Assessment of the potential for geological storage of CO₂ in the vicinity of Moneypoint, Co. Clare, Ireland

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Abstract

The largest single point CO₂ emitter in Ireland, the Moneypoint Power Station (3.95 Mt CO₂ per annum), is located in Co. Clare and geologically lies within the Clare Basin. In terms of the economics of transportation of CO₂ from Moneypoint, a possible local storage site would be favoured. The study investigated a number of critical criteria with respect to potential geological storage of CO₂ within the onshore portion of the Clare Basin.

In a screening study of this nature, the objective is to search for subsurface reservoirs that have sufficient storage capacity, good injection properties and sufficient confining potential. These properties depend on a number of geological parameters for each of the targeted formations. Reservoir size (CO₂ storage capacity) depends on, among other factors, the pore volume that is available and reservoir depth. The rate at which CO₂ can be injected into the reservoir is determined by the permeability and thickness of the reservoir formation(s). Confining potential depends on the seal rock type, thickness, the presence of faults and the type of trap structures. Other geological properties that are relevant for aquifer size, injectivity and seal quality also need to be considered in site characterisation studies.

This study examined these key parameters using a modular approach. Extensive data collection was followed by several interpretational programmes including a detailed re-logging programme of deep historical boreholes to maximise the sub-surface data available to the project. The resultant datasets were assimilated into a Petrel geological model for the area. Two boreholes were completed at key sites within the Clare Basin. A primary objective of the drilling programme was to provide fresh material for porosity/permeability test work. Results from the rock characterisation studies were integrated into the geological model. This allowed a final assessment of the potential storage volume and suitability, revealing that the onshore portion of the Clare Basin is unsuitable for CO₂ storage.

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1. Introduction

Ireland’s largest single point emitter is the Moneypoint Power Station (currently emitting 3.95 Mt CO₂ per annum) which is located on the north side of the Shannon Estuary in Co. Clare. Geologically the area is underlain by a thick sequence of Carboniferous aged sediments that lie within a structure termed the Clare Basin. This geological structure was considered as part of an all-Ireland assessment of the potential for geological storage of CO₂. The economics of CCS transport from Moneypoint to what appears to be the geographically closest practical storage site at the Kinsale hydrocarbon field has previously been considered, both in the All-Island study [1], and earlier by Monaghan et al. [2]. This scenario would involve significant investment in pipeline infrastructure, and consequently, a local storage site would be logistically and financially more attractive.

The primary objective of this assessment was to identify a suitable subsurface reservoir that has sufficient storage capacity, good injection properties and good confining potential for geological storage of CO₂ in the onshore portion of the Clare Basin.

2. Potential Saline Aquifers

The geology of the onshore Clare Basin is dominated by sub-crop of Namurian aged sediments (Figure 1). The Dinantian succession is seen only in a number of deep boreholes including Doonbeg 1, IPP-1 and IPP-2. These boreholes were examined as part of a core re-logging programme during which efforts were made to reconcile the borehole successions to the published stratigraphy. The Viséan succession in the boreholes was found to be distinct to that recorded elsewhere in the Irish Midlands and there was inadequate information to allow subdivision. Therefore the general term of “Dinantian Limestone” is herein interpreted as including all pre-Namurian carbonates within the project area.

Figure 1 Simplified geological map of the Clare area showing deep historical and project borehole locations
The stratigraphy of the overlying Namurian succession within the Clare Basin has been described by various authors. As discussed in Sleeman and Pracht [3], much of this work was based on detailed examination of coastal exposure. However, a dearth of inland information makes correlation difficult. Several approaches to stratigraphic subdivision have been adopted by previous workers including biostratigraphy (Hodson and Lewarne [4]), sedimentology (Pulham [5]) and sequence stratigraphy (Davies and Elliott [6]). For this project, the stratigraphic subdivision of the Namurian used by the Geological Survey of Ireland (Sleeman and Pracht [3]) and supported by Pyles [7] and others was adopted. This involves a tri-partite subdivision of the Namurian into the Clare Shale Formation, Shannon Group and Central Clare Group (Figure 1). The Shannon Group includes the Ross Sandstone Formation and overlying Gull Island Formation. The Central Clare Group consists of five cyclothemic sequences, three of which are individually named (Tullig, Kilkee and Doonlicken Cyclothemes).

