| | |
|---|---|
| **Title** | Carbon Capture and Storage Potential in Ireland — Returning Carbon Whence It Came |
| **Authors(s)** | English, Joseph M., English, Kara L. |
| **Publication date** | 2022-05-01 |
| **Publication information** | English, Joseph M., and Kara L. English. “Carbon Capture and Storage Potential in Ireland — Returning Carbon Whence It Came.” European Association of Geoscientists & Engineers, May 1, 2022. https://doi.org/10.3997/1365-2397.fb2022035. |
| **Publisher** | European Association of Geoscientists & Engineers |
| **Item record/more information** | http://hdl.handle.net/10197/25185 |
| **Publisher's version (DOI)** | 10.3997/1365-2397.fb2022035 |

# Carbon capture and storage potential in Ireland — returning carbon whence it came

Joseph M. English[1,2*] and Kara L. English[1,2].

## Summary

Carbon capture and storage (CCS) involves the capture of $CO_2$ emissions produced from industrial and electricity generation sources, followed by transport to permanent underground geological storage. Hence, CCS is one mitigation option available to achieve the targets set out in the Paris Agreement. Here we discuss CCS potential with particular reference to Ireland's emission targets, policy positions and geological storage options. In Ireland, CCS could be utilised (1) with gas-powered electricity to provide secure and reliable low-emissions electricity, (2) to reduce emissions in hard-to-abate industries such as cement manufacturing, and (3) to facilitate the future deployment of negative emissions technologies. Ireland has significant potential to store $CO_2$ in geological formations in depleted gas fields and deep saline aquifers in its offshore sedimentary basins. Two high-graded options are the offshore Kinsale Head and Corrib gas fields. Provisional estimates for the $CO_2$ storage capacity of these two fields are 321 Mt and 44 Mt respectively. The depleted Kinsale Head gas field alone could have sufficient storage capacity to take the equivalent of up to 40 years of $CO_2$ emissions from the top 10 point-source emitters in Ireland. Further work is needed to fully characterise and mature the potential for CCS in Ireland.

## Introduction

CCS is one of a number of mitigation options that can be considered to stabilize atmospheric greenhouse gas concentrations in order to meet the targets set out in the Paris Agreement (e.g. Pacala & Socolow, 2004; IPCC, 2005, 2014; Haszeldine, 2009; Ringrose, 2017, 2020). CCS involves the separation and capture of 90-98% of carbon dioxide ($CO_2$) emissions produced from industrial and electricity generation sources, followed by transport to underground geological storage and hence permanent isolation from the atmospheric system. An introductory overview of CCS and its potential role in the energy transition is provided by English & English (2022). This article provides

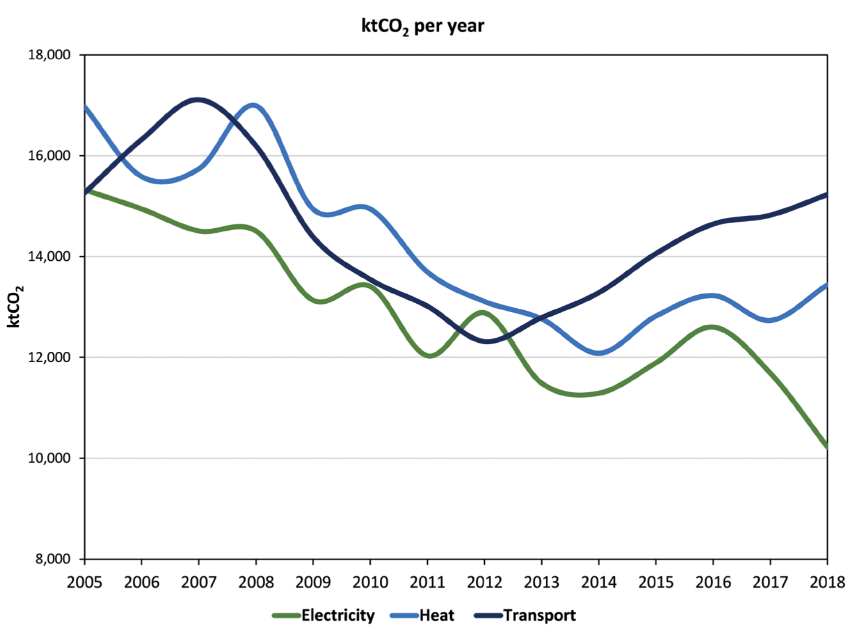


**Figure 1** Energy-related $CO_2$ emissions ($ktCO_2$) by mode in Ireland over 2005-2018 (SEAI, 2020).

[1] Sustainable GeoEnergy Group, University College Dublin | [2] Stellar Geoscience Limited
[*] Corresponding author, E-mail: joseph.english@ucd.ie, je@stellargeoscience.com
DOI: 10.3997/1365-2397.fb2022035

(1) a review of Ireland's current greenhouse gas emissions and the climate action targets that have been adopted by the Irish government, and (2) an introduction to two potential geological sites, the offshore Kinsale Head and Corrib gas fields, that could be utilised for CCS in Ireland. Preliminary $CO_2$ storage capacity estimates are provided for both candidate CCS sites.

