Overview of Hydrogen and Geostorage Potential in Ireland

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Summary

International efforts to decarbonise the global energy sector require the immediate deployment of all available clean energy technologies including a major push to increase energy efficiency and a significant scaling up of renewable energy. Herein, we provide a short overview of the role hydrogen can play in decarbonising the energy sector and on the primary sources of hydrogen. Ireland has significant potential for domestic green hydrogen production because of its considerable offshore and onshore wind potential. Hydrogen can also be used as a temporary energy store and help to address challenges associated with the future ramping up of renewable electricity generation. This will require hydrogen to be stored in high pressure tanks on surface or in underground (geological) storage. Salt cavern geostorage potential exists within Permian and Triassic basins, and we provisionally estimate a hydrogen working gas capacity of 1.6 TWh for a planned storage facility on Islandmagee in Northern Ireland. Hydrogen geostorage potential also exists in depleted gas fields, and we provisionally estimate hydrogen working gas capacities of 67 TWh and 38 TWh for the Kinsale Head and Corrib gas fields, respectively. Further research is required to properly assess the hydrogen geostorage potential in Ireland.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) published the Working Group 1 contribution to its Sixth Assessment Report on the Physical Science Basis of climate change in August 2021 and stated that limiting warming to the target set out in the Paris Agreement will be beyond reach unless there is an immediate and significant reduction in the emissions of greenhouse gas (IPCC, 2021). Noting that the global energy sector currently accounts for around three-quarters of greenhouse gas emissions, the International Energy Agency (IEA) has published a roadmap for this sector to get to net-zero emissions by 2050 (IEA, 2021). This pathway relies on the immediate deployment of all available clean energy technologies including a major push to increase energy efficiency and a significant scaling up of renewable energy such as wind and solar.

Fossil fuels, such as oil and gas, can be characterised as both natural resources and energy carriers and they are relatively efficient to produce and transport. Conversely, renewable energy sources, such as wind and solar, are used to produce electricity which is not an ideal energy carrier because of capacity limitation on the electrical grid and the inability to store sufficient energy in batteries. However, hydrogen is emerging as a potential flexible solution to manage the intermittency of these renewable energy sources (e.g., Ball and Weeda, 2015; Brandon and Kurban, 2017). Excess electricity from renewable sources can be used to generate hydrogen, which can act as a temporary energy store or as an alternative energy carrier to fossil fuels.

This short paper is the last in a series focused on Energy Transition geoscience themes with a focus on Ireland (see Carbon Capture and Storage: English and English, 2022a, 2022b; Geothermal energy: English et al., 2022). Herein, we provide a short review of the role hydrogen can play in decarbonisation during the Energy Transition and an overview on the primary sources of hydrogen. We then move on to discuss the different options for geostorage of hydrogen with a particular focus on Ireland. Preliminary hydrogen storage capacity estimates are provided for the offshore Kinsale Head and Corrib gas fields.

POTENTIAL ROLES OF HYDROGEN FOR DECARBONISATION

Most of the hydrogen produced globally today is used for industrial purposes such as ammonia production (53%), petroleum industry and methanol synthesis (40%), and the production of polymers and resins (7%) (Brandon and Kurban, 2017). Most of the ammonia is used for producing nitrogen fertilisers, and the petroleum industry uses hydrogen for refining crude oil and for removing impurities such as sulphur. In addition to these current uses, hydrogen can potentially play a future role in decarbonisation across each of the following three categories (see Brandon and Kurban, 2017 and references therein):

- **Transport:** The transport sector is still heavily reliant on fossil fuels and currently accounts for close to a quarter of global energy-related CO_2 emissions (IEA, 2022). Carbon-free driving could be achieved via hydrogen fuel cell electric vehicles (FCEVs) if the hydrogen is produced from renewable sources. However, the lack of hydrogen refuelling infrastructure remains a major barrier to deployment of FCEVs, particularly in comparison to plug-in battery electric vehicles (BEVs). While BEVs hold an advantage for smaller vehicles, especially in urban settings, there may still be a role for FCEVs in the decarbonisation of larger vehicles due to longer-distance driving and faster refuelling (Gröger et al., 2015; Staffell et al., 2019). The use of hydrogen in other transport applications including marine, aviation and rail is also under development.
- **Heat:** Heat generation accounts for more than 50% of global final energy consumption and around a third of global energy-related CO_2 emissions (Eisentraut and Brown, 2014). Hydrogen is one option available to decarbonise heating (Dodds et al., 2015; Staffell et al., 2019). Converting the gas network to hydrogen, or blending hydrogen with natural gas, could reduce the carbon footprint of heating while maintaining some of the existing infrastructure, particularly the low-pressure polyethylene distribution system (as opposed to the high-pressure steel transmission system). The introduction of low-carbon hydrogen on the gas network, with accurate metering of a reduced calorific gas, could also create synergies with efforts to further decarbonise transport, commercial buildings and industry. However, due to ready availability of heat pumps, electrification of the heat sector is more likely to play a prominent role in decarbonisation in the near term compared to hydrogen (e.g., SEAI, 2022) if electricity generation is also decarbonised. Geothermal energy and district heating provide other alternative technologies.
- **Electricity generation:** Intermittent power generation from renewable energy sources requires grid-scale electricity storage technologies to provide storage capacity to balance supply and demand and to minimise curtailment. Storage options include

lithium-ion batteries, compressed air energy storage, thermal energy storage and hydrogen among others (Brandon et al., 2016). In the case of hydrogen, this can be generated via electrolysis using excess electricity from renewable sources. The hydrogen can then be stored in pressurised tanks (for small-scale applications) or underground geological storage (for grid-scale applications). The hydrogen can subsequently be re-electrified when needed using a fuel cell or a hydrogen gas turbine. Changing the energy carrier from electricity to hydrogen therefore allows the temporal decoupling of supply and demand. The hydrogen could also be exported from areas of high renewable potential to other markets.

SOURCES OF HYDROGEN

Hydrogen (H) is the lightest element found on Earth and is present in great abundance in molecules such as water (H_2O), methane (CH_4) and ammonia (NH_3). Natural hydrogen gas (H_2), or **white hydrogen**, has not been commonly found in significant quantities in the subsurface, although interest in hydrogen exploration is growing after the discovery of a large hydrogen accumulation in Mali (Prinzhofer et al., 2018). Natural hydrogen is produced via abiotic processes including hydration of ultramafic and mafic rocks (i.e., where Fe^{2+} bearing minerals and water are converted to magnetite Fe_3O_4 and H_2) and radiolysis of water by natural radioactivity (Sherwood Lollar et al., 2014). These processes are mostly associated with (1) serpentinised ultramafic rocks at ophiolite-peridotite massifs and mid-ocean ridges, and (2) Precambrian crystalline shields (Gaucher, 2020). These geological environments have seen little drilling activity in the petroleum industry and hence there is much still to learn about natural hydrogen exploration.