Following initial reviews of the geology of the Clare Basin, two potential host formations for CCS were identified: the Namurian Ross Sandstone Formation and the underlying Dinantian Limestone. The Ross Sandstone Formation was selected as the primary potential saline aquifer on the basis of the high proportion of sand content within the contained turbidites. Owing to the good seal properties of the Clare Shale Formation, the Dinantian carbonate succession was considered as a potential secondary aquifer. These principal target horizons remained constant throughout the project lifespan and the subsequent analysis was focused primarily on their assessment.

3. Assessment Criteria

A number of critical criteria were investigated with respect to potential CO₂ storage within the Clare Basin. These included examination of the following features:

- **Seal**: The storage site must be able to retain the injected CO₂ indefinitely. An adequate seal for a potential aquifer is essential to prevent upward migration of injected CO₂. The extent of the seal must be at least as large as the expected size of the plume of free CO₂ in the reservoir.

- **Aquifer Depth**: Reservoir depth must be greater than about 800 m, to ensure that CO₂ is stored in a dense phase, optimising the use of storage space. At these depths, CO₂ has a density of the order of 700 kg/m³. The phase change from gas phase to dense phase occurs at a pressure near 80 bar, corresponding to depths around 800 m.

- **Trap**: A trapping mechanism within target horizons is also a prerequisite for site selection. Suitable traps include anticlinal dome structures or fault traps. The threshold for trap volume is that the volume should be large enough to contain the injected volume of CO₂.

- **Reservoir Quality/Injection Rate**: Reservoir quality and injection rates are largely governed by the permeability of the saline aquifer in question. Porosity is also a consideration, however low order porosities can be offset by good permeability throughout a thick saline aquifer. As such, permeability is regarded as the primary criterion for current purposes. To ensure adequate injection rates and storage, permeabilities in the order of 200 mD (milli-Darcy) are considered necessary to ensure injection at a rate in the order of mega tonnes per annum. Reservoirs which are characterized by a combination of high porosity and permeability tend to represent the best storage sites. In these cases, high porosity provides an increased storage capacity and higher permeability requires lower applied CO₂ injection pressure that is less damaging to the rock formation.

- **Presence of Faults**: The ideal CO₂ storage reservoir contains no faults. Faults can impede the flow of CO₂ and/or brine and in the case of sealing faults the reservoir can be compartmentalised. Such reservoirs require multiple wells to access all compartments. Where faults are present, the integrity of the seal must be proven. In general, a reservoir with fewer faults is better. However, the presence of faults is not by itself a reason to dismiss a site for CO₂ storage.

- **Storage Capacity**: The storage capacity, (expressed in Mt of CO₂ that can be stored) of a subsurface reservoir must be large enough to render the investment of developing an injection site economically viable. While a site-specific study is required in each case, a lower limit for deep saline aquifers of 100 Mt has been used.
(Dynamis [8]). In the present case of storing CO₂ to be captured at the Moneypoint power plant, a quantity of the order of 200 Mt CO₂ must be stored throughout the expected lifetime of the (new) power plant.

While not exhaustive, these features were considered to be the most important screening factors for assessment of a saline aquifer in terms of a pre-feasibility study.

4. Methodology

In order to assess these critical features, the project was undertaken using the following modules:

1. Data Capture
2. Interpretative Processing
3. Project Borehole Programme
4. Rock Characterisation Studies
5. 3D Geological Modelling
6. Assessment of CO₂ Storage Potential

Where possible, several modules were undertaken concurrently. Additionally, iterative programmes, such as the 3D geological modelling module, were undertaken periodically throughout the project lifespan whereby interim models were revised as new data became available.

An extensive data gathering exercise of all available geological records and subsequent compilation to a GIS database was undertaken. Once completed, initial geological modelling, using Petrel 2009, commenced in tandem with a number of interpretative exercises based on the compiled data. These included re-processing of historical downhole petrophysical surveys, seismic surveys and regional geophysical datasets. Amongst other elements of the interpretation module, a detailed re-logging programme, including biostratigraphic dating, of deep historical boreholes was completed to maximise the sub-surface data available to the project. All data arising from the interpretative processes were incorporated into the evolving 3D model.

At an early stage in the project it became apparent that suitable samples of the target formations were required for analysis. A borehole programme was undertaken as part of the project in conjunction with the Geological Survey of Ireland.