## Greenhouse gas emissions in Ireland

The two most important greenhouse gases are carbon dioxide ($CO_2$) and methane ($CH_4$). In Ireland, $CH_4$ emissions come mostly from agriculture livestock, while $CO_2$ emissions come predominantly from the combustion of fossil fuels for energy, industrial processes such as cement manufacturing, fertilizer spreading in agriculture and refrigeration gases. Fossil fuel combustion for energy comprised 59% of all Ireland's greenhouse gas emissions in 2018 with 34% from agriculture, 6% from industrial processes and 1% from waste (SEAI, 2020). Energy-related $CO_2$ emissions and their associated mitigation plans can be split into three separate categories:

- **Transport:** Transport remains almost entirely dependent on oil and was the largest source of energy-related $CO_2$ emissions (40%) in Ireland in 2018 (SEAI, 2020). Private vehicles are responsible for the greatest share of transport emissions (40%), followed by aviation (22%) and then heavy goods vehicles (14%). $CO_2$ emissions from transport have increased 24% since 2012 (Figure 1). Under the 2019 Climate Action Plan, the Irish Government has set a target of 950,000 electric vehicles (EVs) in use by 2030, and that by this time, all new cars and vans will be electric vehicles (EVs) (DCCAE, 2019).
- **Heat:** Heat amounted to 33% of energy-related $CO_2$ emissions in Ireland in 2018 (SEAI, 2020). Between 2005 and 2018, the amount of oil used for heating was reduced by 35% with most of this reduction happening in industry (55%). Despite a small increase in the amount of heat generated from renewable energy, Ireland still has the second lowest proportion of renewable heat within the EU. Overall, emissions from heat have been increasing since 2014 (Figure 1). Under the 2019 Climate Action Plan, the Irish Government has set a target to upgrade circa 500,000 existing homes to B2 Building Energy Rating (BER), deliver two new district heating systems and install heat pumps in 400,000 existing homes (DCCAE, 2019).
- **Electricity generation:** Electricity generation was responsible for 27% of energy-related $CO_2$ emissions in Ireland in 2018 (SEAI, 2020), but the overall emissions have dropped 33% between 2005 and 2018 (Figure 1). This is, in a large

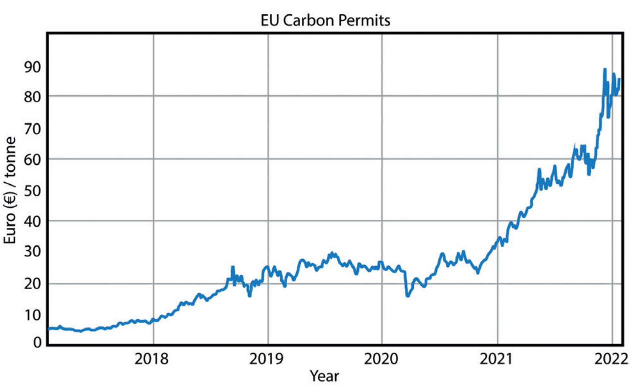


**Figure 2** EU carbon permit price (€/tonne) over past 5 years (data from Trading Economics, 2022).

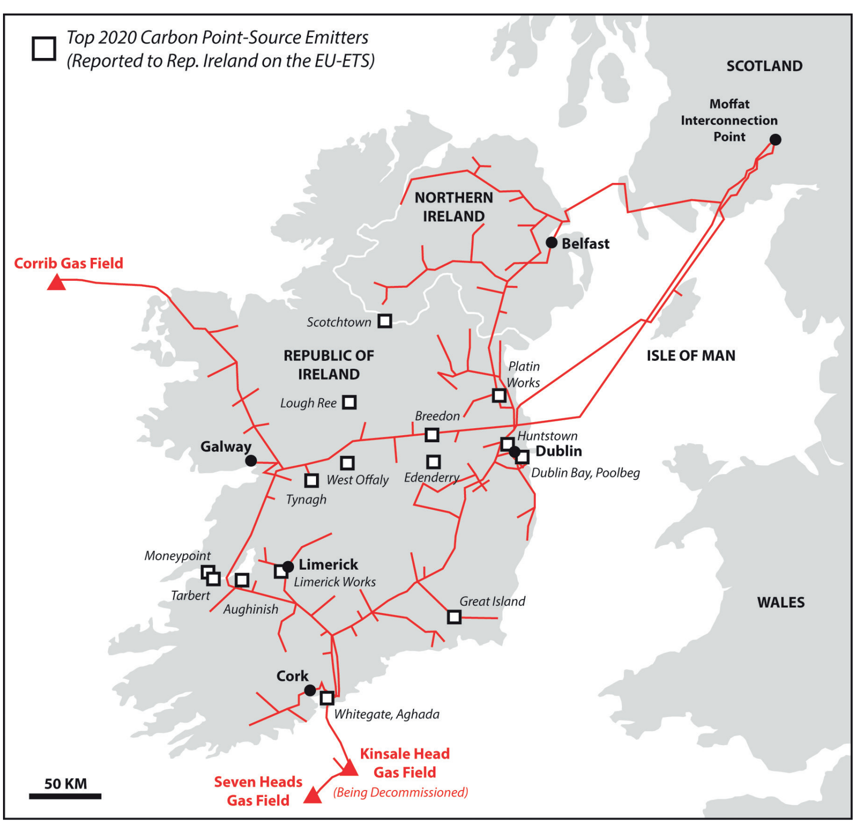


**Figure 3** Map of the major gas transmission lines in Ireland including the locations of the Kinsale Head and Corrib gas fields. The locations of the major carbon point source emitters in the Republic of Ireland, as reported under the EU-ETS in 2020 are also shown; see Table 1 for further details.

