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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Hydrogen Salt Storage Assessment (HYSS) 21/RDD/725
Lead Grantee (Organisation)	SLR Consulting
Lead Grantee (Name)	Nick O Neill
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Report Submission Date	

	Name	**Organisation**
Project Partner(s)	James White	Illmatic Energy
Collaborators		

Project Summary (max 500 words)

Please provide an overview of your project, the context, objectives, key results and outcomes.

This study is the first to assess the hydrogen storage potential within manmade salt caverns offshore Ireland. The report uses legacy oil and gas exploration data with datasets from INFOMAR to assesses the potential for bilocation of hydrogen storage and offshore wind farms in the Kish, Irish Sea and Celtic Basins.

The construction timeline for an Offshore Green Hydrogen Production Facility is estimated to be seven years and is expected to be constructed in three stages,

Stage 1 - Construction of the offshore wind farm.
Stage 2 - Geological site characterisation of the proposed subsea salt storage site
Stage 3 - Construction of the subsea salt cavern by cavern solution and laying of an export hydrogen pipeline to shore.

Salt intervals were identified in existing oil and gas wells drilled offshore. A robust regional interpretation of the salt intervals away from the well control points was achieved using legacy oil and gas seismic data. Thickness maps were prepared for each of the salt intervals and checked

against the salt thickness seen in the exploration wells. In addition, wireline logs were examined to identify the purest salt intervals with a minimum amount of clay and shale.

Industry knowledge and literature review (HyStorIES; Caglayan *et. al.*, 2020) has established that salt in excess of 150m thick at a depth of 1000m to 1500m is optimal for hydrogen storage in man-made salt caverns. The gross salt interval in the oil and gas wells ranges from 30m to 769m, including shale/silt interbeds. The seismic data exhibits signs of salt movement (halokinesis), specifically the development of localised thick salt pillows, which provides thick pure salt ideal for solution mining of salt caverns.

Cavern solution mining involves drilling a wellbore into a suitable salt formation, dissolving the salt by circulating fresh water into the wellbore and withdrawing the brine to the surface in a controlled manner until the salt cavern is leached out. The walls of the salt are impermeable to gas up to specific pressure thresholds, ensuring containment of hydrogen gas within the cavern.

The calculations of cavern storage capacity were made using the methodology of Caglayan *et. al.* 2020 and Williams *et. al.* 2020. A typical salt cavern can store 105 GWh - 146 GWh of hydrogen. The identified salt occurs between circa 10km - 100kms offshore in water depths 5m to 125m in the Kish, Irish and Celtic Sea Basins.

The project has identified over 6,000 potential manmade salt caverns at the optimum depth and thickness for hydrogen gas storage in the Kish, Irish Sea and Celtic Sea Basins. Assuming only 3% of the identified potential was viable, and each cavern could deliver in the region of 0.13 TWh of hydrogen storage, or >23 TWhH2 cumulatively, this would be more than sufficient to meet the indicative 90-day hydrogen storage needs for 2050 demand estimates of 18.4 TWhH2 (High Case; National Hydrogen Strategy 2023).

The project has highlighted geohazard and environmental constraints Mitigation measures have been identified to address these.

Keywords (min 3 and max 1)	Hydrogen Offshore Renewables Storage Energy Salt Halite Cavern Decarbonisation Energy Security

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

Decarbonisation and enhancing energy security are policy drivers for developing hydrogen storage infrastructure in Ireland. The HYSS project is the first to assess the hydrogen storage potential within manmade salt caverns off the coast of Ireland. This report uses legacy oil and gas exploration data with datasets from INFOMAR to assesses the potential for bilocation of hydrogen storage and offshore wind farms. An offshore green hydrogen production facility is likely to be constructed in three stages, stage 1 will be the construction of the offshore wind farm, stage 2 will be geological site characterisation of the proposed subsea salt storage site and stage 3 will be the construction of the subsea salt cavern by cavern solution and laying of an export hydrogen pipeline to shore. The construction timeline for such an Offshore Green Hydrogen Production Facility is estimated to be seven years.

Salt intervals ranging in thickness from 5m to 769m were identified in eleven wells drilled in the Kish, Irish Sea and Celtic Sea Basins. Data from an additional 12 wells in the UK sector demonstrated significant thickening due to halokinesis. A robust regional interpretation of the salt intervals away from the well control points was achieved using legacy oil and gas seismic data. In areas of poor seismic imaging a robust interpretation was achieved using gross seismic character and overall structural style. The time-based interpretation was then converted to depth.

The output from the depth conversion process was depth grids for the top of the salt intervals interpreted in the Kish, Irish and Celtic Basins. Thickness maps were prepared for each of the salt intervals and checked against the salt thickness seen in the exploration wells. In addition, wireline logs from the oil and gas exploration wells were examined to identify the purest salt intervals with a minimum amount of clay and shale. Industry knowledge and literature review (HyStorIES; Caglayan *et. al.*, 2020) has established that salt in excess of 150m thick at a depth of 1000m to 1500m is optimal for hydrogen storage in man-made salt caverns. The gross salt interval in the oil and gas exploration wells ranges from 5m to 769m, including shale/silt interbeds. The seismic data exhibits signs of salt movement (halokinesis) in both the Irish and UK sector, specifically the development of localised thick salt pillows, which provides thick pure salt ideal for solution mining of salt caverns.

Cavern solution mining is accomplished by drilling a wellbore into a suitable salt formation, dissolving the salt by circulating fresh water into the wellbore and withdrawing the brine to the surface. As the salt is dissolved in a controlled fashion according to a specific plan, the wellbore grows to form a cavern in the salt formation. Once the geometrical design volume is reached, gas is injected into the cavern displacing and emptying the brine out of the cavern, making it ready for gas storage operations. The well is then engineered to establish a controlled connection between

the salt cavern and the surface gas storage injection/withdrawal facilities. The walls of the salt are impermeable to gas up to specific pressure thresholds, ensuring containment of the gas stored in the cavern. In addition, fractures and faults within the salt formation are healed by the viscoplastic behaviour of the salt under the overburden pressure. There is no microbial activity in salt caverns to degrade or contaminate the hydrogen stored.