However, the current focus is on the artificial production of hydrogen via different chemical reactions (Brandon and Kurban, 2017). Currently, most hydrogen is produced via Steam Methane Reforming (SMR) using fossil fuels as a source. Initially, high temperature steam (H_2O) is used to generate H_2 and carbon monoxide (CO) from methane (CH_4):

$$CH_4 + H_2O \Rightarrow 3H_2 + CO \qquad (1)$$

The hydrogen yield is further increased using the water-gas-shift reaction, where the produced carbon monoxide reacts with water to produce hydrogen and carbon dioxide:

$$H_2O + CO \Rightarrow H_2 + CO_2 \qquad (2)$$

This process which involves the generation of hydrogen from natural gas is known as **grey hydrogen** in the case where the produced CO_2 emissions are not captured (Figure 1). However, if this process is decarbonised via Carbon Capture and Storage (CCS), the produced carbon-neutral hydrogen is known as **blue hydrogen**.

Alternatively, hydrogen produced via renewable sources is known as **green hydrogen**. One example of this is the splitting of water via electrolysis:

$$2H_2O \Rightarrow 2H_2 + O_2 \qquad (3)$$

When renewable energy is used to power the electrolysers, the hydrogen production is carbon-neutral with no need for CCS because oxygen (O_2) is the only by-product. An added advantage is that this process allows excess electricity to be converted into hydrogen which can be stored for future use. Other green hydrogen production options under development include photoelectrochemical processes and biological processes.

GEOLOGICAL STORAGE OF HYDROGEN

If significant quantities of hydrogen are generated using excess electricity from renewable sources in future, underground storage in salt caverns or depleted oil and gas fields may be required to even out the supply versus demand (energy buffering) because of the limited storage capacity of surface facilities (Hassanpouryouzband et al., 2021). There are several geological aspects that need to be evaluated when assessing the feasibility of a potential underground storage site for hydrogen (Juez-Larré et al., 2019; Visser, 2020; Hassanpouryouzband et al., 2021).

- **Density:** The density of hydrogen increases with increasing pressure and decreasing temperature. To achieve hydrogen densities of 10 kg m^{-3}, storage sites would need to be at a depth of over 1500m below surface (Figure 2).
- **Capacity:** The storage capacity of geological storage sites will be significantly higher than above-ground storage facilities. Salt caverns will tend to have smaller storage capacity compared to depleted oil and gas fields and saline aquifers.
- **Discharge Time:** A storage site would ideally facilitate high injection rates to efficiently store hydrogen at times of peak hydrogen generation and low demand and, conversely, facilitate high production rates from the storage site during times of peak demand and energy shortage. Salt caverns typically enable higher rates and hence may

be suitable in balancing diurnal variations in energy supply (Figure 3). Depleted gas fields have greater capacity and slower response times and are considered more suitable for seasonal variations.

- **Cushion Gas:** During cyclic storage, a certain volume of gas needs to be injected to maintain a minimum pressure in the geological container to allow for adequate production rates during the withdrawal season. This is known as cushion gas. Salt caverns need less cushion gas than depleted gas fields. Hydrogen can be used as cushion gas to keep the overall hydrogen concentration as pure as possible. However, because hydrogen is costly to produce, relatively inert gases such as nitrogen could be evaluated as alternatives.
- **Leakage:** Hydrogen, like any fluid that is less dense than formation water, is susceptible to vertical leakage from geological storage sites. This risk is lowest for salt caverns because the hydrogen will be sealed by impermeable salt layers. In depleted gas fields, the presence of an effective seal rock layer is proven by the existence of natural gas which has been trapped over geological timescales. However, these seal rocks could start to partially leak once a threshold capillary pressure has been exceeded during injection, or if microfracturing impacts the integrity of the topseal. Hydrogen loss via diffusion is an additional factor to consider (Reitenbach et al., 2015; Hassanpouryouzband et al., 2021). These risks need to be evaluated and mitigated in any planned development.
- **Chemical Reactions:** Underground storage of hydrogen entails a risk of (a) hydrogen loss by bacterial conversion to methane (CH_4) and hydrogen sulphide (H_2S), and (b) gas–water–mineral interactions that can lead to porosity and permeability changes within the reservoir (Hemme and van Berk, 2018). Acidification of the reservoir could also pose a threat to the integrity of steel alloys used at the storage site. Each of these potential issues needs to be evaluated for each candidate site.
- **Seismic Risks:** Induced seismicity is a risk than needs to be monitored and mitigated in any operation that involves large pressure changes in the subsurface. This risk may be easiest to mitigate in depleted gas fields where an abundance of data is already available from the progressive production (depletion) history of the field. During cyclic storage, the reservoir pressure can be maintained between a safe upper and lower limit to reduce the risk of seismicity. Local surface subsidence is another risk that needs to be assessed above man-made salt caverns, generated via solution mining.

In general, salt caverns could be considered the most suitable option for initial development of geological hydrogen storage. Salt caverns provide the shortest response times because of their high production rates and have the lowest risk of losses due to chemical reactions and leakage. Salt caverns have lower gas capacities, but several adjacent caverns could be used to increase yield. Salt caverns are already being used for hydrogen storage in the United Kingdom (Gammer, 2015) and in the United States (Lord et al., 2014). Depleted gas fields could represent an attractive option when scaling up storage volumes or addressing longer term (seasonal) variations in energy supply (Amid et al., 2016; Brandon and Kurban, 2017). Depleted gas fields already have an abundance of available data for subsurface characterisation and existing infrastructure could potentially be repurposed to convert a production site to a storage facility. Saline aquifers carry many of the same risks as depleted gas fields but do not have the benefit of existing geological data and infrastructure.

OPPORTUNITIES IN IRELAND

Energy-related CO_2 emissions can be split into three main categories, transport, heat and electricity generation. In 2018, these three sectors corresponded to 40%, 33% and 27% of Ireland’s energy-related CO_2 emissions, respectively (SEAI, 2020). As part of the 2021 Climate Action Plan, the Irish Government has committed to halving carbon emissions by 2030 and achieving net-zero greenhouse gas emissions relative to pre-industrial 1990 levels by 2050 (DECC, 2021a). Ireland’s proposed decarbonisation plan is to focus initially on energy efficiency and the electrification of key sectors including heating and transport, but green hydrogen could play a future role in the hard-to-abate sectors such as electricity generation, industry and certain parts of the transport sector (DECC, 2022).

SEAI (2022) modelled several pathways to net-zero in the heat sector in Ireland by 2050 and proposed a role for hydrogen to produce medium-grade and high-grade heat in industrial manufacturing processes. However, the role of hydrogen is less evident for lower temperature space and water heating where other alternative options such as heat pumps and geothermal can be utilised. In the transport sector, the 2021 Climate Action Plan (DECC, 2021a) sets out targets for BEVs which represent the most advanced and readily deployable solution for decarbonising passenger cars and other lightweight vehicles. However, hydrogen (via FCEVs or green ammonia fuel) could still form part of the solution for heavy-duty vehicles, maritime and aviation transport, where full electrification may remain a challenge (DECC, 2022).