| Entity | Activity | Verified 2020 Emissions ($tCO_2$) | Share of Total |
|---|---|---|---|
| Ryanair DAC | Aircraft operator | 4,165,343 | 23% |
| Aughinish Alumina | Alumina refinery | 1,224,809 | 7% |
| Irish Cement Limited (Platin Works) | Cement manufacturer | 1,012,063 | 6% |
| ESB Moneypoint Generating Station | Coal-fired power station | 862,922 | 5% |
| Great Island Generating Station | CCGT power plant | 798,519 | 4% |
| Whitegate Power Station | CCGT power plant | 765,553 | 4% |
| Dublin Bay Power Plant | CCGT power plant | 742,726 | 4% |
| Scotchtown Cement Works | Cement manufacturer | 742,599 | 4% |
| Tynagh 400MW CCPP | CCGT power plant | 675,450 | 4% |
| Aghada CCGT | CCGT power plant | 675,188 | 4% |
| Huntstown Power Station | CCGT power plant | 657,649 | 4% |
| Irish Cement Limited (Limerick Works) | Cement manufacturer | 576,681 | 3% |
| ESB Poolbeg Generating Station (CCGT) | CCGT power plant | 543,271 | 3% |
| CCGT HPC2 (Huntstown Power Phase II) | CCGT power plant | 537,790 | 3% |
| ESB West Offaly | Peat-fired power station | 412,725 | 2% |
| Breedon Cement Ireland Limited | Cement manufacturer | 352,627 | 2% |
| ESB Lough Ree Power | Peat-fired power station | 309,095 | 2% |
| Irving Oil Whitegate Refinery Limited | Oil refinery | 300,762 | 2% |
| Edenderry Power Plant | Peat/biomass-fired power | 292,674 | 2% |
| Aer Lingus Limited AOHA | Aircraft operator | 213,783 | 1% |
| Tarbert Generating Station | Oil-fired power station | 194,511 | 1% |

**Table 1** Top 2020 carbon emitters reported to Ireland under the EU-ETS.

part, due to a major increase in the contribution of zero-carbon renewable energy (mainly wind) to Ireland's electricity supply, up from 7% in 2005 to 33% of all electricity in 2018. However, while coal and peat generated only 14% of electricity in 2018, they were responsible for 40% of the $CO_2$ associated emissions. Natural gas generated 52% of the electricity in 2018 and was responsible for 57% of $CO_2$ emissions. Under the 2021 Climate Action Plan, the Irish Government has set a target to increase the electricity supply from renewable sources to 80% by 2030 and to phase out peat and coal-fired plants (DECC, 2021a).

The EU Emissions Trading System (ETS) sets an absolute limit on the total annual emissions of certain greenhouse gases by any significant company or body within the EU, and this annual allowable emissions limit is reduced over time. It is noteworthy that the price of tradable EU carbon permits under this scheme has almost trebled over the course of 2021 (Figure 2). Entities covered by the system include large industries, electricity generators and the aviation industry. Greenhouse gas emissions outside these emitters are referred to as non-ETS emissions and are managed at member state level under the Effort Sharing Regulation. Non-ETS emissions include those associated with road transport, residential heating and cooling, small businesses, agriculture, waste etc. Characterized in this way, the biggest source of emissions in Ireland is from the combustion of fossil fuels in the non-ETS sector (i.e., homes and cars) which amounted to 38% of total greenhouse gas emissions in 2018 (SEAI, 2020). In comparison, agriculture was responsible for 34% and companies in the ETS were responsible for 25% of the total greenhouse gas emissions in 2018 (SEAI, 2020). Ireland is relatively unusual in that $CO_2$ emissions from households is higher than from industry because (1) Ireland does not have as much heavy industry such as steel or fertilizer manufacture compared to other countries, and (2) there is a greater use of carbon intensive fuels such as coal, peat and oil in Irish homes compared to other EU countries (SEAI, 2020).

Table 1 shows the most significant entities in terms of 2020 carbon emissions reported to Ireland under the EU-ETS. The major point source emitters in Ireland include power generation plants, cement and lime production plants and oil refineries (Figure 3), but the list also includes other sectors such as food and drink, pharmaceuticals and semi-conductors. Note that some mobile sources such as large aircraft are now included in the ETS; aviation emissions assigned to Ireland relate mainly to incoming and outgoing flights but also to flights anywhere within the European Economic Area (EEA) where the Irish Aviation Authority has issued the operating licence to the aircraft carrier.

Under the 2021 Climate Action Plan, the Irish Government has committed to achieving net-zero carbon emissions by 2050 and it has also set a target of reaching 80% of annual electricity production from mainly wind and solar by 2030 (DECC, 2021a). However, in spite of having a large percentage of its electricity needs met by intermittent renewable generation, Ireland is still expected to require low-carbon dispatchable power generation as back-up when there is not any renewable generation available (GNI, 2018, 2019; DECC, 2021b). Emerging energy storage solutions may reduce this dependence in future (Olabi, 2017; Olabi & Abdelkareem, 2021).

The Irish Academy of Engineering (IAE) has stated that significant gas-fired generation capability and a secure gas supply will be critical for the next two decades in order for Ireland to maintain power system reliability standards while phasing out power generation from high-carbon sources such as coal, oil and peat generation (IAE, 2021a). Gas supply in Ireland currently comes from domestic production at the Corrib field, located offshore the west coast of Ireland, and also from pipeline imports via Great Britain. Gas production in Corrib has reduced by circa 50% over the past four years due to natural decline; Corrib is anticipated to supply only 15% of Ireland's annual demand by 2025. In the absence of (1) a liquefied natural gas (LNG) import facility, (2) any gas storage facilities or (3) new commercial gas discoveries in the Irish offshore, Ireland will become totally dependent on imports from Great Britain by 2030 (IAE, 2021a). In the near-term, there are also concerns about a potential shortfall of electricity supply in Ireland over the next five winters (EirGrid, 2021; Department of the Taoiseach, 2021). Discussions are now ongoing about delaying the planned closures of some older, more carbon-intensive generators (e.g., the Tarbert oil-fired power station was scheduled to shut in 2023 and the Moneypoint coal-fired power station was scheduled to close in 2025) until replacement capacity is operational (CRU, 2021). These concerns about electricity supply raise a question mark about Ireland's ability to meet the additional demand to power the 950,000 electric vehicles and 400,000 electrical heat pumps by 2030, as proposed in the 2019 Climate Action Plan, while simultaneously closing over 1550MW of coal, oil and peat/biomass-fired power stations (IAE, 2021b).