From an economic perspective, excessively small caverns tend to be marginal as some fixed costs are carried regardless of cavern size (leaching station construction and commissioning, connection to gas infrastructure, fixed drilling costs, etc.). From a technical point of view, excessively large caverns present some challenges too as they imply longer leaching durations, increased leaching rates that require large diameter pipe with increased lead times and costs, drilling challenges and the need for heavier duty drilling rigs. The Hystories project proposed a salt cavern with a Free Gas Volume ranging from 185,000 m^3 to 815,000 m^3 as optimum.

The calculations of cavern storage capacity were made using the methodology of Caglayan *et. al.* 2020 and Williams *et. al.* 2020. A typical salt cavern can store between 105 GWh and 146 GWh of hydrogen. The salt identified in this research occurs at the optimum hydrogen storage depth between circa 10km and 100kms offshore in water depths of between 5m and 125m in the Kish, Irish and Celtic Sea Basins.

The extent of salt occurrence in the Kish Basin at the required depth of 1,000m to 1500m and >300m thickness (providing at least 150m clean halite) is such that over 270 salt caverns could be solution mined, sufficient for seasonal hydrogen storage. An area adjacent to the proposed Dublin Array wind farm has the potential for 8 salt caverns (up to 1 TWh of hydrogen).

In the Irish Sea and Celtic Sea Basins the research has identified over 6,000 potential locations for manmade salt caverns. An area of interest, close to the Labadie Bank in the Celtic Sea, has water depth as shallow as 62m, suitable for fixed bottom wind turbines, or fixed bottom hydrogen facilities. An oil and gas exploration well at this location has proven 769m of gross salt thickness, see Figure 2.4.8.

In total, the project has identified over 6,000 potential manmade salt caverns at the optimum depth and thickness for hydrogen gas storage in the Kish, Irish Sea and Celtic Sea Basins. Assuming only 3% of the identified potential was viable, and each cavern could deliver in the region of 0.13 TWh of hydrogen storage, or >23 TWhH2 cumulatively, this would be sufficient to meet the indicative 90 day hydrogen storage needs for 2050 demand estimates of 18.4 TWhH2 (High Case; National Hydrogen Strategy 2023).

The geohazard study has highlighted several risks posed by the presence of shallow gas, near surface glacial channel complexes, tectonically active faults and protruding bedrocks at or near the seafloor. These hazards can be managed or avoided as demonstrated by successful oil and gas drilling in the area in recent decades. There are several significant environmental constraints including the disposal of concentrated brine from salt cavern mining and the disruption to shipping and fishing activity in an exclusion zone around the hydrogen production facility. Mitigation measures have been identified to address these environmental constraints. The regulatory risk in

Ireland is significant because until now the drilling of offshore wellbores came under petroleum legislation and regulation.

Recommendations arising from this study include the development of a regulatory regime to facilitate development of man-made salt cavern storage offshore Ireland; investigation of the role of public private partnerships in the development of offshore hydrogen storage infrastructure; support for the development of regional hydrogen clusters or hubs and a detailed costing for the development of offshore salt cavern hydrogen storage and transportation infrastructure to inform commercial decisions of offshore wind developers.

2.2 Introduction to Project

This research assesses the potential for bilocation of hydrogen storage and wind farms, thus promoting the generation and storage of green hydrogen at offshore windfarm locations. Offshore energy storage will have the dual benefit of reducing dispatch down (which reached 11.4% in 2020) while also creating green hydrogen for domestic use or export. Finding solutions, to store excess electricity generated by offshore wind for later despatch at an optimum price, or to sell green hydrogen into a local aviation and shipping transport e-fuels market or for export, will be critical in meeting Irish and European climate action targets.

Hydrogen has been stored in geological salt formations since 1972 (Teeside in the UK) and there are over 2,000 salt stores in the United States and over 300 in Germany (Panifilov, 2016). Large man-made caverns of 10,000 m3 to 1,000,000 m3 (4 to 400Olympic sized swimming pools) can be leached within salt formations creating an alternative to other porous stores (Bunger *et. al.* 2016). Salt caverns are the ideal store for hydrogen as salt is non-porous and retains gases even at high pressure, it also has the advantage of ensuring purity of the stored hydrogen and allowing high injection and production rates (Panfilov, 2016). Additional advantages are low geological risk, low cushion gas requirements and high safety levels with only one well per storage cavern.

Caglayan *et. al.* (2019) assessed the potential for hydrogen storage in geological salt formations across Europe (in known salt accumulations). The overall technical storage potential was estimated at 84.8 PWhH2, though there is no assessment for Ireland. This research addresses this data gap and integrates existing technology concepts to identify the best offshore sites for combining electricity generation from wind, green hydrogen production from electrolysis, and energy storage in underlying/adjacent salt caverns. This has the benefit of utilising electricity dispatch down from offshore wind to provide green hydrogen energy storage for use in transport, electricity generation or net energy export.

The presence of geological salt formations has been proven in several sedimentary basins offshore Ireland (Naylor & Shannon, 2011) though it's extent and thickness has never been mapped for the purposes of storage assessment. This report focusses on defining the salt extent, thickness and appropriateness for hydrogen storage offshore Ireland.

2.3 Project Objectives

No:	Objective Description:
1.	*Access available Oil & Gas industry datasets and public domain surface datasets for offshore Ireland, collate onto one interpretation platform*
2.	*Focus Area 1 Kish Bank Basin Evaluate potential salt cavern storage potential and engineering review and cross reference with available surface and subsurface risks, including overview of potential environmental issues.*
3.	*Focus Area 2 Irish Sea Basins Evaluate potential salt cavern storage potential and engineering review and cross reference with available surface and subsurface risks, including overview of potential environmental issues.*
4.	*Focus Area 3 Celtic Sea Basins Evaluate potential salt cavern storage potential and engineering review and cross reference with available surface and subsurface risks, including overview of potential environmental issues.*
5.	*Focus Area 4 Atlantic Margin Basins Evaluate potential salt cavern storage potential and engineering review and cross reference with available surface and subsurface risks, including overview of potential environmental issues.*
6.	*Reporting of hydrogen storage potential within man-made salt caverns.*

2.4 Summary of Key Findings/Outcomes

Figure 2.4.1 highlights the areas identified from the HYSS project where there is sufficient halite present for potential salt cavern development which is suitable for hydrogen storage offshore Ireland.
The three areas identified are 1. The Kish Basin, offshore Dublin. 2. The Irish Sea Basins, offshore Wexford and 3. The Celtic Sea Basins, offshore Cork.