Despite having a large proportion of its electricity needs met by renewables (33% in 2018), Ireland is still expected to require low-carbon dispatchable power generation to provide back-up because of the intermittent nature of renewable generation (GNI, 2018, 2019; DECC, 2021b). The Irish Government has committed to ramping up renewable generation, targeting 80% of annual electricity production from mainly wind and solar by 2030 (DECC, 2021a), and further increasing thereafter. The deployment of green hydrogen fuel with hydrogen-ready gas turbines could help to decarbonise conventional back-up generation in addition to enhancing energy security by increasing domestic supply. Hydrogen could also be used as an (excess) energy store and help to address the challenges associated with ramping up renewable generation such as grid stability, intermittency, and curtailment (DECC, 2022). Ireland has significant potential to produce green hydrogen because of its considerable offshore and onshore wind potential. The 2021 Climate Action Plan has set a target of the development of at least 5 GW of offshore wind by 2030 (DECC, 2021a), and the Government is currently developing a long-term hydrogen strategy to establish how Ireland can best take advantage of and utilise its offshore renewable energy potential (DECC, 2022). In future, Ireland could also become an exporter of green hydrogen, or ammonia, to larger European markets.

Green hydrogen could be stored using high pressure tanks on surface or in underground (geological) storage such as salt caverns, depleted gas fields and saline aquifers. Currently, there is no regulatory or legislative framework in place for the geological storage of hydrogen in onshore or offshore Ireland. The potential for geological storage of hydrogen requires further research and development, and pilot projects will be required to identify the challenges and opportunities with this proposed energy pathway (DECC, 2022). In late 2022, ESB (Ireland's largest energy provider) and dCarbonX (and affiliate of Snam, Europe's largest gas storage provider) signed a joint venture agreement to progress large-scale energy storage projects offshore Ireland. In the next section, we provide some preliminary observations on the geostorage potential for hydrogen in Ireland.

HYDROGEN GEOSTORAGE OPTIONS IN IRELAND

As noted above, salt caverns and depleted gas fields represent the leading candidates for geological storage of hydrogen. However, salt deposits and depleted gas fields are not present everywhere in the subsurface. Ireland is surrounded by numerous offshore Mesozoic to Cenozoic sedimentary basins, and the stratigraphy is relatively well-constrained due to past hydrocarbon exploration drilling (Naylor and Shannon, 2009; Merlin Energy Resources Consortium, 2020). In the Republic of Ireland, salt deposits tend to be restricted to offshore Permian and Triassic sedimentary basins along the east, south and northwest coasts (Figure 4), where existing borehole and seismic data can facilitate the future characterisation of these salt deposits for potential geological storage of hydrogen. This may be of particular interest underneath future offshore wind farms where green hydrogen could be produced and stored during times of excess electricity generation. However, there are no subsurface basins with halite (salt) onshore the Republic of Ireland. In Northern Ireland, a subsurface Permian halite deposit (Andeskie and Benison, 2021) is being developed for natural gas or hydrogen storage on Islandmagee, County Antrim (Infrastrata Energy, 2021). Infrastrata Energy has been granted a licence to construct seven underground caverns (80m in diameter and 160m in height) within a salt layer more than 200m thick at a depth of approximately 1,400m below Larne Lough (Infrastrata Energy, 2020). The proposed storage facility will be capable of holding a working volume of circa 500 MMcm of natural gas, and allow for a withdrawal capacity of 22 MMcm/d and injection capacity of 12 MMcm/d.

The use of existing natural gas fields in Ireland (i.e., Corrib and Kinsale Head) for hydrogen storage should also be a focus of future assessments. This is because the sealed reservoirs have been proven to hold gas for geological time periods, thus reducing the geological risk of leakage. The Kinsale Head gas field is a depleted natural gas field located in the NE-SW-trending North Celtic Sea Basin, circa 50 km off the south coast of County Cork (Figure 4). The field was originally discovered in 1971 and commenced production in 1978. The primary reservoirs are Early Cretaceous in age (Taber et al., 1995; Figure 5) and some key parameters for the field are presented in Table 1. The Kinsale Head gas field produced a cumulative volume of 1.77 Tcf (50.1 Bcm) of natural gas from stacked reservoir units (Kinsale Energy, 2018). Production ceased in 2020 and the field is currently in the process of being decommissioned. It is noteworthy that one small compartment of the Kinsale Head complex, the SW Kinsale gas field (O’Sullivan, 2001), was previously utilised for natural gas storage within the Bream Sandstone Member (Figure 5) between 2001 and 2017. The SW Kinsale gas field is estimated to have 29 Bcf (0.8 Bcm) of total recoverable gas with a working natural gas storage volume of circa 7 Bcf (0.2 Bcm), and the maximum injection and production rates were 50 MMscf/d (1.4 MMcm/d) and 100 MMscfd (2.8 MMcm/d), respectively (CRU, 2005).

The Corrib gas field is located in the Slyne Basin, a narrow Triassic/Jurassic half-graben, circa 80 km off the west coast of County Mayo (Figure 4). The field was discovered in 1996 in a reservoir over 3 km beneath the seafloor, and production commenced in 2015. The reservoir is comprised of Triassic fluvial sandstones and is sealed by overlying Triassic halites (Dancer et al., 2005; Figure 5). Some key parameters for the field are presented in Table 1. The Corrib gas field is estimated to hold 0.87 Tcf (24.6 Bcm) of recoverable natural gas (Dancer et al., 2005). Peak production has passed, and the field is currently in decline. Field life was estimated at 15-20 years (Enterprise Energy Ireland Ltd, 2001), which may mean the end of field life as early as 2031 (IOOA, 2019). Unless additional new (yet to be discovered) gas volumes can be tied-in to these facilities, the depleted Corrib gas field may become a potential candidate for hydrogen storage in circa 10 years' time.