The European Commission issued the CCS Directive in 2009 (Directive 2009/31/EC) that lays out a legal framework for the environmentally safe geological storage of $CO_2$. Ireland opted out of implementing the Directive in 2011, stating it

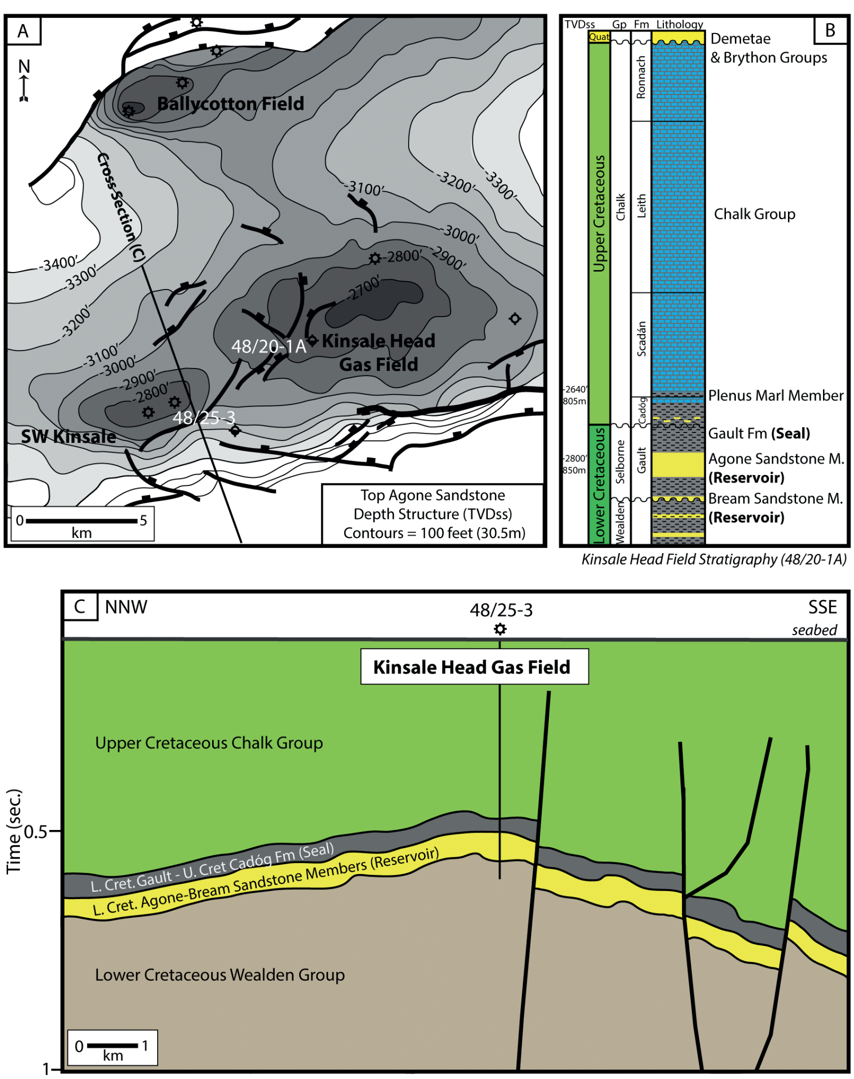


**Figure 4** (A) Kinsale Head gas field and satellite fields (SW Kinsale, Ballycotton) depth structure map of top reservoir (Agone Sandstone Member). Cross section line indicated on SW flank of Kinsale Head and SW Kinsale fields. Well symbols indicate bottom hole locations. Modified from Taber et al. (1995). (B) General stratigraphy of the Kinsale Head structure based on well 48/20-1A. The main reservoir units include the Agone Sandstone and Bream Sandstone Members (of the Selborne Group) and upper Wealden Group. The reservoirs are sealed by the shale dominated Gault and Cadóg Formations. Adapted from Merlin Energy Resources Consortium (2020). (C) Schematic cross section of the southwest flank of the Kinsale Head field illustrating the geometry of the anticline and continuous reservoir and seal. Modified from Taber et al. (1995). TVDss = True Vertical Depth subsea; Gp. = Group; Fm. = Formation; M. = Member; U. = Upper; L.= Lower; sec. = seconds.

would await development and progress of the technology within the other EU Member States, and keep the topic under active review (Statutory Instrument No. 575/2011). The Irish government published a National Mitigation Plan in 2017 and recognised that 'CCS could facilitate decarbonisation of our electricity sector while allowing an appropriate level of gas-fired generation to balance intermittent renewable generation' (DCCAE, 2017). The government set up a CCS Steering Group as one of the actions following the 2019 Climate Action Plan with the objective to assess the potential future application of CCS in Ireland (DCCAE, 2019). The updated 2021 Climate Action Plan has strengthened this view, stating that the deployment of CCS in the industrial sector is one of the measures that may be required to achieve the 2030 target of a 51% reduction in emissions, and a policy framework and roadmap for CCS deployment are under development (DECC, 2021a).