The salt extent at the required depth of 1,000m-1500m and >150m thickness is such that many salt caverns could be solution mined, sufficient for seasonal hydrogen storage as part of a standalone green hydrogen production project in conjunction with floating offshore wind. The calculations of cavern storage capacity were made using the methodology of Caglayan *et. al.* 2020 and Williams *et. al.* 2020. A typical salt cavern can store between 105 GWh and 146 GWh of hydrogen.

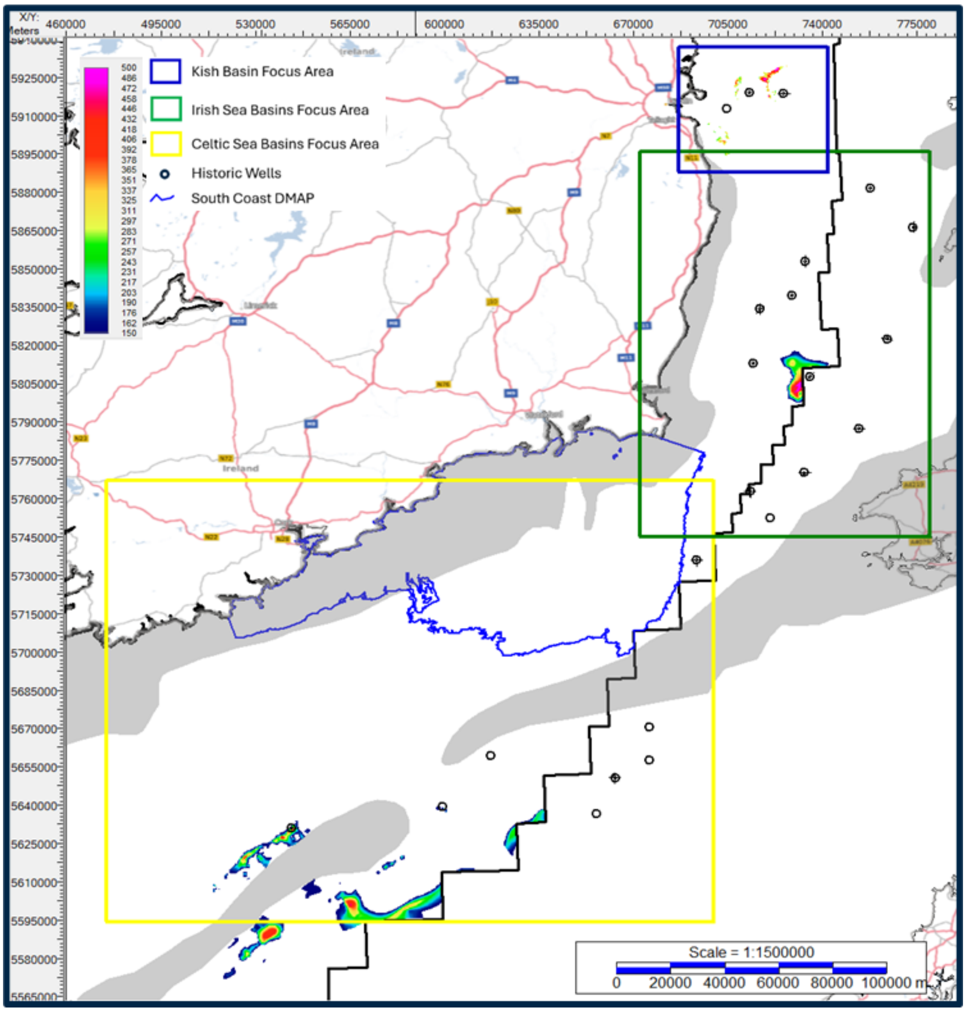

Figure 2.4.1 – Map of areas with suitable salt presence and depth offshore Ireland, with colours representing the thickness of the salt.

2.4.1 The Kish Basin

Four salt intervals were identified from three oil and gas exploration wells drilled in the Kish Basin during the 1980s. A robust regional interpretation of the four salt intervals away from the well control points was achieved using legacy oil and gas seismic data. In areas of poor seismic imaging a robust interpretation was achieved using gross seismic character and overall structural style. The time-based interpretation was converted to depth.

Thickness maps were prepared for each of the 4 salt intervals and QC'd against the thickness in the 3 offshore wells. In addition, the wireline logs were examined to identify the purest salt intervals with a minimum amount of clay and shale. The presence of clays increases the amount of bulk insoluble volume in the salt cavern when the solution mining process is completed. The cleanest salt interval in the Kish Basin is the Preesall Halite Formation. However, where salt movement (or halokinesis) has occurred the salt interval is likely to be pure salt with little or no clay present as demonstrated in Figure 2.4.2. These areas would be more suitable to salt cavern development as they could contain a higher net salt thickness, Figure 2.4.4. In the Kish, areas with excess of 300m gross salt interval were deemed appropriate to yield a suitable net salt thickness for cavern development.

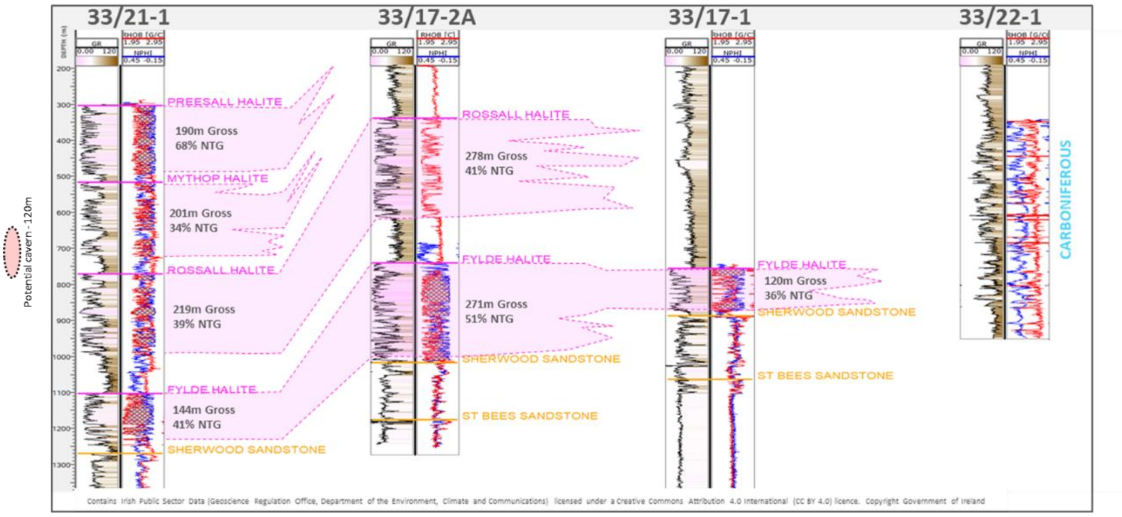

Figure 2.4.2 - Figure showing proven salt (in pink) within existing wellbore data in the Kish Basin, note potential cavern size annotated on left hand side.