Based on observations from the interim geological model and local reconnaissance geological mapping, two drill sites were selected at the eastern and western margins of the project area (Figure 1). Hole GSI 09/04 at Killadyser was drilled to test the nature and thickness of the Ross Sandstone Formation in east Clare. Hole GSI 09/05 was sited at Faha, Co. Kerry to help increase the geographical distribution of samples from the target Ross Sandstone Formation, for permeability and porosity testing. Petrophysical surveys were conducted on the project boreholes. Both holes intersected the primary potential reservoir, the Ross Sandstone Formation and provided fresh material for rock characterisation tests in addition to critical geological information at key sites.

Rock characterisation tests primarily focused on a porosity/permeability sampling programme. The objective of this programme was to assess the permeability of the main target horizons from selected sites within the study area. A total of 30 samples were taken from both historical and project boreholes in addition to a number of outcrop samples.

Higher values for the primary aquifer target, the Ross Sandstone Formation, were recorded from outcrop samples which are subject to surface weathering conditions. When unweathered core samples are considered in isolation, the ranges of results for the main units under consideration are as follows (Table 1).
Table 1 Ranges for porosity/permeability results - unweathered samples only (cc = cubic centimetre; psig = pound force per square inch gauge).

<table>
<thead>
<tr>
<th>Formation</th>
<th>No. of samples</th>
<th>Max./Min.</th>
<th>Gas permeability @ 400 psig (mD)</th>
<th>Porosity (%)</th>
<th>Grain density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross Sandstone Formation</td>
<td>9</td>
<td>Max.</td>
<td>0.008</td>
<td>1.2</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0.003</td>
<td>0.1</td>
<td>2.68</td>
</tr>
<tr>
<td>Gull Island Formation</td>
<td>4</td>
<td>Max.</td>
<td>0.006</td>
<td>0.8</td>
<td>2.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0.003</td>
<td>0.4</td>
<td>2.67</td>
</tr>
<tr>
<td>Dinantian Limestone</td>
<td>13</td>
<td>Max.</td>
<td>0.009</td>
<td>1.5</td>
<td>2.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0.003</td>
<td>0.2</td>
<td>2.70</td>
</tr>
</tbody>
</table>

The rock characterization tests show low order porosity and permeability ranges for both the Ross Sandstone Formation and underlying Dinantian Limestone succession. The results for the Ross Sandstone Formation are consistent with recent petrographic studies undertaken by University College Dublin on samples from Loop Head (west Clare) which show the sandstones contain a quartz cement which serves to anneal primary porosity and reduces permeability. Similarly poor porosity and permeability results for the Dinantian succession are considered representative of tight limestones in which the porosity has been filled by carbonate cements.

Results from the rock characterization tests were integrated into the geological model and a detailed analysis of the structural setting and reservoir characteristics of the Clare Basin was undertaken. This allowed a final assessment of the potential storage volume and suitability of the onshore portion of the Clare Basin for CO\textsubscript{2} storage to be determined.

5. Results

The potential for geological storage of CO\textsubscript{2} in the onshore portion of the Clare Basin was assessed in terms of a number of screening criteria considered critical appraisal of a saline aquifer at pre-feasibility level. The project results are discussed in terms of these criteria in the following sections.

5.1. Seal

Two potential seals have been identified within the Clare Basin; the Clare Shale Formation as a seal lithology for the Dinantian Limestone succession and the Gull Island Formation as a seal lithology for the Ross Sandstone Formation. The Clare Shale Formation is laterally extensive across the project area and is generally in excess of 180m in thickness. For this reason, it is considered a suitable seal horizon. The Gull Island Formation consists of interbedded mudstones and siltstone with subordinate sandstones. Mudstone dominant units are present within the succession and have potential to be adequate seals. However, there are concerns relating to the lateral continuity of mudstone packages within the Gull Island Formation. Additionally, the Gull Island Formation shows evidence of slump tectonics within the mudstone layers causing disturbed bedding which, in turn, could provide upward migration paths for CO\textsubscript{2}. Given the overall mudstone content within the Gull Island succession (thickness <300 m), it is considered possible that the formation could provide an adequate seal. However, more detailed studies such as seismic surveying would be required to determine the lateral continuity and extent of individual impermeable layers. Therefore, the validity of the Gull Island Formation as a seal horizon to a potential Ross Sandstone Formation storage aquifer remains open to question.

