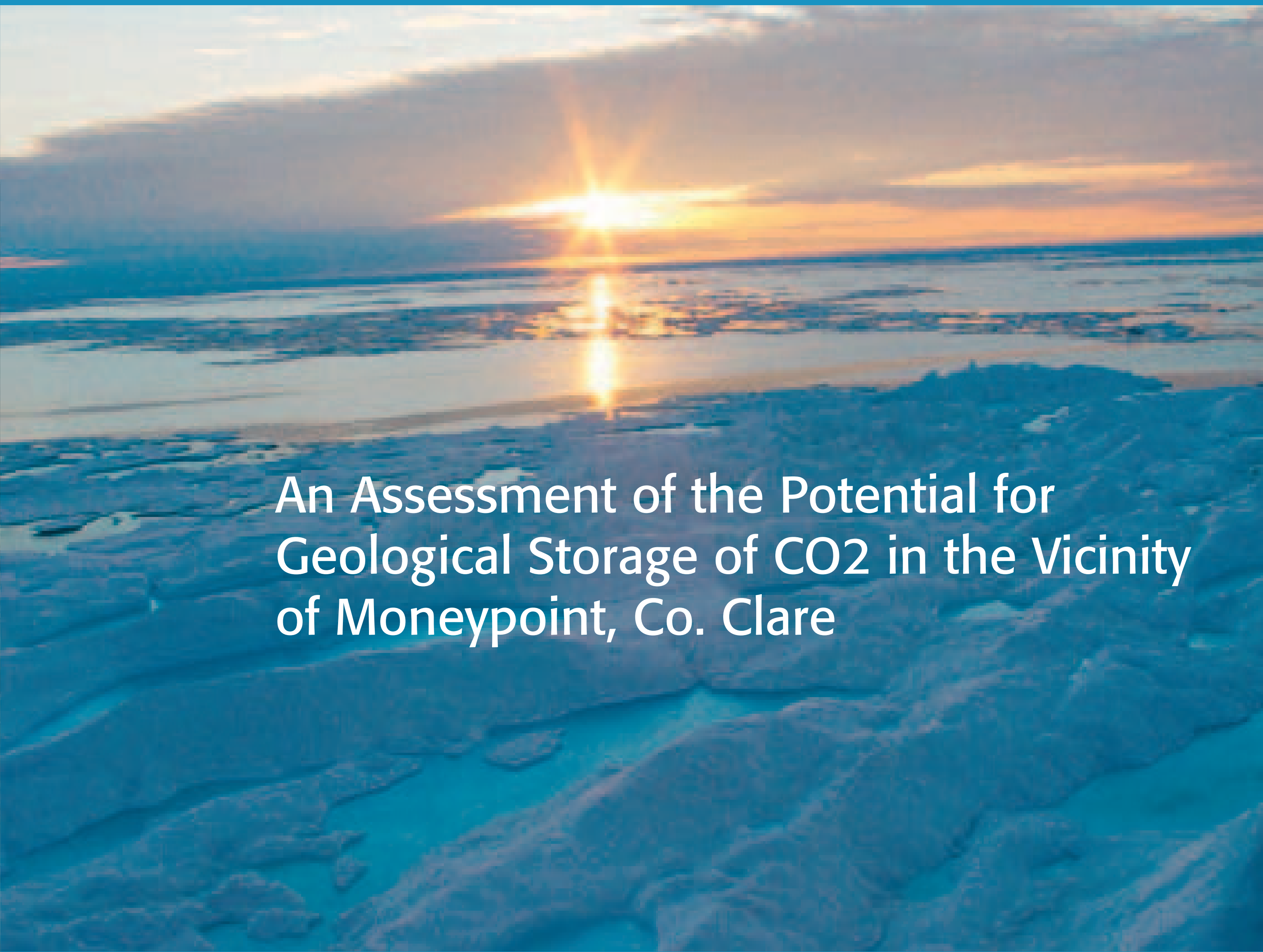
National Development Plan 2007 - 2013

Environmental Protection Agency

An Ghníomhaireacht um Chaomhnú Comhshaoil

Climate Change Research Programme (CCRP) 2007-2013



An Assessment of the Potential for Geological Storage of CO2 in the Vicinity of Moneypoint, Co. Clare

Comhshaol, Oidhreacht agus Rialtas Áitiúil

Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Heritage and Local Government.

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- Office of Environmental Enforcement
- Office of Environmental Assessment
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet several times a year to discuss issues of concern and offer advice to the Board.

EPA Climate Change Research Programme 2007–2013

An Assessment of the Potential for Geological Storage of CO_2 in the Vicinity of Moneypoint, Co. Clare

(CCRP-2008-CCS)

CCRP Report

End of Project Report available for download on http://erc.epa.ie/safer/reports

Prepared for the Environmental Protection Agency in partnership with the Geological Survey of Ireland

by

Aurum Exploration Services in association with
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The EPA CCRP Programme addresses the need for research in Ireland to inform policy makers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contribution to the necessary debate on the protection of the environment.