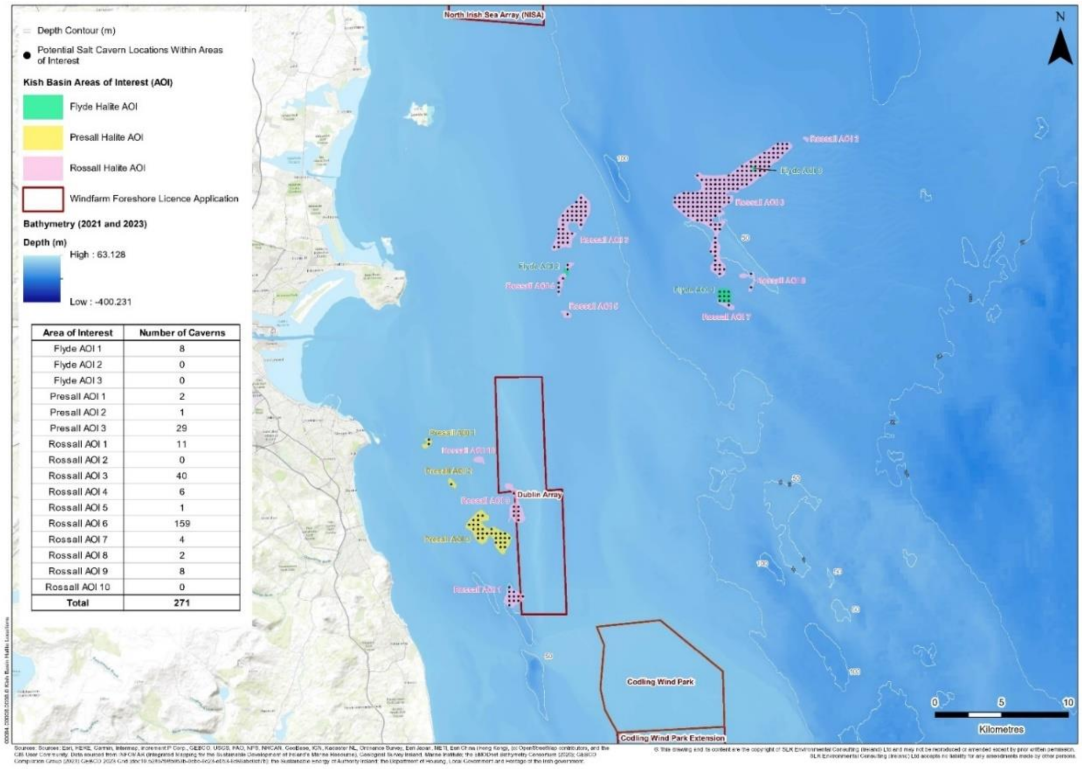

Figure 2.4.3 - This map shows the areas where the halite occurs at depths of 1,000m to 1,500m and is more than 300m thick, the optimum depth and thickness for salt cavern storage of gas in the Kish Basin.

Overlaying a simple grid of potential cavern sizes and separations (black dots) yields a potential for 271 caverns in the Kish Basin area, see table in the legend of Figure 2.4.3. It also shows that in the zone of interest A09, which lies beneath the offshore wind licence area for the Dublin Array, there is the potential for 8 standard size salt caverns to be developed for hydrogen storage. This is equivalent to approximately 1.0 TWh_{H2}.

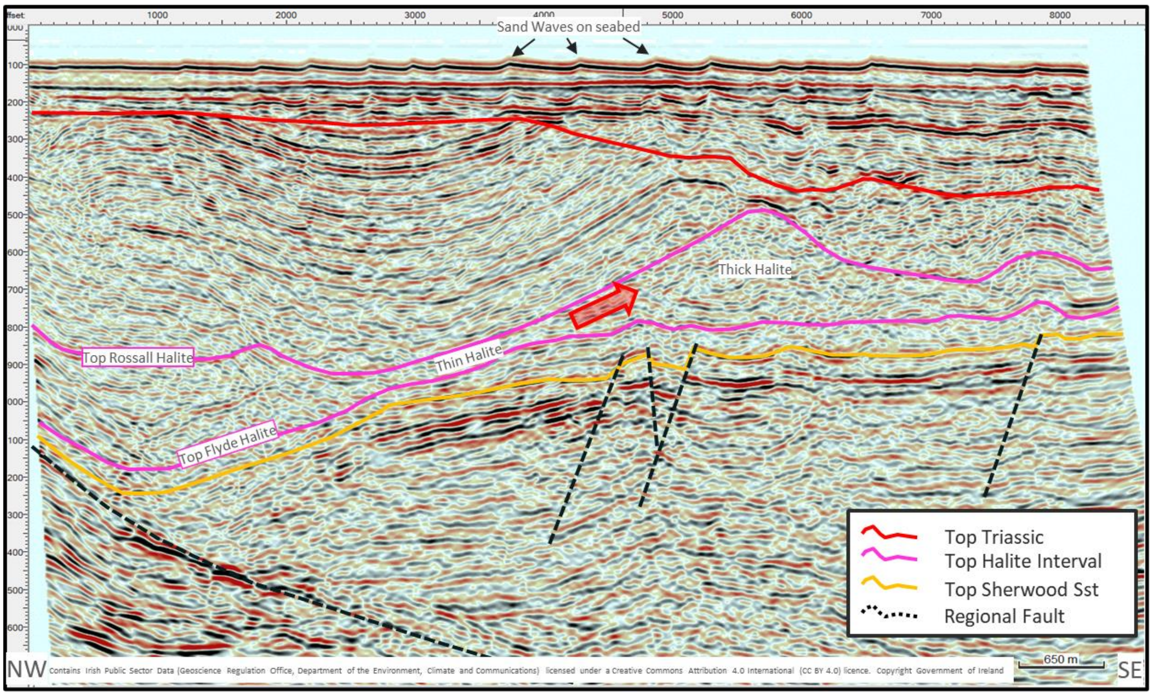

Figure 2.4.4 - Halokinesis evident where halite has moved from thin area to thick area, as annotated by the red arrow.