5.2. Aquifer Depth

An aquifer depth of greater than 800 m is required to ensure that any injected CO\textsubscript{2} will remain in dense form. The depth setting of the identified target horizons, the Ross Sandstone Formation and Dinantian Limestone was
considered in detail. Based on analysis of various data sources and detailed geological modelling, the volume of the Ross Sandstone Formation below the critical depth is low (132 km$^3$). Given the depth setting of the Dinantian, which is stratigraphically below the Ross Sandstone, there is a larger area of the succession below the critical depth with a corresponding volume of 300 km$^3$.

5.3. Traps

The volume estimates presented above are for full capacity of potential aquifers within the carbon storage window (i.e. below 800 m depth). A trapping mechanism within target horizons is also a pre-requisite for site selection. Suitable traps include anticlinal dome structures or fault traps. A full analysis of the structural setting for the Clare Basin was undertaken. This examination suggests that a “basin” geometry developed in response to local and regional tectonic stress. Structural elements in west County Clare dip eastwards towards a central area in which a horizontal structural orientation is predominant. At the eastern margin occasional steep fold axes plunge towards the basin centre. This basin configuration is extremely unfavourable for the generation of trap structures. Closures formed by domal anticlines are restricted to the central part of the basin which, in turn, limits the overall area available for CO$_2$ storage. Given the overall basin geometry, it is also considered likely that the identified traps would be prone to potential leakage along the up-dipping western and eastern margins.

5.4. Reservoir quality and injection rate

To ensure adequate injection rates and storage, permeabilities in the order of 200 mD (milli-Darcy) are considered necessary to ensure injection at a rate in the order of mega tonnes per annum.

Permeability and porosity tests carried out as part of this study clearly demonstrate that the Ross Sandstone Formation and Dinantian Limestone have a tight character. The results for both horizons range from 0.003-0.009 mD. This is considered consistent with the interpretation that the sandstones of the Ross Formation contain a quartz cement which anneals the primary porosity. Similarly, poor results for the Dinantian Limestone succession suggest that the porosity has been sealed by carbonate cements. These results are orders of magnitude lower than those required for successful carbon storage, and effectively militate against the primary potential saline aquifers considered within this study: the Ross Sandstone Formation and Dinantian Limestone.

5.5. Presence of faults

Although the overall tectonic style is ductile, some brittle deformation is evident. This includes thrust, strike-slip and a subordinate number of extensional faults. In the absence of new seismic data, detailed field mapping would be required to determine the tenor of these structures. However, based on the available information, it is clear that the zones of the onshore portion of the Clare Basin are structurally complex. For this reason, it is considered probable that fault compartmentalisation of the Ross Sandstone Formation and Dinantian succession occurs and that multiple injection sites would be required to access individual compartments of any potential reservoir.

5.6. Storage Capacity

For completeness, preliminary volumetric estimates for the potential storage aquifers were conducted. The proportions of the Ross Sandstone Formation and Dinantian Limestone package below the critical depth of 800 m and within identified traps were calculated. Based on this information, basic volumetric estimates were undertaken. The volumetric estimates were then converted to CO$_2$ storage capacity. The results are detailed in Table 2.

For the storage capacity of aquifer volume, a storage efficiency factor of 2% was used. As the hydraulically connected reservoir volume can not be determined with certainty, due to unknown connectivity of the reservoir formations throughout the Clare Basin, the reservoir volume at depths below 800 m was used. The conversion from bulk volume to pore volume was done for a porosity of 1%, which is a representative, if somewhat high, average
value for both formations. The storage capacity, based on total available pore volume in the potential reservoirs, is 18 Mt and 42 Mt, for the Ross Sandstone and Dinantian Limestone succession, respectively.

### Table 2: Volumetric and storage capacity estimates for potential saline aquifers in the onshore portion of the Clare Basin

<table>
<thead>
<tr>
<th>Potential aquifer</th>
<th>Bulk formation at depths &gt; 800 m</th>
<th>Theoretical storage capacity in entire aquifer volume</th>
<th>Bulk formation in traps (estimated)</th>
<th>Theoretical storage capacity in traps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ross Sandstone Formation</td>
<td>132 km³</td>
<td>18 Mt CO₂</td>
<td>1.5 km³</td>
<td>4 Mt CO₂</td>
</tr>
<tr>
<td>Dinantian Limestone Succession</td>
<td>300 km³</td>
<td>42 Mt CO₂</td>
<td>4 km³</td>
<td>11 Mt CO₂</td>
</tr>
</tbody>
</table>

Storage capacity can also be limited by the volume in the traps. Table 2 shows that this is the case for both potential reservoirs. The storage capacity of the traps in these formations was computed by assuming a CO₂ saturation of 40 % in the trap, which is a value that follows from modelling CO₂ flow in homogeneous formations (Pruess [9]). It should be noted that similar work for heterogeneous reservoirs resulted in lower values, in the range 1 – 10 % (van der Meer [10]; Doughty et al. [11], USDoE [12]). Therefore the values reported here should be regarded as an upper limit of trap capacity.