The hydrogen storage capacity of depleted gas fields can be estimated based on the mass of hydrogen that could utilise pore space previously occupied by the recoverable reserves of natural gas. This relationship is given by (Hassanpouryouzband et al., 2021):

$$SC_{H_2,\ Max} = \left(\frac{V_{GAS}\,(sc)}{FVF}\right) \times \rho_{H_2} \times HHV_{H_2} \qquad (4)$$

where SC_{H2} = hydrogen storage capacity (TWh), sc = standard conditions for temperature and pressure, $V_{GAS}\ (sc)$ = volume of ultimately recoverable gas at sc (Bcm = 10^9 m^3), FVF = gas formation volume factor (from reservoir conditions to sc), ρ_{H2} = density of hydrogen at reservoir conditions (kg m^{-3}), HHV_{H2} = higher heating value for hydrogen (39.41 kWh kg^{-1}). The density of hydrogen at reservoir conditions can be calculated using the Nobel-Abel equation of state (Scafidi et al., 2021):

$$\rho_{H_2} = \frac{P}{(RT + bP)} \qquad (5)$$

where ρ_{H2} is the density of hydrogen (kg/m^3), P is pressure (Pa), R is the gas constant (4160 J kg^{-1} K^{-1} for hydrogen), T is temperature (K), and b is the co-volume (15.84 cm^3 mol^{-1} for hydrogen (San Marchi et al., 2007) which is equal to 0.007858 m^3 kg^{-1}). Using equations (4) and (5), we estimate the total energy storage capacity for the Kinsale Head and Corrib gas fields at circa 134 TWh and 75 TWh, respectively (Table 1). However, only a proportion of this total volume comprises the working gas capacity (i.e., total gas minus cushion gas). If we assume a cushion gas requirement of 50%, for example, the maximum working gas capacity estimates are 67 TWh and 38 TWh, respectively, if all reservoir units are used. Assuming similar gas properties to the main Kinsale Head gas field, the proven working natural gas volume of circa 7 Bcf (0.2 Bcm) for the SW Kinsale gas storage field would equate to 0.5 TWh of working capacity for hydrogen. For comparison purposes, the final energy consumption of electricity in Ireland was 28.7 TWh in 2020 (SEAI, 2021). However, it is important to note that these are only indicative capacity estimates for the moment – detailed research and numerical modelling is required to properly assess these fields in addition to evaluating recovery efficiencies and rates etc. The total void space in the proposed salt cavern storage facility on Islandmagee in Northern Ireland is approximately 5.6 MMcm. Assuming a hydrogen density of circa 9.7 kg m^{-3} (hydrostatic pressure and 47°C temperature at a depth of 1400m), the total energy storage capacity for hydrogen in this facility would be approximately 2.2 TWh. Assuming 25% requirement for cushion gas volume in salt caverns, the working gas capacity would be 1.6 TWh.

CONCLUSIONS

The IPCC has stated that the targets set out in the Paris Agreement will be beyond reach unless there is an immediate and significant reduction in the emissions of greenhouse gas. Ireland's decarbonisation plan is to focus initially on energy efficiency and the electrification of key sectors including heating and transport. However, green hydrogen could also play a role in the hard-to-abate sectors such as industry, electricity generation and certain parts of the transport sector. Ireland has significant potential for domestic green hydrogen production because of its considerable offshore and onshore wind potential. The deployment of green hydrogen fuel with hydrogen-ready gas turbines could help to decarbonise conventional back-up generation in addition to enhancing energy security. Hydrogen could also be used as a temporary energy store and help to address some key challenges associated with the proposed ramping up of renewable electricity generation as part of the Climate Action Plan.

The geostorage potential for hydrogen in Ireland needs further evaluation. In general, Permian and Triassic salt deposits tend to be restricted to offshore sedimentary basins along the east, south and northwest coasts, and these may be of particular interest if co-located with future offshore wind farms where green hydrogen could be produced and stored during times of excess electricity generation. In Northern Ireland, an onshore Permian halite deposit is being developed as an underground storage site with a working volume capacity of circa 500 MMcm (natural gas) across seven adjacent underground caverns. We provisionally estimate a hydrogen working gas capacity of 1.6 TWh for the same proposed facility. Hydrogen geostorage potential also exists in offshore gas fields, where we provisionally estimate maximum hydrogen working gas capacities of 67 TWh and 38 TWh for the Kinsale Head and Corrib gas fields, respectively. One compartment of the Kinsale Head complex, the SW Kinsale gas field, was previously utilised for natural gas storage between 2001 and 2017 and we estimate a hydrogen working gas capacity of 0.5 TWh for this particular site. However, these are only indicative capacity estimates for the moment, and further research is required in future to properly assess the hydrogen geostorage potential across the island of Ireland, both onshore and offshore.

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Nomenclature

b = co-volume (15.84 $\text{cm}^3\ \text{mol}^{-1}$ for hydrogen)

Bcf = billion cubic feet

Bcm = billion cubic metres (standard)

FVF = gas formation volume factor (from reservoir conditions to sc)

HHV_{H2} = higher heating value for hydrogen (39.41 kWh kg^{-1})

kWh = kilowatt-hours

MMcm = million cubic metres (standard)

MMcm/d = million cubic metres (standard) per day

MMscf/d = million cubic feet per day

ρ_{H2} = density of H_2 at reservoir conditions (kg m^{-3})

R = gas constant (4160 $\text{J kg}^{-1}\ \text{K}^{-1}$ for hydrogen)

sc = standard conditions for temperature and pressure

SC_{H2} = hydrogen storage capacity (TWh)

Tcf = trillion cubic feet

TVDss = True Vertical Depth subsea

TWh = Terawatt-hours

V_{GAS} (sc) = volume of ultimately recoverable gas at sc (Bcm)

References

Amid, A., Mignard, D. and Wilkinson, M. [2016]. Seasonal storage of hydrogen in a depleted natural gas reservoir. *International Journal of Hydrogen Energy*, **41**, 5549–5558. https://doi.org/10.1016/j.ijhydene.2016.02.036.

Andeskie, A.S. and Benison, K.C. [2021]. A missing link in the mid-late Permian record of north-eastern Pangea: A sedimentological evaluation of the Permian Belfast Harbour Evaporite Formation of County Antrim, Northern Ireland. *The Depositional Record*, **7**(3), 451–469. https://doi.org/10.1002/dep2.144.

Ball, M. and Weeda, M. [2015]. The hydrogen economy – Vision or reality? *International Journal of Hydrogen Energy*, **40**, 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032.

Brandon, N.P. and Kurban, Z. [2017]. Clean energy and the hydrogen economy. *Philosophical Transactions of the Royal Society A*, **375**, 20160400. https://doi.org/10.1098/rsta.2016.0400.

Brandon, N.P., Edge, J.S., Aunedi, M., Barbour, E.R., Bruce, P.G., Chakrabarti, B.K., Esterle, T., Somerville, J.W., Ding, Y.L., Fu, C., Grant, P.S., Hall, P.J., Huang, C., Leng, G.H., Li, Y.L., Martins, V.L., Navaroo, M.E., Gil Posada, J.O., Rennie, A.J.R., Rogers, D.J., Strbac, G., Pérez Villar, S., Yufit, V., Wang, J. and Worsley, D.A. [2016]. *UK research needs in grid scale energy storage technologies*. See http://energysuperstore.org/wp-content/uploads/2016/04/IMPJ4129_White_Paper_UK-Research-Needs-in-Grid-Scale-Energy-Storage-Technologies_WEB.pdf. Accessed 25th September 2022.

Colley, M.G., McWilliams, A.S.F. and Myers, R.C. [1981]. Geology of the Kinsale Head Gas Field, Celtic Sea, Ireland. In: In: Illing, L.V. and Hobson, G.D. (Eds.) *Petroleum Geology of the Continental Shelf of North-West Europe*. Heyden, London, 504–510.