2.4.2 The Irish Sea Basins

In the Irish Sea Basins four offshore wells contained thin salt less than 50m thick within the Irish offshore, Figure 2.4.5. The project accessed data from the UK sector which demonstrated significant thickening in the UK sector due to halokinesis. A robust regional interpretation of the salt intervals away from the well control points was achieved using legacy oil and gas seismic data. In areas of poor seismic imaging a robust interpretation was achieved using gross seismic character and overall structural style. The time-based interpretation was converted to depth. The output from the depth conversion process was depth grids for the top of the salt intervals interpreted. Thickness maps were prepared for each of the salt intervals and checked against the salt thickness seen in the exploration wells.

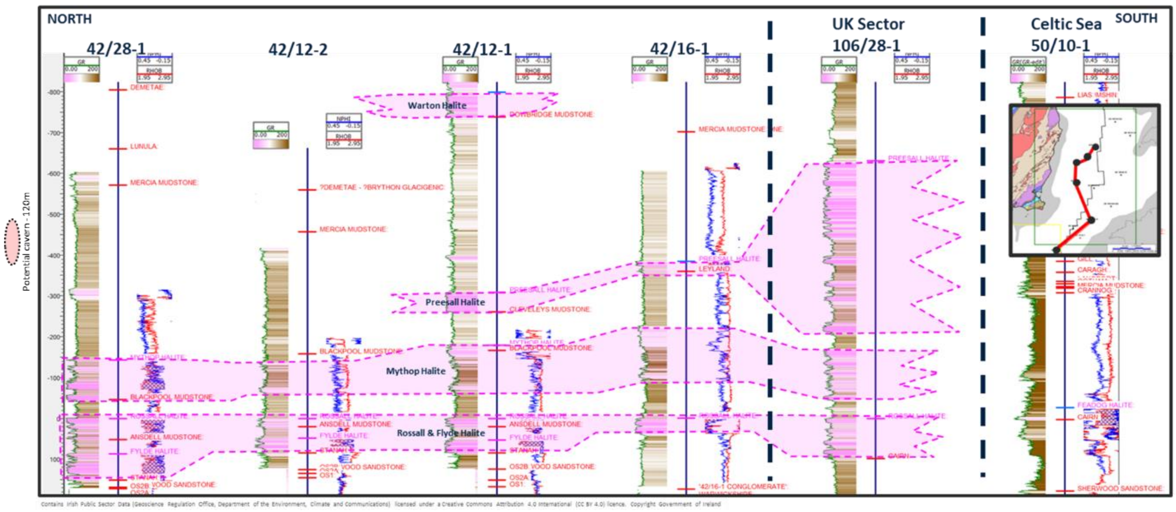

Figure 2.4.5– The Irish Sea Basins well stratigraphy highlighting salt units (halite) in pink, flattened on Top Rossall Halite, note potential cavern size annotated on left hand side.

In the Irish Sea Basins where the Warton Halite is not seen in wells, predominantly in the shallower Irish areas where it has been eroded, the interpretation of Top Halite is the underlying Preesall Halite. The Feadóg/Warton and Preesall halites in the well and seismic data show thickening towards the UK, with the salt being sufficiently thick in the UK wells to be of interest for potential salt cavern development, Figure 2.4.5.

A lower halite section is encountered in the Irish Sea Basins (Mythop, Rossall, Flyde, which are also present in the Kish Basin) but the net thickness in the wells remains relatively constant at less than 50 meters thick, which is insufficient for cavern development. This interval is mapped on the seismic data where well control and seismic imaging is sufficient to provide a confident interpretation, though its extent is likely to be greater than currently mapped.