EirGrid, the operator of the Irish electricity transmission system, modelled three different scenarios for Ireland's clean energy transition over the next 20 years; two of the three modelled scenarios assumed the utilisation of CCS as a decarbonising technology on new CCGT (combined cycle gas turbine) power plants, becoming operational in 2031 and 2040, while the third 'Delayed Transition' scenario did not meet any of the government's targets and did not assume the deployment of CCS (EirGrid, 2019). A combination of wind, solar and gas-powered electricity with CCS could provide Ireland with secure and reliable electricity with very low emissions. It is noted, however, that carbon capture at power plants may become less economically attractive over time due to the projected decline of the generating station capacity factors, as the penetration of renewable electricity is further increased. CCS could also potentially be utilised to decarbonise other industries in Ireland such as cement manufacturing, oil refining and incineration (GNI, 2018, 2019, 2020). The 2022 National Heat Study presented four different scenarios that align with a future pathway to net zero by 2050 and estimated that carbon capture, utilisation and storage (CCUS) and bioenergy with carbon capture and storage (BECCS) could abate between 2.7 $MtCO_2$ and 16.9 $MtCO_2$ per year by 2050, depending on the scale and focus of deployment (SEAI, 2022). The 2021 Climate Action Plan states that the retrofit of carbon capture on two out of four Irish cement/lime plants by 2030 could deliver further abatement of emissions by 1.5 $MtCO_2$eq per year (DECC, 2021a). The government plans to undertake a programme of work to identify two potential sites in the country that represent the best CCS opportunities for future deployment. It is noted that cement manufacturing is currently responsible for four of the most significant point source emitters in Ireland (Table 1). Finally, viable geological storage options are also needed if negative emissions technologies (NETs) such as BECCS or direct air capture with carbon storage (DACCS) are to be deployed in Ireland in future as a means to compensate for residual emissions in hard-to-abate sectors, or to correct an overshoot of the national $CO_2$ quota under the Paris Agreement (McMullin et al., 2020).

## CCS opportunities in Ireland

A number of scoping assessments have been carried out regarding the potential for geological storage of $CO_2$ in Ireland (Bentham et al., 2008; SEAI, 2008; Lewis et al., 2009; Farrelly et al., 2010; Bentham et al., 2014; Vincent et al., 2014; Bentham, 2015). Lewis et al. (2009) presented an initial assessment of potential geological storage sites for all of Ireland, in areas where sufficient data were available at that time. Lewis et al. (2009) concluded that the greatest potential exists offshore in saline aquifers (i.e., a total theoretical $CO_2$ storage capacity of 88.8 Gt in saline aquifers that were assessed) but that the most accessible geological storage is in depleted gas fields such as the Kinsale Head gas field. Herein, we provide a short summary of the storage potential in the depleted Kinsale Head gas field and in the currently producing Corrib gas field. Note that the true volumetric potential for geological storage in offshore Ireland will be much higher when additional areas beyond the immediate fields are included (i.e., other geological structures or widespread saline aquifers in general).

The methodology used here to calculate a preliminary estimate of the carbon storage potential follows that of Bachu and Shaw (2003), Lewis et al. (2009) and Ringrose (2020) for depleted gas fields. The mass of $CO_2$ that could utilise pore space previously occupied by the recoverable reserves of natural gas is given by:

$$m_{CO2} = \left( \frac{V_{GAS}(sc)}{FVF} \right) \rho_{CO2} \qquad (1)$$

where $m_{CO2}$ = $CO_2$ storage capacity (Mt =$10^6$ tonnes), 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), $\rho_{CO2}$ = density of $CO_2$ at reservoir conditions (kg/$m^3$). The value calculated in equation (1) should be discounted to allow for factors that could reduce the amount of pore space available for $CO_2$ such as water invasion during and after gas production. In the absence of detailed reservoir simulations, a value of 0.9 is assumed for gas fields with depletion drive and a value of 0.65 is assumed for gas fields with water drive (Lewis et al., 2009).

## Kinsale Head gas field

The Kinsale Head gas field is a depleted natural gas field located 50 km off the coast of County Cork in the North Celtic Sea Basin, a NE-SW-trending basin situated off the south coast of Ireland. The field was discovered in 1971 and commenced production in 1978. The primary reservoirs in the Kinsale Head field are Early Cretaceous in age. The shallow-marine Agone Sandstone Member reservoir ('A' Sand in older literature) within the Selbourne Group is sealed by the overlying Gault Formation claystone, while the underlying Bream Sandstone Member and fluvio-deltaic upper Wealden Group ('B' Sand in older literature) reservoirs are separated from the Agone Sandstone Member by a ~15m claystone section (Taber et al., 1995; Lewis et al., 2009; Shannon et al., 2021). The trapping mechanism for the Kinsale Head field is a relatively simple structural trap formed during Tertiary inversion (Figure 4). Some key parameters for the field are presented in Table 2. A cumulative volume of 1.77 Tcf (50.1 Bcm) of natural gas was produced from the Kinsale Head gas field (Kinsale Energy, 2018) and production ceased in 2020 after a period of 42 years. The field is currently in the process of being decommissioned.

The Kinsale Head gas field may represent an attractive target for CCS because the overall capacity and injectivity appears to be satisfactory based on historical gas production performance (Lewis et al., 2009). Lewis et al. (2009) also flagged that the field is relatively shallow and, hence, containment risks, such as those related to existing wells, crestal faulting on the field and the possibility of modification of the caprock during pressure depletion, need to be evaluated. Gas Networks Ireland (GNI) and Ervia are currently working on a feasibility study to assess the potential for a large-scale CCS development at the Kinsale Head gas field which could capture $CO_2$ from an industrial cluster in Cork including heavy industry (oil refinery) and two gas-fired CCGT power plants (GNI, 2019, 2020). It is noted that one small compartment of the Kinsale Head complex, the SW Kinsale gas field (O'Sullivan, 2001), was utilised for natural gas storage between 2001 and 2017; in effect proving the concept that gas can be reinjected into this reservoir which acts as a sealed container. We provisionally estimate a $CO_2$ storage capacity of 321 Mt for the Kinsale Head gas field (see Table 2 for details),

| | 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]<br>(1336.8 psia) | - | ~40.7 [11]<br>(~5900 psia) |
| Pressure gradient (kPa/m) | ~10<br>(hydrostatic) | - | ~11<br>(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]<br>(1.84 Tcf) | | 34.0 [6]<br>(1.2 Tcf) |
| Recoverable gas (Bcm) | 50.1 [5]<br>(1.77 Tcf) | | 24.6 [6]<br>(870 Bcf) |
| **Carbon Storage Potential** | | | |
| $CO_2$ density at reservoir condition ($kg/m^3$) | 720 | | 740 |
| Assumed discount factor | 0.90 | | 0.65 |
| $CO_2$ storage capacity (Mt = $10^6$ tonnes) | 321 | | 44 |