Corcoran, D.V. and Doré, A.G. [2002]. Depressurization of hydrocarbon-bearing reservoirs in exhumed basin settings: evidence from Atlantic margin and borderland basins. In: Doré, A.G., Cartwright, J.A., Stoker, M.S., Turner, J.P. and White, N. (Eds.) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*. Geological Society Special Publication, **196**, 457–483. https://doi.org/ 10.1144/GSL.SP.2002.196.01.25.

Corcoran, D.V. and Mecklenburgh, R. [2005]. Exhumation of the Corrib Gas Field, Slyne Basin, offshore Ireland. *Petroleum Geoscience*, **11**, 239–256. https://doi.org/10.1144/1354-079304-637.

Core Laboratories [1978]. *48/24-2 Geochemical Evaluation (Fluid Analysis) Report*. CSA Group [2008]. *Assessment of the Potential for Geological Storage of CO_2 for the Island of Ireland*.

CRU [2005]. *An assessment of the technical and economic requirement for third party access to a proposed storage facility at the Kinsale Head gas facility in Ireland (CER/05/221)*.

CSA Group [2008]. *Assessment of the Potential for Geological Storage of CO_2 for the Island of Ireland*.

Dancer, P.N., Kenyon-Roberts, S.M., Downey, J.W., Baillie, J.M., Meadows, N.S. and Maguire, K. [2005]. The Corrib gas field, offshore west of Ireland. In: Doré, A.G. and Vining, B.A. (Eds.) *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 1035–1046. https://doi.org/10.1144/0061035.

DECC [2021a]. *Climate Action Plan 2021.*

DECC [2021b]. *Policy Statement on Security of Electricity Supply – November 2021.*

DECC [2022]. *Consultation on Developing a Hydrogen Strategy for Ireland – July 2022.*

Dodds, P.E., Staffell, I., Hawkes, A.D., Li, F., Grünewald, P., McDowall, W. and Ekins, P. [2015]. Hydrogen and fuel cell technologies for heating: A review. *International Journal of Hydrogen Energy*, **40**, 2065–2083. https://doi.org/10.1016/j.ijhydene.2014.11.059.

Edlmann, K., Haszeldine, S., Heinemann, N., Hassanpouryouzband, A. and Thaysen, E. [2021]. *HyStorPor: unlocking the UK's hydrogen storage*. University of Edinburgh.

Eisentraut, A. and Brown, A. [2014]. *Heating without global warming*. International Energy Agency, France.

English, J.M. and English, K.L. [2022a]. An Overview of Carbon Capture and Storage and its Potential Role in the Energy Transition. *First Break*, **40**(4), 35–40. https://doi.org/10.3997/1365-2397.fb2022028.

English, J.M. and English, K.L. [2022b]. Carbon Capture and Storage Potential in Ireland — Returning Carbon Whence It Came. *First Break*, **40**(5), 35–43. https://doi.org/10.3997/1365-2397.fb2022035.

English, J.M., English, K.L., Dunphy, R.B., Blake, S., Walsh, J., Raine, R., Vafeas, N.A. and Rodriguez Salgado, P. [2022]. An Overview of Geothermal Energy and its Potential on the island of Ireland. *First Break*, **XX**(X), XX–XX. https://doi.org/XXX.

Enterprise Energy Ireland Ltd [2001]. *Corrib Offshore EIS.*

Expro [2001]. *Analysis of Enterprise 18/25-3 Formation Fluid.*

Gammer, D. [2015] *The role of hydrogen storage in a clean responsive power system*. Energy Technologies Institute. Loughborough, UK

Gasunie [2022]. *The world of hydrogen*. https://www.theworldofhydrogen.com/gasunie/supply-and-demand/. Accessed 31st October 2022.

Gaucher, E.C. [2020]. New Perspectives in the Industrial Exploration for Native Hydrogen. *Elements*, **16**(1), 8–9. https://doi.org/10.2138/gselements.16.1.8.

GNI [2018]. *Network Development Plan 2018.*

GNI [2019]. *Network Development Plan 2019.*

Gröger, O., Gasteiger, H.A. and Suchsland, J.-P. [2015]. Review—Electromobility: Batteries or Fuel Cells? *Journal of The Electrochemical Society*, **162**(14), A2605–A2622. https://doi.org/10.1149/2.0211514jes.

Hassanpouryouzband, A., Joonaki, E., Edlmann, K. and Haszeldine, R.S. [2021]. Offshore Geological Storage of Hydrogen: Is This Our Best Option to Achieve Net-Zero? *ACS Energy Letters*, **6**, 2181–2186. https://doi.org/10.1021/acsenergylett.1c00845.

Hemme, C. and van Berk, W. [2018]. Hydrogeochemical modeling to identify potential risks of underground hydrogen storage in depleted gas fields. *Applied Sciences*, **8**, 2282. https://doi.org/10.3390/app8112282.

IEA [2021]. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. International Energy Agency, France.

IEA [2022]. *Global energy-related CO_2 emissions by sector*. International Energy Agency, France. https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector. Accessed 25th September 2022.

Infrastrata Energy [2020]. *The Proposed Islandmagee Natural Gas Storage Facility. Environmental Statement – Non-Technical Summary.*

Infrastrata Energy [2021]. *Northern Ireland's transition to Net Zero: a case for large-scale energy storage.*

IPCC [2021]. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, UK.

IOOA [2019]. *Value of the indigenous oil and gas industry to Ireland.*

Juez-Larré, J., van Gessel, S., Dalman, R., Remmelts, G. and Groenenberg, R. [2019]. Assessment of underground energy storage potential to support the energy transition in the Netherlands. *First Break*, **37**(7), 57–66. https://doi.org/10.3997/1365-2397.n0039.

Kinsale Energy [2018]. *Kinsale Area Decommissioning Project: Decommissioning Plan – Kinsale Head Petroleum Lease (OPL1) – Consent Application No.1.*

Lord, A.S., Kobos, P.H. and Borns, D.J. [2014]. Geologic storage of hydrogen: scaling up to meet city transportation demands. *International Journal of Hydrogen Energy*, **39**, 15570–15582. https://doi.org/10.1016/j.ijhydene.2014.07.121.

Merlin Energy Resources Consortium [2020]. *The Standard Stratigraphic Nomenclature of Offshore Ireland: an Integrated Lithostratigraphic, Biostratigraphic and Sequence Stratigraphic Framework. Project Atlas*. Petroleum Affairs Division, Department of the Environment, Climate and Communications. Special Publication 1/21.

Naylor, D. and Shannon, P.M. [2009]. Geology of offshore Ireland. In: Holland, C.H. and Sanders, I.S. (Eds.) *The Geology of Ireland*. Dunedin Academic Press, Edinburgh, Scotland, 405–460.