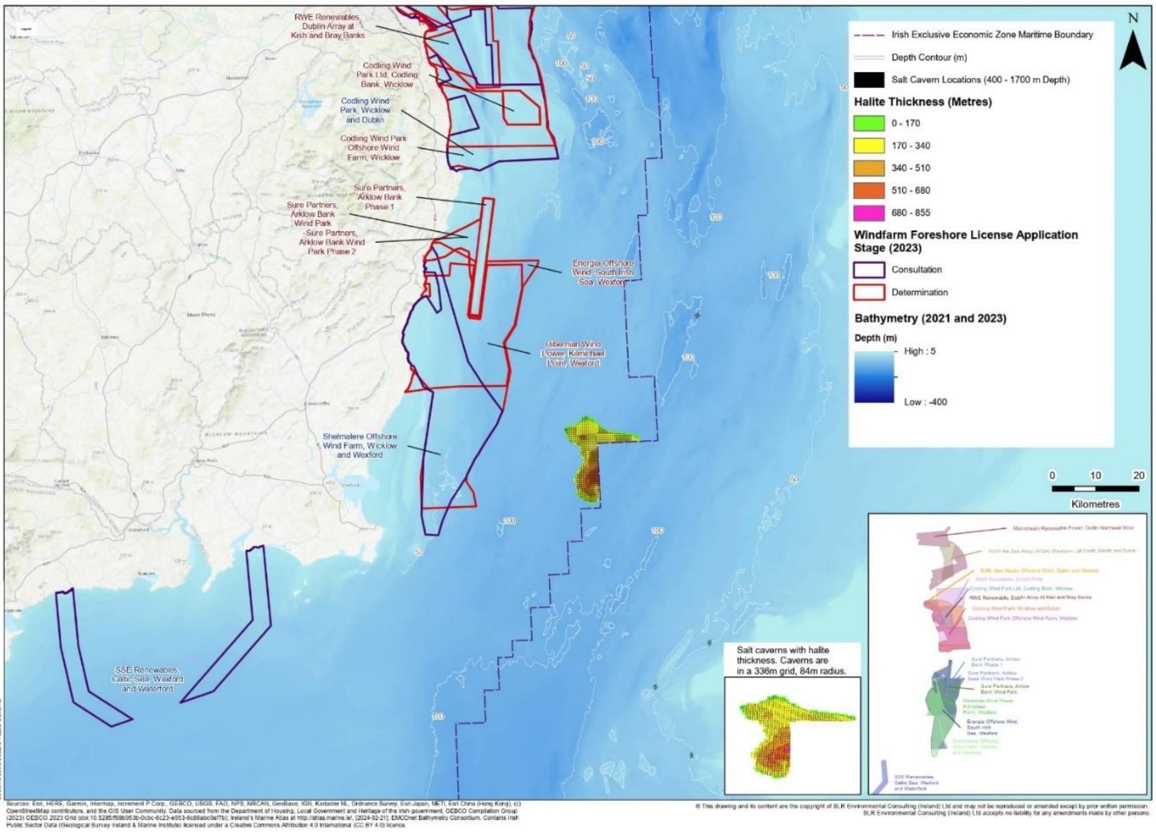

Figure 2.4.6 - This map shows the areas where the halite occurs at depths of 1,000m to 1,500m and is more than 150m thick, the optimum depth and thickness for salt cavern storage.

The Irish Sea Basins have the potential for 1,069 standard size salt caverns (Figure 2.4.6) for hydrogen storage at the optimum subsurface depths and salt thickness. Just 1% of this potential is equivalent to approximately 1.4 TWhH2.

2.4.3 The Celtic Sea Basins

The salt in the Celtic Sea Basins close to Ireland is relatively thin or too deep to be of interest. Further offshore, approaching the UK sector, the well control demonstrates thick salt deposits, Figure 2.4.7. The salt occurs at the optimum hydrogen storage depth of 1,000m-1,500m between 50km and 100kms offshore in water depths of between 60m and 125m in the Celtic Sea Basins, Figure 2.4.8. On the Labadie Bank in the Celtic Sea the water depth shallows to 62m, suitable for fixed bottom wind turbines, a seismic line adjacent to this area demonstrates the seismic character of the salt proven in the 57/9-1 well, Figure 2.4.9. The project has identified over 5,200 potential manmade salt caverns at the optimum depth and thickness for hydrogen gas storage in the Celtic Sea Basins. Assuming only 1% of the identified potential was viable, and each cavern could deliver in the region of 0.13 TWh of hydrogen storage, or 6.7 TWhH2 cumulatively.

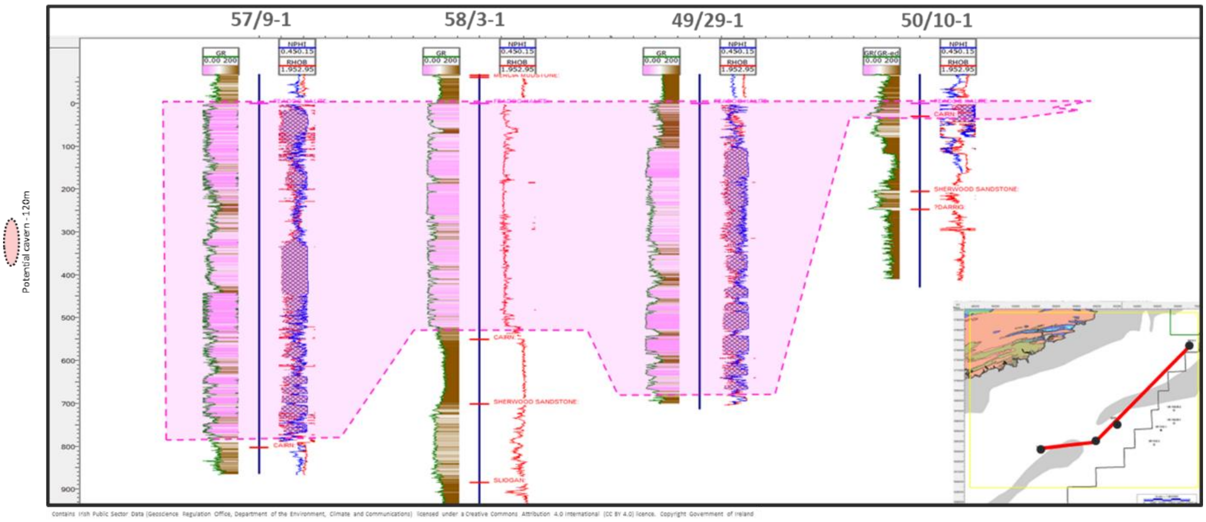

Figure 2.4.7 – The Celtic Sea Basins well stratigraphy highlighting salt units (halite) in pink, flattened on top Halite, note potential cavern size annotated on left hand side.

