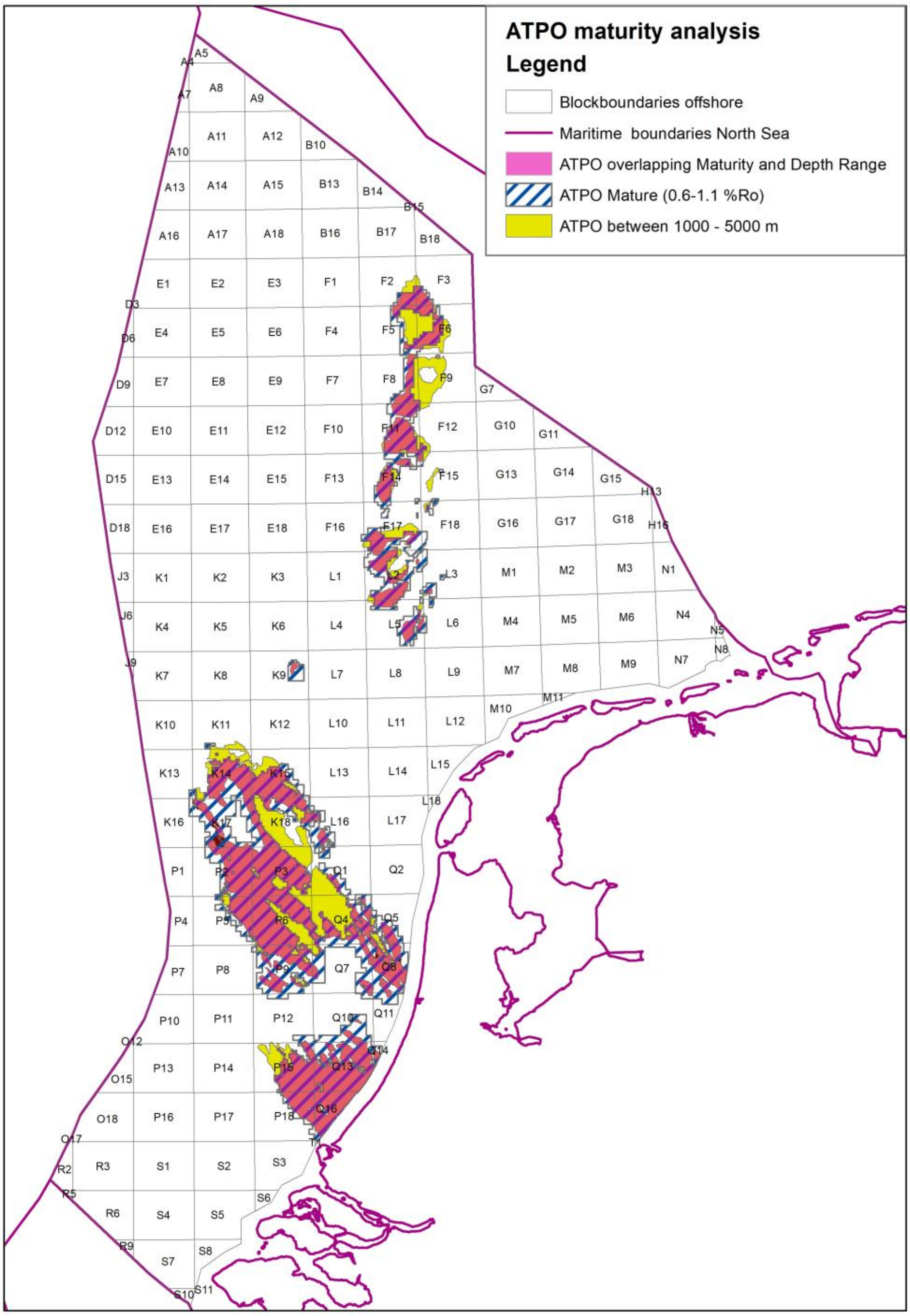

Figure 3.12 Mature areas of the Lower Jurassic Posidonia Shale Formation with a depth cut-off of 5 km in the Dutch offshore area.

4 SUMMARY AND CONCLUSIONS

4.1 Future Work (conventional) WP 2.2 and 2.6

Current and future work for the conventional work package 2.2 will focus on reconciling cross-border issues in order to create harmonised datasets across the study area. The main focus will be on the final compilation and harmonisation of the play maps created for each country to date, and using these to define any further areas of interest (for example, regional trends in chalk or HPHT reservoirs). The group also aim to link quantitative information on resources with individual plays where possible and to incorporate further information on seal and migration either in GIS or as text descriptions. As part of work package 2.6, GIS layers for alternate use will also be harmonised and included in the GIS deliverable.

In some areas, such as the UK, it is hoped to be able to separate further sets of plays where supporting information is available (for example, in well-understood fields) and tie those to well information.

For work package 2.6, the team will provide a brief report on potential hazards and alternative uses in the study area. Current work on defining a final list of hazards to discuss is underway.

4.2 Future work (unconventional) WP 2.3

Future work on the unconventional work package 2.3 will focus on the assessment of the *yet-to-find* resource associated with the unconventional plays. The assessment will be based on Monte Carlo simulations. The assessment will focus on the thirteen shale plays reflecting four main stratigraphical levels (Carboniferous, Triassic, Lower and Upper Jurassic) that have been identified to hold potential unconventional resources in the North Sea area.

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6 APPENDIX

Appendix 1 contains details of all plays for each country and is included as a separate document "D2_2_Appendix_v4_country_plays.docx"