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Executive Summary

Climate change caused by enhanced atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2) is a major threat for the global environment and socio-economic systems. The International Panel on Climate Change (IPCC) has clearly outlined these issues, including the adverse effects of climate change. The options to address these include the technology of carbon capture and storage (Metz et al., 2005). International action is required to address climate change, including actions to limit or eliminate emissions of CO_2 from energy generation. Internationally these efforts are being progressed under the UN Framework Convention on Climate Change (UNFCCC[1]) and the Kyoto Protocol.

A transition towards a low-carbon sustainable energy supply is required. During the transition period extensive efforts are required to mitigate the effects of global warming including sea-level rise. Reduction of greenhouse gas emissions can be accomplished through a shift to sustainable energy sources and energy conservation. However, to bridge the period to sustainability, a portfolio of mitigating and adaptation measures is required. Currently CO_2 capture and storage (CCS) is considered to be one of the most promising and cost-effective options for the transition period, as recently elaborated by the IPCC (Metz et al., 2005). At EU level, the EU Commission published its draft Directive on the Geological Storage of CO_2 in April 2009, with the objective that member states would transpose it into national legislation by mid-2011.

In the CCS chain, CO_2 is captured at major emission sources like refineries and power stations, transported by pipeline or ship to a suitable sink and stored in depleted natural gas reservoirs and aquifers, or used for enhanced hydrocarbon and coal bed methane recovery.

Ireland's largest single-point emitter at Moneypoint Power Station (currently emitting 3.95 Mt CO_2 per annum) is located in Co. Clare and geologically lies within the Clare Basin. This geological structure was considered as part of an all-Ireland assessment of the potential for geological storage of CO_2, but the study noted that there were significant data gaps pertaining to the area.

In terms of the transportation economics of CO_2 from Moneypoint, a possible local storage site would be a very attractive option. Therefore, it was recognised that a detailed study to assess the potential for geological storage of CO_2 within the Clare Basin was required.

The primary objective of this project is to assess the potential for geological storage of CO_2 in hypothetical deep saline aquifers in the vicinity of Moneypoint, Co. Clare, through provision of a synthesis and interpretation of both existing and newly acquired data.

An extensive data-gathering exercise from a variety of sources and subsequent compilation to a GIS database was undertaken. Once completed, initial geological modelling, using Petrel 2009[2], commenced in tandem with a number of interpretative processes based on the compiled data.

Amongst other elements of the interpretation module, a detailed re-logging programme of deep historical boreholes was completed to maximise the subsurface data available to the project. All data arising from the reinterpretation exercises were incorporated into a 3D model. Based on observations from the interim model and local reconnaissance geological mapping, two boreholes were completed at key sites in the eastern and western margins of the project area. Additionally, downhole petrophysical surveys were conducted at both drill sites. A primary objective of the drilling programme was to provide fresh material for rock characterisation studies. Samples were taken from the project boreholes and historical boreholes for this purpose. Results from the rock characterisation analyses were integrated into the final 3D geological model. Thereafter, a final assessment of the potential storage volume and suitability of the onshore portion of the Clare Basin was undertaken.

In a screening study of this nature, the objective is to search for subsurface reservoirs that have

1 www.unfccc.de

2 Unified seismic interpretation, geological modeling, and reservoir engineering software

sufficient storage capacity, good injection properties and acceptable confining potential. These properties depend on a number of geological parameters for each of the targeted formations. Reservoir size (CO_2 storage capacity) depends on, among other factors, the pore volume that is available and reservoir depth. The rate at which CO_2 can be injected into the reservoir depends on the permeability and thickness of the reservoir formation(s). The 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, such as injectivity and seal quality, also need to be considered in site characterisation studies.

The study investigated a number of critical criteria with respect to potential CO_2 storage within the onshore portion of the Clare Basin. The factors listed below are considered to be the most important aspects for assessment of a saline aquifer in terms of a pre-feasibility study:

- Seal;
- Aquifer depth;
- Trap;
- Reservoir quality/injection rate;
- Size – storage capacity;
- Presence of faults.

The Ross Sandstone Formation and Dinantian Limestone were identified as the primary target horizons for CO_2 storage within the Clare Basin. Therefore this study focused on the assessment of these critical criteria with respect to both geological units.