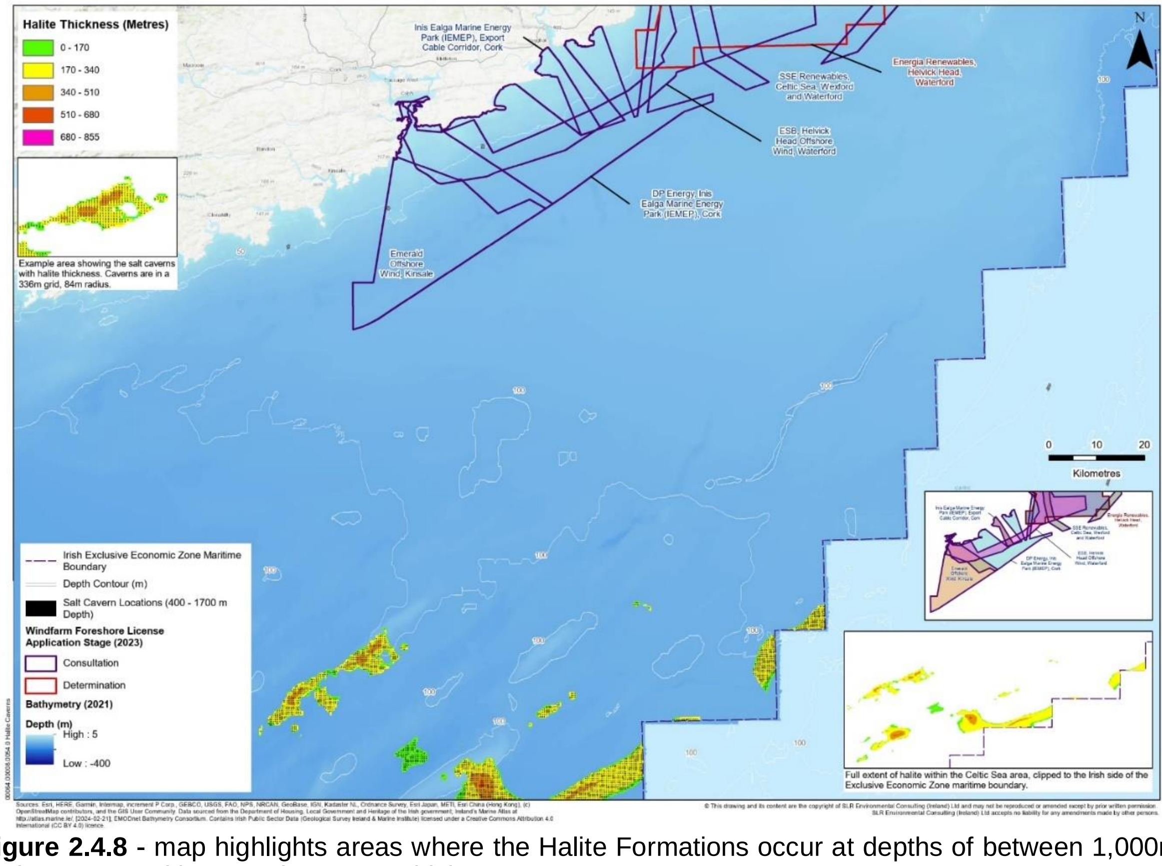

Figure 2.4.8 - map highlights areas where the Halite Formations occur at depths of between 1,000m and 1,500m and is more than 150m thick.

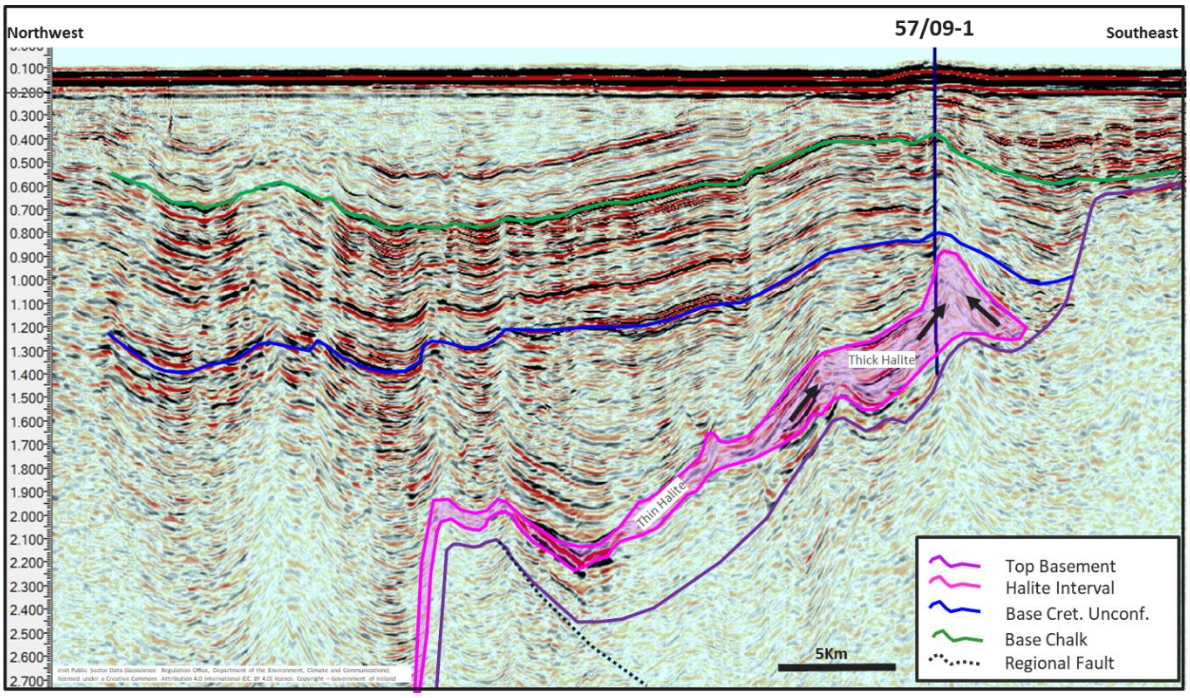

Figure 2.4.9 – Seismic line showing presence of salt, and thick salt interval confirmed by 57/09-1 well.

2.4.4 Offshore Green Hydrogen Production Facility Concept

An offshore green hydrogen production facility is likely to be constructed in three stages, Figure 2.4.10.

Stage 1 - Construction of offshore wind turbines, offshore substations (OSS), inter turbine array cables to the OSS, export DC electricity cable to shore and onshore substation.

Stage 2 - Geological site characterisation to confirm the geological feasibility of the proposed subsea salt storage site identified from seismic. This will include a 3D seismic survey, drilling of an appraisal well with comprehensive formation logging and coring programme and laboratory testing and analysis of cores. The geological site characterisation will take three years to complete. A 3D seismic survey acquired early in the first year will be processed and interpreted before the appraisal well is drilled in the following year. Analysis of the well data to establish geomechanical constraints and design of the cavern solution programme will be completed in the third year.

Stage 3 - Construction of the subsea salt cavern by cavern solution mining using a jackup or semi-submersible drilling rig at the appraisal well, construction of an offshore platform above the salt cavern to house the hydrogen plant, installation of inter turbine array cables to the offshore platform and laying of an export hydrogen pipeline to shore. The construction of the salt cavern is likely to take two to three years and will involve the temporary installation of a jackup or semi-submersible drilling rig, drilling of a borehole to about 1,000 m subsea, cavern solution / leaching of the salt formation, and completion of the borehole to establish a controlled connection between the salt cavern, where hydrogen gas will be stored, and the surface facilities at the wellhead. The installation of the offshore platform and laying of an export hydrogen pipeline to shore is anticipated to take several months.