**Table 2** Representative Properties for Kinsale Head and Corrib gas fields.
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).

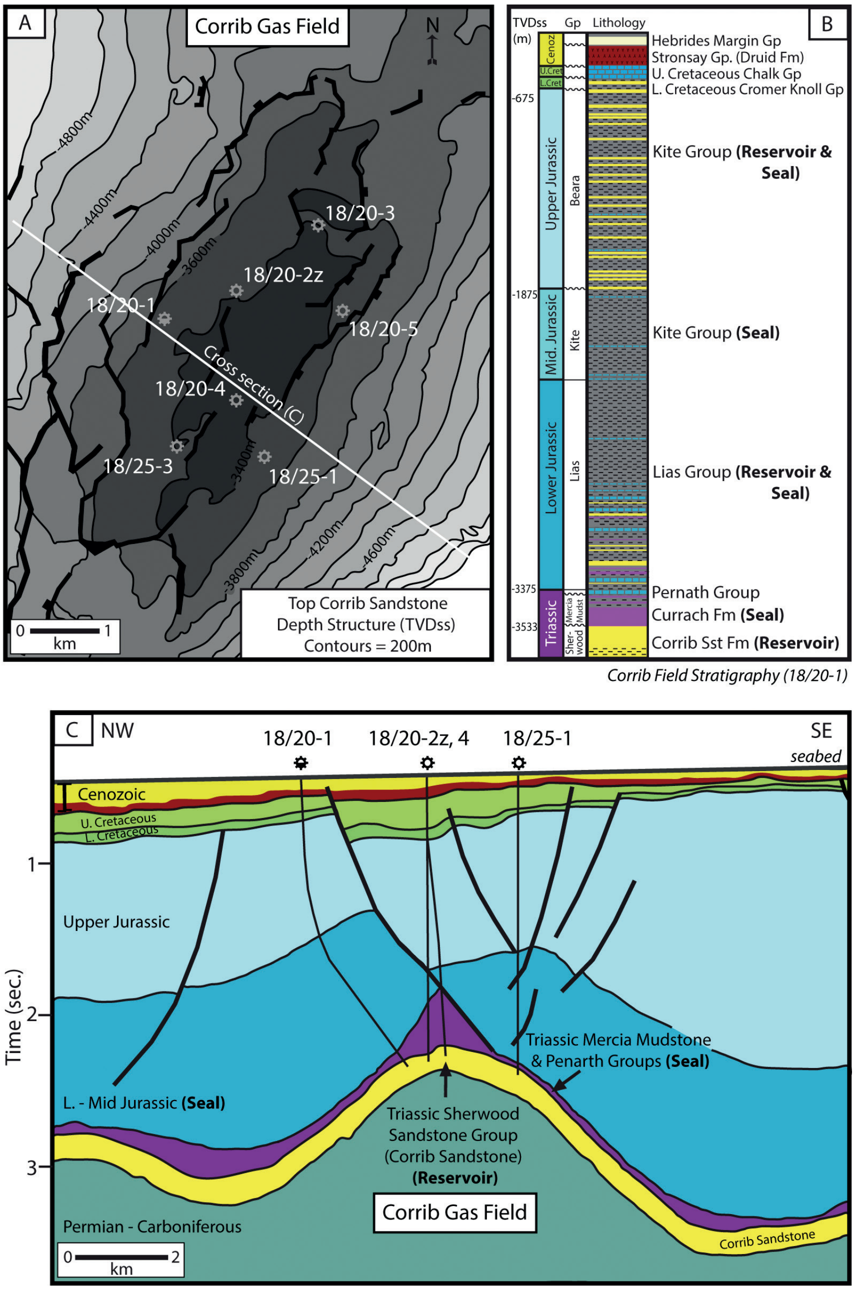


**Figure 5** (A) Corrib gas field depth structure map of top reservoir (Corrib Sandstone Formation) illustrating the NE-SW trending anticline. Well symbols indicate bottom hole locations. Cross section location indicated. Modified from Dancer et al. (1995). (B) General stratigraphy of the Corrib structure, based on well 18/20-1. The main reservoir is the Corrib Sandstone, sealed by the Currach Formation, containing the Uilleann Halite Member. The thickness of the sealing Uilleann Halite Member thickens towards the crest of the anticline. Adapted from Merlin Energy Resources Consortium (2020). (C) Schematic cross section of the Corrib gas field. Triassic Corrib sandstone formation (Sherwood Sandstone Group) is sealed by the Mercia Mudstone Group, containing the Currach Formation and Uilleann Halite Member. Modified from Dancer et al. (1995) and from O'Sullivan and Childs (2021). TVDss = True Vertical Depth subsea; Gp. = Group; Fm. = Formation; U. = Upper; L.= Lower; sec. = seconds.

which is within a few percent of the previous estimate of 330.9 Mt by Lewis et al. (2009). Lewis et al. (2009) estimated a $CO_2$ storage capacity of 5 Mt for the SW Kinsale gas field. In 2020, the top 10 point-source emitters in Ireland were responsible for ~ 8 Mt of $CO_2$ emissions (Table 1); to provide a sense of scale, the depleted Kinsale Head gas field could have sufficient storage to take the equivalent of up to 40 years of emissions from these 10 point-source emitters.