O'Sullivan, J.M. [2001]. The geology and geophysics of the SW Kinsale gas accumulation. In: Shannon, P.M., Haughton, P.D.W. and Corcoran, D.V. (Eds.) *The Petroleum Exploration of Ireland's Offshore Basins*. Geological Society Special Publication, **188**, 189–199. https://doi.org/10.1144/GSL.SP.2001.188.01.10.

Prinzhofer, A., Tahara Cissé, C.S. and Diallo, A.B. [2018]. Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). *International Journal of Hydrogen Energy*, **43**, 19315–19326. https://doi.org/10.1016/j.ijhydene.2018.08.193.

Reitenbach, V., Ganzer, L., Albrecht, D. and Hagemann, B. [2015]. Influence of added hydrogen on underground gas storage: a review of key issues. *Environmental Earth Sciences*, **73**, 6927–6937. https://doi.org/10.1007/s12665-015-4176-2.

San Marchi, C., Somerday, B.P. and Robinson, S.L. [2007]. Permeability, solubility and diffusivity of hydrogen isotopes in stainless steels at high gas pressures. *International Journal of Hydrogen Energy*, **32**, 100–116. https://doi.org/10.1016/j.ijhydene.2006.05.008.

Scafidi, J., Wilkinson, M., Gilfillan, S.M.V., Heinemann, N. and Haszeldine, R.S. [2021]. A quantitative assessment of the hydrogen storage capacity of the UK continental shelf. *International Journal of Hydrogen Energy*, **46**, 8629–8639. https://doi.org/10.1016/j.ijhydene.2020.12.106.

Schmid, S., Worden, R.H. and Fisher, Q.J. [2004]. Diagenesis and reservoir quality of the Sherwood Sandstone (Triassic), Corrib Field, Slyne Basin, west of Ireland. *Marine and Petroleum Geology*, **21**(3), 299–315. https://doi.org/10.1016/j.marpetgeo.2003.11.015.

SEAI (Sustainable Energy Authority of Ireland) [2020]. *Energy-related CO_2 emissions in Ireland 2005-2018 (2020 report).*

SEAI (Sustainable Energy Authority of Ireland) [2021]. *Energy in Ireland (2021 report).*

SEAI (Sustainable Energy Authority of Ireland) [2022]. *National Heat Study: Net Zero by 2050 – Key Insights, Evidence and Actions*.

Sherwood Lollar, B., Onstott, T.C., Lacrampe-Couloume, G. and Ballentine, C.J. [2014]. The contribution of the Precambrian continental lithosphere to global H_2 production. *Nature*, **516**, 379–382. https://doi.org/10.1038/nature14017.

Smith, N.J.P., Evans, D.J. and Andrews, I.J. [2005]. *The geology of gas storage in offshore salt caverns*. Marine, Coastal and Hydrocarbons Programme, British Geological Survey.

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P.E., Ekins, P., Shah, N. and Ward, K.R. [2019]. The role of hydrogen and fuel cells in the global energy system. *Energy and Environmental Science*, **12**, 463. https://doi.org/10.1039/c8ee01157e.

Taber, D.R., Vickers, M.K. and Winn Jr, R.D. [1995]. The definition of the Albian 'A' Sand reservoir fairway and aspects of associated gas accumulations in the North Celtic Sea Basin. In: Croker, P.F. and Shannon, P.M. (Eds.) *The Petroleum Geology of Ireland's Offshore Basins*. Geological Society Special Publication, **93**, 227–244. https://doi.org/10.1144/GSL.SP.1995.093.01.16.

Tappin, D.R., Chadwick, R.A., Jackson, A.A., Wingfield, R.T.R. and Smith N.J.P. [1994]. *The geology of Cardigan Bay and the Bristol Channel*. United Kingdom offshore regional report, British Geological Survey.

Visser, T.M.R.B. [2020]. Seasonal Hydrogen Storage in Depleted Gas Reservoirs A Feasibility Study for The Netherlands. *MSc thesis*. Delft University of Technology.

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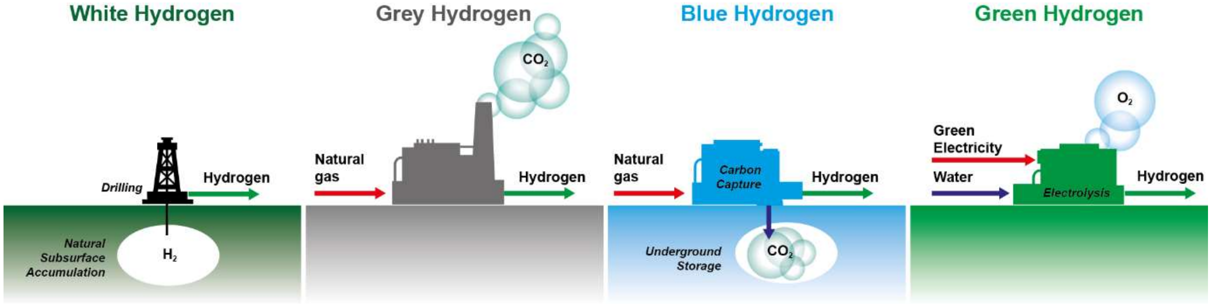
	Kinsale Head		**Corrib**
	Agone Sandstone	**Bream Sst / Wealden Grp**	
Water depth (m)	90[1]	90[1]	350[6]
Depth to top reservoir (m TVDss)	838[1,2]	905[1,2]	3300[6]
Depth to top reservoir (m bml)	748	815	2950
Gas-water contact (m TVDss)	902[1,2]	966[1,2]	3601[6]
Area (km^2)	109[3]	109[3]	15[7] (gas field)
Vertical structural closure (m)	91[3]	91[3]	560[8] (310m gas)
Caprock lithology	Mudstone	Mudstone	Halite
Caprock thickness (m)	45[3]	15[3]	78-777[6]
Gross sand thickness (m)	38[1,2]	-	381+[6]
Net-to-Gross (%)	82[1,2]	7m sand[1,2]	72[6]
Average porosity (%)	20[1,2]	22[1,2]	8.5[6]
Average permeability (mD)	420[1,2]	280[1,2]	15.2[6]
Sw (%)	24.6[1,2]	29.9[1,2]	-
Formation water salinity (g/l)	-	92[4]	326[9]
Formation water density (g/cm^3)	-	1.06	1.24
Reservoir temperature (°C)	29.4[1,2]	32.2[1,2]	~112[10]
Initial reservoir pressure (MPa)	9.2[1] (1336.8 psia)	-	~40.7[11] (~5900 psia)
Pressure gradient (kPa/m)	~10 (hydrostatic)		~11 (slight overpressure)
Gas Composition	C_1 > 99%[2]		C_1 94%, C_2 3%, N_2 3%[6]
Formation Volume Factor - Gas	101		272
Original Gas-In-Place (Bcm)	52.1[5] (1.84 Tcf)		34.0[6] (1.2 Tcf)
Recoverable gas (Bcm)	50.1[5] (1.77 Tcf)		24.6[6] (870 Bcf)
Hydrogen Storage Potential			
H_2 density at reservoir condition (kg/m^3)	6.85		21.18
Energy storage capacity (TWh)	134.0		75.5
Assumed cushion gas requirement	0.50		0.50
Indicative working gas capacity (TWh)	67.0		37.7

Sources: [1] CSA Group (2008), [2] Colley et al. (1981), [3] Taber et al. (1995), [4] Core Laboratories (1978), [5] Kinsale Energy (2018), [6] Dancer et al. (2005), [7] Enterprise Energy Ireland Ltd (2001), [8] Corcoran and Mecklenburgh (2005), [9] Expro (2001), [10] Schmid et al. (2004), [11] Corcoran and Doré (2002).