The Clare Shale Formation is considered an adequate seal for the Dinantian Limestone. Additionally, the depth for this sequence is generally in excess of 800 m throughout the project area. At such depths CO_2 would be present in a dense state, optimising storage space. By comparison, the validity of the Gull Island Formation as a potential seal to the Ross Sandstone Formation remains subject to further examination (internal mudstone continuity is unknown and the presence of potential upward migration paths within slumps considered likely). The depth setting of the Ross Sandstone Formation is variable and only limited portions of the unit are below 800 m within the project area.

Structural traps have been identified for both target horizons. 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.

Although the predominant deformation style is ductile in character, a number of thrust, strike slip and extensional faults have been interpreted within the project area. For this reason, it is considered that fault compartmentalisation of the Ross Sandstone Formation and Dinantian Limestone succession is likely and that multiple injection sites would be required.

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 permeability results for both horizons range between 0.003–0.009 mD (milliDarcy). To ensure adequate injection rates and storage, permeabilities in the order of 200 mD are considered necessary to ensure injection at a rate in the order of mega tonnes per annum.

In spite of the poor permeability results, storage capacity estimates for the trapped portions of each saline aquifer were calculated, based on the available information and using optimistic CO_2 saturation factors. As such, these values should be considered as upper limits for trapped capacity.

The storage capacity (theoretical) for the trapped portion of the Ross Sandstone Formation is in the order of 4 Mt CO_2, while the traps in the Dinantian Limestone are estimated at 11 Mt CO_2.

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

Based on these criteria, the primary conclusion of this study is that the onshore portion of the Clare Basin in unsuitable for CO_2 storage in saline aquifers.

A review of alternative CO_2 storage sites to the Clare Basin was undertaken. This appraisal was based entirely on published data available in Bentham et al. (2008). It was noted that within the Bentham report, an optimistic storage efficiency factor of 40% was used in the calculation of storage capacity for saline aquifers. As aquifer storage is limited by the amount the average pressure in the aquifer can be increased, realistic storage capacities are of the order of 1–2% of the total available pore space. A revised storage capacity estimate within saline aquifers of approximately 1600 Mt CO_2 for the island of Ireland has been calculated using this revised storage efficiency factor.

Based on the revised estimates for saline aquifers, analysis of data for hydrocarbon fields and subsequent features, events and processes (FEP) analysis, the following target areas have been identified as the most attractive for potential CO_2 storage in the all-Ireland context:

- Peel Basin (saline aquifer);
- Lough Neagh Basin (saline aquifer);
- Kinsale Head (gas field).

The most likely alternative for storing CO_2 from Moneypoint is the Kinsale Head gas field. Its location, storage capacity and its status as an (almost) depleted gas field render it much more attractive than saline aquifers in basins at similar distances from Moneypoint.

Saline aquifers that appear most attractive from the currently available data include the Peel Basin and the Lough Neagh Basin. Data presented by Bentham et al. (2008) suggest that challenges exist for both basins, to be resolved by collecting more data on the subsurface structures.

The secondary conclusion of this study is that the Kinsale Head gas field represents the best potential CO_2 storage option for emissions from the Moneypoint power station.

1 Introduction

Climate change caused by enhanced atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2) is a major threat for the global environment and socio-economic systems. The International Panel on Climate Change (IPCC) has clearly outlined these issues, including the adverse effects of climate change. The options to address these include the technology of carbon capture and storage (Metz et al., 2005). International action is required to address climate change, including actions to limit or eliminate emissions of CO_2 from energy generation. Internationally these efforts are being progressed under the United Nations Framework Convention on Climate Change (UNFCCC[3]) and the Kyoto Protocol.

A transition towards a low-carbon sustainable energy supply is required. During the transition period extensive efforts are required to mitigate the effects of global warming, including sea-level rise. Reduction of greenhouse gas emissions can be accomplished through a shift to sustainable energy sources and energy conservation. However, to bridge the period to sustainability, a portfolio of mitigating and adaptation measures is required. Currently CO_2 capture and storage (CCS) is considered to be one of the most promising and cost-effective options for the transition period, as recently elaborated by the IPCC (Metz et al., 2005). At EU level, the EU Commission published its draft Directive on the Geological Storage of CO_2 in April 2009, with the objective that member states would transpose it into national legislation by mid-2011.

In the CCS chain, CO_2 is captured at major emission sources like refineries and power stations, transported by pipeline or ship to a suitable sink, and stored in depleted natural-gas reservoirs or saline aquifers. Alternatively it may be used for enhanced hydrocarbon or coal-bed methane recovery.