## Corrib gas field

The currently producing Corrib natural gas field is located around 80 km off the coast of County Mayo in the Slyne Basin, a narrow Triassic/Jurassic half-graben that forms part of a series of structurally linked basins along the west coast of Ireland and Great Britain. The field was discovered in 1996, more than 3 km beneath the seafloor, and production commenced in 2015. The reservoir is contained within the Triassic fluvial Corrib Sandstone Formation (Sherwood Sandstone Group) and is sealed by the Triassic Uilleann Halite Member of the Currach Formation (Mercia Mudstone Group) (Dancer et al., 2005; Shannon et al., 2021). The trapping mechanism for the Corrib field is an anticlinal structure but with complex faulting in the overburden that is sealed from the reservoir by the Uilleann Halite Member (Figure 5). It is noteworthy that the Corrib structure is underfilled with natural gas – i.e., the gas Free-Water-Level (FWL) is at -3600m TVDss (True Vertical Depth subsea) and the structural spill-point is deeper at -3850m TVDss (Corcoran and Meckleburgh, 2005). It is not clear if the underfilling is due to an unidentified leak-point in the trap or due to limited charge volumes. Some key parameters for the field are presented in Table 2. The estimated recoverable gas reserves for the field is 0.87 Tcf or 24.6 Bcm (Dancer et al., 2005).

The gas from Corrib is produced via a subsea facility and an 83 km pipeline, and ultimately brought to shore at the Bellanaboy Bridge Gas Terminal. As noted above, the production of the field has passed peak production and is currently in decline. The field life has been estimated to last 15-20 years (Enterprise Energy Ireland Ltd, 2001), which could mean the cessation of production as early as 2031 (IOOA, 2019). Unless additional gas discoveries are made in this area in the coming years that can tie-in to these facilities, the depleted Corrib field may also become a potential candidate for CCS or hydrogen storage in circa 10 years' time. Utilising the same methodology as Lewis et al. (2009), we estimate a $CO_2$ storage capacity of 44 Mt for the Corrib gas field (see Table 2 for details). It must be noted, however, that (1) if the observed underfilling of the Corrib structure with natural gas was due to source-rock charge limitations, the size of the overall sealed structural trap and hence the potential storage volume will be significantly larger than the estimate based on recoverable gas volumes alone, and (2) if the Uilleann Halite Member extends well beyond the limits of the Corrib structure, the Triassic Sherwood Sandstone of the Slyne Basin could become a valid deep saline aquifer target for $CO_2$ storage. These factors require further detailed assessment.

## Conclusion

In Ireland, CCS with gas-powered electricity could be used to back up and support intermittent generation from wind and solar to provide secure and reliable low-emissions electricity. Additionally, CCS could be utilised in Ireland to reduce emissions associated with cement manufacturing and could also facilitate future deployment of negative emissions technologies such as BECCS and DACCS. Ireland has significant potential to store $CO_2$ in geological formations in its offshore sedimentary basins. Two front-running candidates are the Kinsale Head and Corrib gas fields; both structures are already covered by a wealth of geological and engineering data to provide a firm basis for assessing the CCS potential. Provisional estimates for the $CO_2$ storage capacity of the Kinsale Head gas field and the Corrib gas field are 321 Mt and 44 Mt respectively. Production ceased at the Kinsale Head gas field in 2020 and the field is currently being decommissioned. Natural gas production at the Corrib field is expected to continue for another 10-15 years. Based on our preliminary estimates, the depleted Kinsale Head gas field could have sufficient storage capacity to take the equivalent of up to 40 years of $CO_2$ emissions from the top 10 point-source emitters in Ireland as of 2020. Additional potential exists in the Corrib structure and in the saline aquifers surrounding these fields and beyond, due to favourable geology. It is noted that no detailed characterisation and assessment of the storage potential of the Kinsale Head and Corrib gas fields, as per Annex 1 of Directive 2009/31/EC, has been carried out to date. Further work is needed to fully characterise and mature this potential, and in the case of the Slyne Basin, well in advance of the Corrib gas field reaching the end of its production life when all the infrastructure could be removed, and the economic advantage is lost.

## Acknowledgements

The authors would like to acknowledge Ireland's Department of Environment, Climate and Communications for provision of data, and John Walsh (UCD) and iCRAG (SFI Research Centre in Applied Geosciences) for their support. They would also like to thank Frank McGovern (EPA Ireland), John Conroy (Vermilion Energy), Gearóid FitzGerald (Ervia) and Gerry Duggan (Irish Academy of Engineering) for feedback on an earlier version of this manuscript, and the reviewers for their constructive comments.

## Nomenclature

Bcm = billion cubic metres (standard)
FVF = gas formation volume factor (from reservoir conditions to sc)
$ktCO_2$ = thousand tonnes of carbon dioxide
$m_{CO2}$ = $CO_2$ storage capacity (Mt)
Mt = million tonnes
$MtCO_2$ = million tonnes of carbon dioxide
$MtCO_2eq$ = million tonnes of carbon dioxide equivalent
MW = megawatt
$\rho_{CO2}$ = density of $CO_2$ at reservoir conditions (kg/m$^3$)
sc = standard conditions for temperature and pressure
Tcf = trillion cubic feet
$tCO_2$ = tonnes of carbon dioxide
TVDss = True Vertical Depth subsea
$V_{GAS}$ (sc) = volume of ultimately recoverable gas at sc (Bcm)

## References

Bachu, S. and Shaw, J. [2003]. Evaluation of the $CO_2$ Sequestration capacity in Alberta's Oil and Gas Reservoirs at Depletion and the Effect of Underlying Aquifers. *Canadian J. Pet. Technology*, **42**(9), 51-61. https://doi.org/10.2118/03-09-02.