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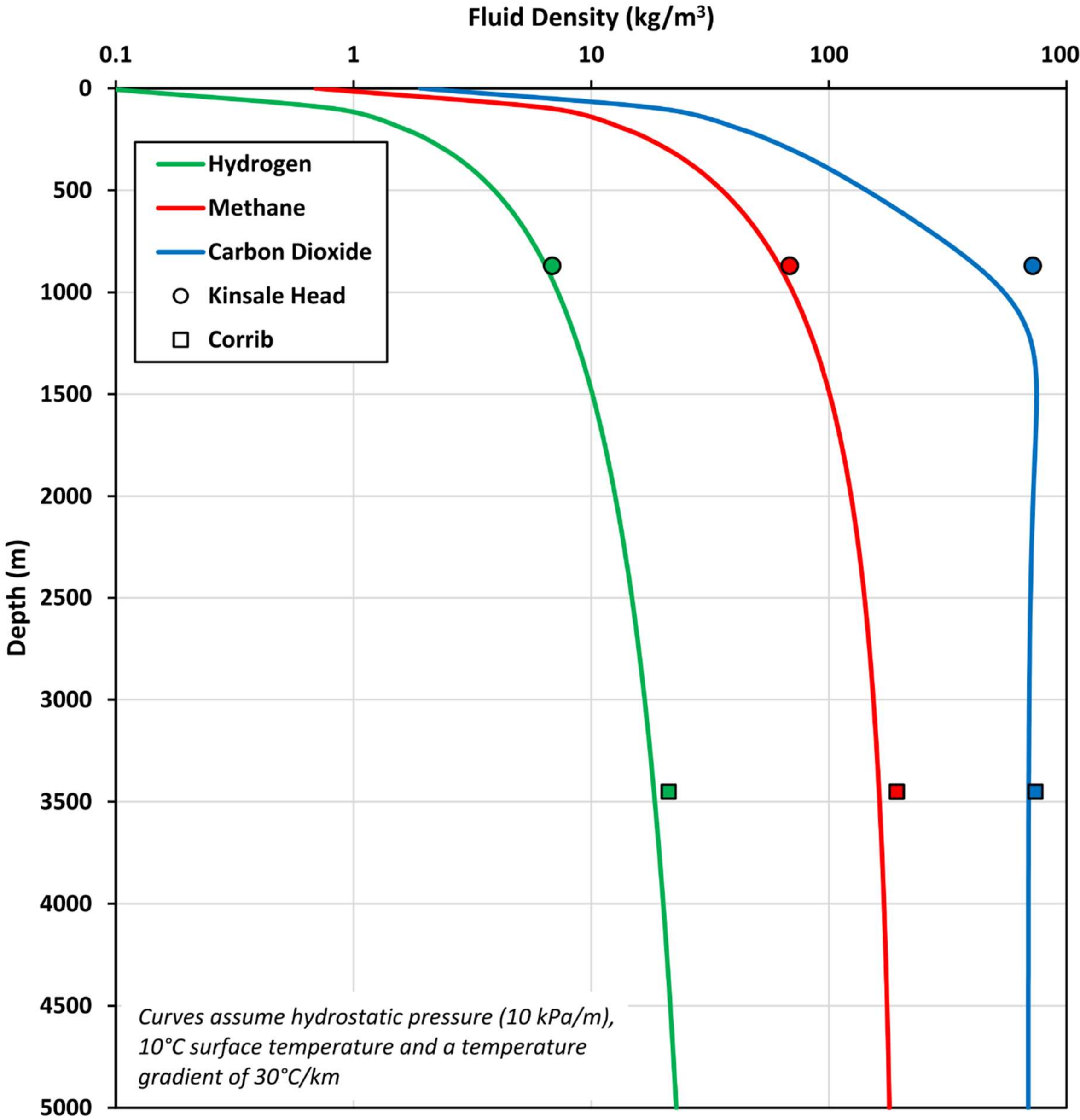

Curves assume hydrostatic pressure (10 kPa/m), 10°C surface temperature and a temperature gradient of 30°C/km

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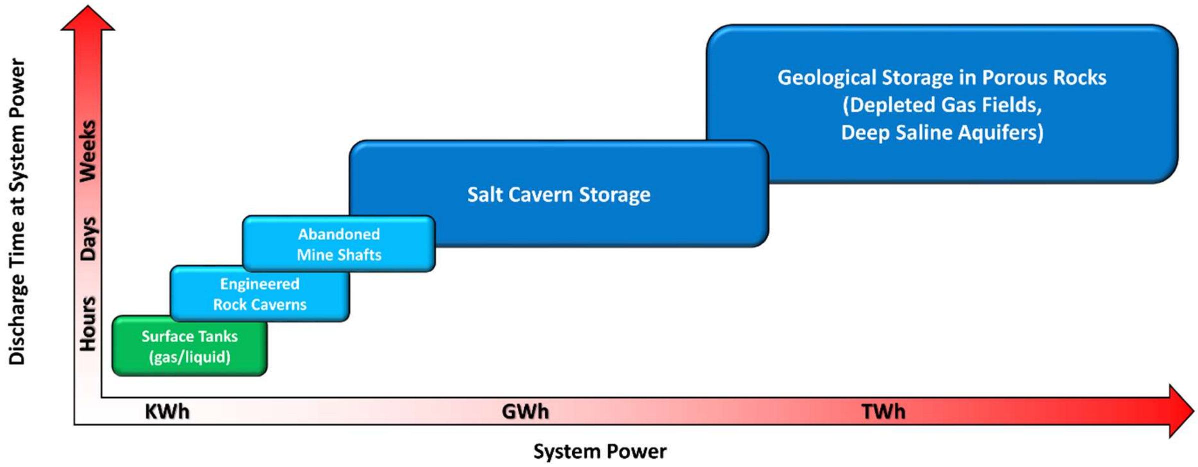