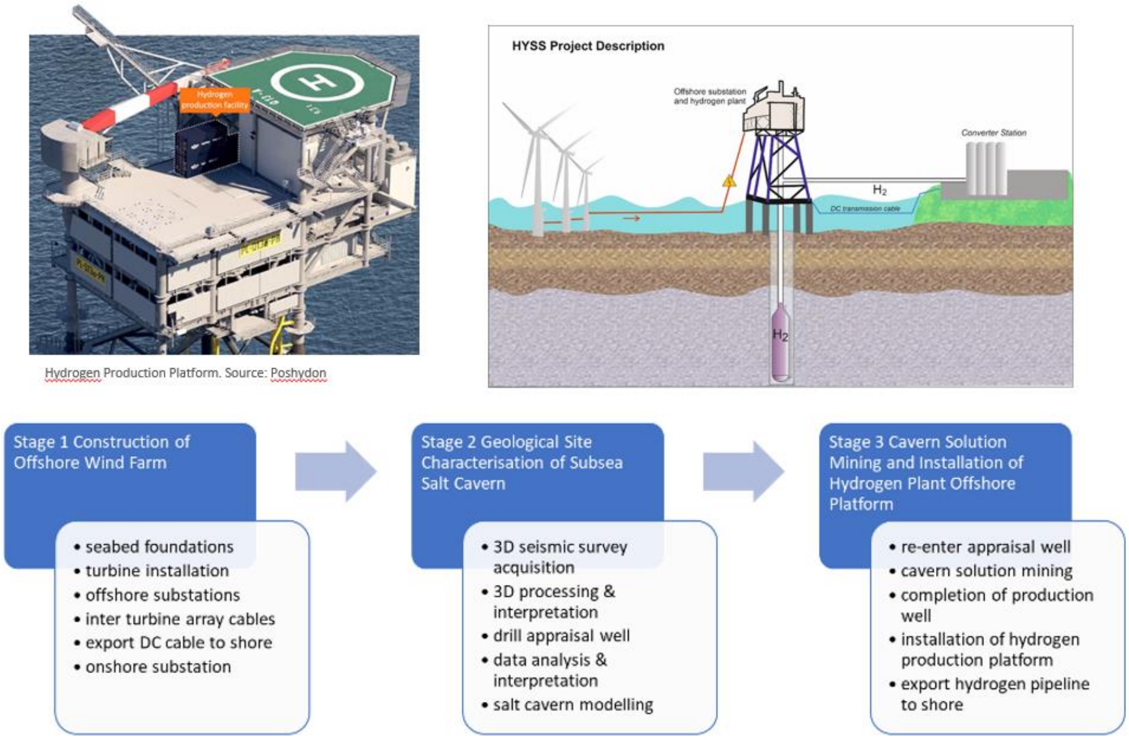

Figure 2.4.10 – Development stages of an offshore Green Hydrogen Production Facility

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

- **Innovation 1**: HYSS is the first study to identify the extent of geological salt formations offshore Ireland.
- **Innovation 2:** This study is the first to assess the hydrogen storage potential within manmade salt caverns off the coast of Ireland.
- **Innovation 3:** The HYSS project is the first study to integrate the potential for co-location of offshore windfarms, green hydrogen production and salt cavern storage offshore Ireland.

2.5 Project Impact

Clearly position the impact of your project with reference to the needs of the Irish Energy Sector, national and international policy objectives, and SEAI's remit.

Decarbonisation and enhancing energy security are policy drivers for developing hydrogen storage infrastructure in Ireland. HYSS supports the transition towards renewables in Ireland, and also the EU. The project is directly relevant to addressing targets set out in Climate Action Plan of 2019, the 2020 Programme for Government and the NECP. The project results specifically define the locations suitable for further detailed analysis for salt cavern storage as well as assisting government policy on marine activity and critical infrastructure in those areas.

Discuss the key impacts of your project: societal, economic, technological or otherwise. Clearly identify and highlight the value of your project in the wider context.

This study may enable the acceleration of an offshore wind to hydrogen pilot. It could also provide significant guidance to regulatory bodies with respect to market opportunities and potential regulatory issues such as geohazards. The significant potential of offshore wind in Ireland to become an export commodity is frequently referred to politically and in the media. Hydrogen is a technology that could enable that, with storage of hydrogen being a critical infrastructural element in the supply of hydrogen, but also the security of supply/strategic energy store for Ireland.

2.6 Recommendations

Please highlight any implications/opportunities/recommendations for Ireland (e.g., for policy makers, for the research community, for industry) based on the work carried out in the project.

1.Propose the development of hydrogen storage infrastructure in salt caverns offshore Ireland as a Project of Common Interest under the Trans-European Network for Energy (TEN-E).

2. Develop a regulatory regime to facilitate prospecting and development of man-made salt cavern storage offshore Ireland.

3. Investigate the role of public private partnerships in the development of hydrogen storage infrastructure offshore Ireland.

4. Support the development of a regional hydrogen cluster or hub in the SE Area, to include a joint UK/Irish strategy to integrate all available datasets and agree extent of the salt.

5. Acquire additional high quality geophysical and geotechnical information to high grade areas for infrastructure development, to include high-definition 3D to define salt extent and highlight subsurface architecture and reduce containment risk.

6. Develop a detailed costing for the development of offshore salt cavern hydrogen storage and transportation infrastructure to inform commercial decisions of offshore wind developers – AACE Class 4 cost estimate for CAPEX with OPEX estimate.

2.7 Conclusions and Next Steps

1. Salt formations occur in the Kish Basin, Irish Sea and Celtic Sea Basins.

2. The salt is sufficiently thick and occurs at the optimum depth for hydrogen storage in man-made salt caverns.

3. The volume of hydrogen gas that can be stored in man-made salt caverns in the Kish Basin, Irish Sea and Celtic Sea Basin is sufficient to meet 100% of the predicted Irish storage requirements in 2050.

4. The geohazards identified that could impact the development of a hydrogen storage project have been successfully managed by the historical oil and gas drilling activity in the area.

5. There is a lack of high-quality 3D deep seismic, shallow seismic, SBP, and geotechnical datasets currently over the Kish, Irish Sea and Celtic Sea areas.

6. The regulatory risk to the development of a hydrogen storage project offshore Ireland is significant.

7. The maps of European salt storage potential need to be updated to reflect the results of this project (H2 Infrastructure Map Europe (h2inframap.eu)).