Bentham, M. [2015]. Irish Sea Carbon Capture and Storage project, final report. British Geological Survey Commissioned Report.

Bentham, M.S., Kirk, K.L. and Williams, J. [2008]. Basin-by-basin analysis of the $CO_2$ storage potential of all-island Ireland. British Geological Survey Internal Report, CR/08/036.

Bentham, M., Williams, J. and Hannis, S. [2014]. An assessment of the potential for subsurface $CO_2$ storage in two regions of the Central Irish Sea Basin. British Geological Survey Internal Report, CR/14/128.

Colley, M.G., McWilliams, A.S.F. and Myers, R.C. [1981]. Geology of the Kinsale Head Gas Field, Celtic Sea, Ireland. 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.

CRU [2021]. CRU Information Paper Security of Electricity Supply – Programme of Actions.

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.

DCCAE [2017]. National Mitigation Plan.

DCCAE [2019]. Climate Action Plan 2019.

DECC [2021a]. Climate Action Plan 2021.

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

Department of the Taoiseach [2021]. Draft National Risk Assessment – Overview of Strategic Risks 2021/2022.

Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12 /EC, 2008/1/EC and Regulation (EC) No 1013/2006 (1). *Official Journal of the European Union 2009*; L140:114-35.

EirGrid [2019]. Tomorrow's Energy Scenarios 2019 Ireland.

EirGrid [2021]. All-Island Generation Capacity Statement 2021-2030.

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

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

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

Farrelly, L.J., Loske, B., Neele, F.P. and Holdstock, M.P. [2010]. An assessment of the potential for geological storage of $CO_2$ in the vicinity of Moneypoint, Co. Clare. EPA Climate Change Research Programme Report (CCRP-2008-CCS).

GNI [2018]. Network Development Plan 2018.

GNI [2019]. Network Development Plan 2019.

GNI [2020]. Network Development Plan 2020.

Haszeldine, R.S. [2009]. Carbon capture and storage: how green can black be? *Science*, **325**, 1647-1652. https://doi.org/10.1126/science.1172246.

IAE [2021a]. National Energy and Climate Plan – The Challenge of High Levels of Renewable Generation In Ireland's Electricity System.

IAE [2021b]. Sustainable Electricity in 2030 - Reliable? Affordable?

IPCC [2005]. IPCC Special Report Carbon Dioxide Capture and Storage. Cambridge University Press, UK.

IPCC [2014]. Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth 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.

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

Lewis, D., Bentham, M., Cleary, T., Vernon, R., O'Neill, N., Kirk, K., Chadwick, A., Hilditch, D., Michael, K., Allinson, G., Neal, P. and Ho, M. [2009]. Assessment of the potential for geological storage of carbon dioxide in Ireland and Northern Ireland. *Energy Procedia*, **1**, 2655-2662. https://doi.org/10.1016/j.egypro.2009.02.033.

McMullin, B., Jones, M.B., Price, P.R., McGeever, A. and Rice, P. [2020]. IE-NETs: Investigating the potential for negative emissions technologies (NETs) in Ireland. Project Report no. 354. Environmental Protection Agency (Ireland).

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.

Olabi, A.G. [2017]. Renewable energy and energy storage systems. *Energy*, **136**, 1-6. https://doi.org/10.1016/j.energy.2017.07.054.

Olabi, A.G. and Abdelkareem, M.A. [2021]. Energy storage systems towards 2050. *Energy*, **219**, 119634. https://doi.org/10.1016/j.energy.2020.119634.

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.

O'Sullivan, C. and Childs, C. [2021]. Kinematic interaction between stratigraphically discrete salt layers; the structural evolution of the Corrib gas field, offshore NW Ireland. *Marine and Petroleum Geology*, **133**, 105274. https://doi.org/10.1016/j.marpetgeo.2021.105274.

Pacala, S. and Socolow, R. [2004]. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, **305**, 968–972. https://doi.org/10.1126/science.1100103.

Ringrose, P.S. [2017]. Principles of sustainability and physics as a basis for the low-carbon energy transition. *Petroleum Geoscience*, **23**(3), 287–297. https://doi.org/10.1144/petgeo2016-060.

Ringrose, P.S. [2020]. How to Store $CO_2$ Underground: Insights from early-mover CCS Projects. Springer International Publishing.

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 [2008]. Assessment of the potential for geological storage of carbon dioxide for the island of Ireland.

SEAI [2020]. Energy-related $CO_2$ emissions in Ireland 2005-2018.

SEAI [2022]. Carbon Capture Utilisation and Storage (CCUS): Suitability, Costs and Deployment Options in Ireland. Report 6 of the National Heat Study.

Shannon, P.M., English, K.L., Hanrahan, M. [2021]. The Stratigraphic Nomenclature of the Irish Offshore Basins. Department of Communication, Climate Action and Environment, PAD Special Publication 2/21.

Statutory Instrument No. 575/2011 – European Communities (Geological Storage of Carbon Dioxide) Regulations, 2011.

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.

Trading Economics [2022]. https://tradingeconomics.com/commodity/carbon; accessed 21st January 2022.

Vincent, C.J., Kirk, K.L. and Pharoah, T.C. [2014]. An assessment of the potential for subsurface $CO_2$ storage in the Celtic Sea Basin. British Geological Survey Commissioned Report, CR/14/134.