In summary, the theoretical storage capacity for the trapped portion of the Ross Sandstone Formation is in the order 4 Mt CO₂, while the traps in the Dinantian Limestone are estimated at 11 Mt CO₂.

However, the practical storage capacity for both formations is zero due to the extremely low permeability detected by this study.

### Table 3: Required parameters for successful carbon storage in Clare (required situation, resulting in a storage capacity of over 200 Mt) listed against actual situation determined by this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required Situation</th>
<th>Actual Situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer Size</td>
<td>900 km²</td>
<td>Small</td>
</tr>
<tr>
<td>Depth</td>
<td>800 m+</td>
<td>Limited area below 800 m</td>
</tr>
<tr>
<td>Permeability</td>
<td>200 mD +</td>
<td>Poor (&lt;0.009 mD)</td>
</tr>
<tr>
<td>Seal</td>
<td>Impermeable/Tested</td>
<td>Gull Island Fmn - moderate seal/Clare Shales - good seal</td>
</tr>
<tr>
<td>Aquifer/Reservoir</td>
<td>Ross Sandstone/Dinantian Lst</td>
<td>Ross Sandstone Formation/Dinantian Limestone</td>
</tr>
<tr>
<td>Porosity</td>
<td>20%+</td>
<td>Poor (&lt;1.54%)</td>
</tr>
<tr>
<td>Traps</td>
<td>Well developed</td>
<td>Limited</td>
</tr>
<tr>
<td>Thickness</td>
<td>80 m+</td>
<td>0-200 m</td>
</tr>
<tr>
<td>Basin Architecture</td>
<td>Unfaulted with structural traps</td>
<td>Steep sided basin, potential spill points, limited traps</td>
</tr>
<tr>
<td>Risks</td>
<td></td>
<td>Ross Sandstone sub-crops at eastern margin of basin (spill points)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor injectivity rates (permeability parameter unfulfilled)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor porosity not compensated by reservoir horizon thickness</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gull Island Formation is a questionable seal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dinantian Limestone has low porosity/permeability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fracture porosity in the Dinantian Limestone likely to be filled/tight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Facies variation within the Ross Sandstone Formation is unfavourable (eastward thinning of sandstones)</td>
</tr>
</tbody>
</table>
6. Conclusions

This study has demonstrated that certain key parameters for CO₂ storage are unfulfilled. The saline aquifer size, within the carbon storage window, is small for both the Ross Sandstone Formation and the Dinantian Limestone succession. Permeability results suggest that the reservoir lithologies are tight and are orders of magnitude below the accepted thresholds for injection and successful storage of CO₂. Significant concerns have been raised with respect to the validity of the Gull Island Formation as a seal to a Ross Sandstone Formation reservoir. Additionally, both potential saline aquifers are likely to be structurally compartmentalised with the possibility of seal penetration considered probable. Aside from other considerations, such as likely spill points at the western and eastern margins of the project area, any one of these “failed criteria” militates against carbon storage in the Clare Basin.

For comparative purposes, the project results have been placed in context against a “required situation”, whereby carbon storage in the Clare Basin would be permissible, in Table 3. The parameters documented under the “required situation” reflect the criteria necessary for storage of total emissions of 200 Mt of CO₂ with injection rates in the order of 5 Mt CO₂ per annum and assuming a storage efficiency factor of 2%.

Parameters such as overall aquifer size, proportion of the aquifer within the carbon storage window (<800 m) and trapping mechanisms, all serve to limit the volume of both the Ross Sandstone Formation and Dinantian Limestone as potential saline aquifers. Additionally, the available permeability data shows that both aquifers are tight and would not support the injection rates or storage envisaged by the project.

Based on the available data and subsequent interpretation, it is the primary conclusion of this study that the onshore portion of the Clare Basin is unsuitable for geological storage of CO₂ within saline aquifers.

7. Acknowledgements

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