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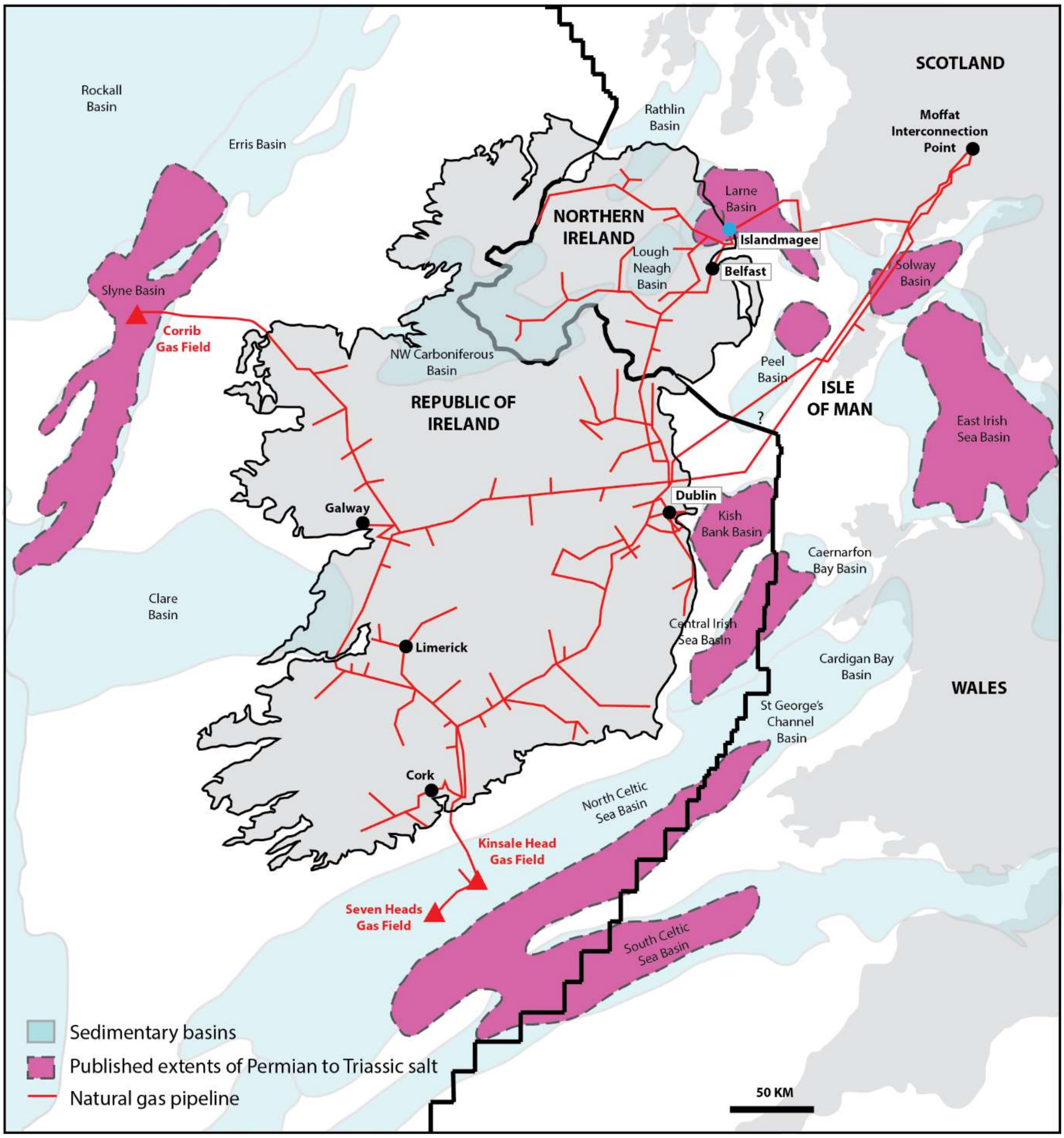

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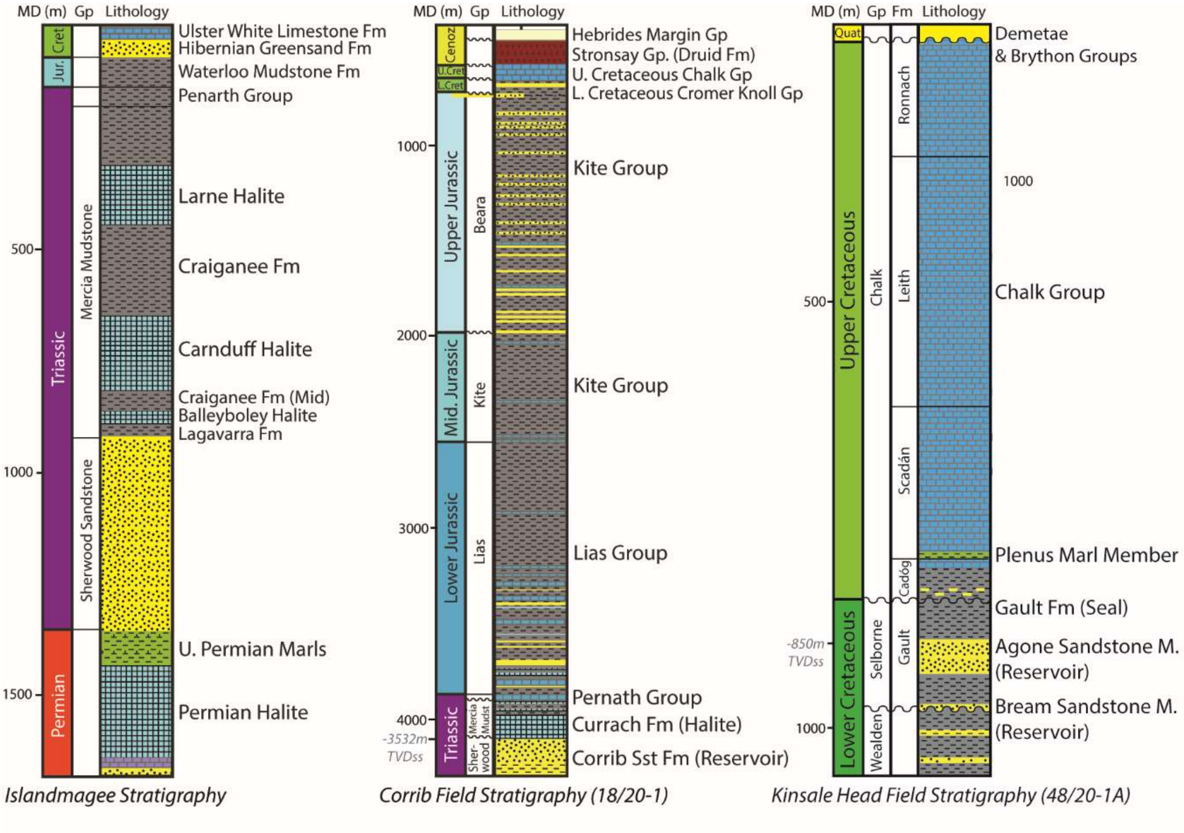

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