Ireland's largest single-point emitter at Moneypoint Power Station (currently emitting 3.95 Mt CO_2 per annum) is located on the north side of the Shannon Estuary in Co. Clare. Geologically the area is underlain by a thick sequence of Carboniferous sediments that lie with 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 CO_2. The economics of CCS transport from Moneypoint to what appears to be the geographically closest practical storage site at the Kinsale Head gas field has previously been considered, both in the CSA group[4] report (2008) and earlier by Monaghan et al. (2006). This scenario would involve significant investment in pipeline infrastructure and, consequently, a local CCS storage site would be logistically and financially more attractive. The Geological Survey of Ireland (GSI) in 2007 conceived a project to test for the existence of geological reservoirs in the Clare Basin region which resulted in IDCSSTI[5] funding for work in this area under the Climate Change Research Programme managed by the Environmental Protection Agency (EPA). The GSI, EPA and others partners initiated this project: 'Assessment of the Potential for Geological Storage of CO_2 in Hypothetical Deep Saline Aquifers in the Vicinity of Moneypoint, Co. Clare'. The project was managed by the EPA and GSI with technical and advisory support and input from a broad-based steering group (Appendix).

In terms of geological storage of CO_2, a number of mechanisms have been identified. The primary storage mechanisms include sequestration within depleted hydrocarbon fields and deep saline aquifers. In this scenario, CO_2 is injected at depths in excess of 800 m where it achieves a dense state in response to ambient pressure and temperature conditions. A density contrast between the injected fluid and existing fluids within the pore space results in an upward migration of CO_2 where it accumulates beneath a seal horizon. The injected fluid partially fills the pore space within the target horizon and causes expulsion of the in situ fluids. Within hydrocarbon reservoirs the injected CO_2 can replace a significant proportion of the available pore space. By comparison, estimates of potential storage volume within saline aquifers are significantly

3 www.unfccc.de

4 Now SLR Consulting Ltd.

5 Interdepartmental Committee for the Strategy for Science Technology and Innovation

higher, even though the proportion of pore space that can be replaced by the injected CO_2 is much lower and dependent on local geological factors (such as fault compartmentalisation which can inhibit displacement of in situ fluids).

1.1 Assessment Criteria

The project objective for the Clare Basin is to identify a suitable subsurface reservoir that has sufficient storage capacity, good injection properties and good confining potential for geological storage of CO_2. The critical criteria in assessment of a suitable reservoir are given below.

1.1.1 Reservoir Size (Storage Capacity)

The storage capacity, (expressed in Mt of CO_2 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, 2007). In the present case of storing CO_2 to be captured at the Moneypoint power plant, a quantity of the order of 200 Mt CO_2 must be stored throughout the expected lifetime of the (new) power plant.

The case for gas or oil fields is different, as the existing infrastructure might be reused, and a lower threshold may be possible. For depleted gas or oil fields, the common assumption regarding storage capacity is that the entire volume of produced gas or oil can be replaced by CO_2 (for oil fields, minus the net volume of injected water); as such, the uncertainty in storage capacity is relatively small.

For saline aquifers, the storage capacity depends on the pore volume available for accommodating the elevated pressure that is the result of injecting CO_2 in the brine-filled formation. The pressure increase that is applied to an aquifer must be well below the leak-off pressure, which is the pressure at which the formation fractures and at which leakage into overlying strata can occur. A pressure increase of about 10% (or about 10 bar at a depth of 1000 m) is considered safe (van der Meer and Egberts, 2008; van der Meer and Yavuz, 2009). At this pressure increase the compressibility of brine in the formation results in a volume available for storing CO_2 that is of the order of 1–2% of the total available aquifer pore volume (van der Meer and Yavuz, 2008). Recent work by the United States Department of Energy (USDoE, 2009) suggests that the total available pore volume is of the order of 1% of the net pore volume, due to such phenomena as porosity variations and non-interconnectedness of parts of the reservoir. The uncertainty in the storage capacity is large, as often the total connected volume cannot be defined from pre-existing data. Heterogeneity in the reservoir, transmissivity of faults and the lateral extent of sand bodies are all difficult to define with certainty. A well injection test must be done to test the injection rates and estimate storage capacity.

In deep saline formations, additional storage capacity can be created by producing formation fluids. This also mitigates the pressure increase due to CO_2 injection. If this approach is shown to be both environmentally and economically possible, storage efficiency factors can be much larger than 1–2%.

1.1.2 Porosity

Porosity is a key factor with respect to overall storage capacity within a geological reservoir. While porosity is important, it does not represent a single discriminatory determinant for the feasibility of CO_2 storage sites. For example, a low-porosity geological formation with high permeability and significant total aquifer pore volume can provide a suitable reservoir for CO_2 storage. Therefore porosity cannot be considered in isolation as a screening criterion for a potential site and must be assessed in terms of related requirements such as permeability, reservoir bulk volume, system compressibility and associated pressure increase. Reservoirs which are characterised 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 a lower applied CO_2 injection pressure that is less damaging to the rock formation.

1.1.3 Traps

During the injection period, and in the short term following site closure, almost all of the CO_2 injected will exist in a free phase. Mineralisation and dissolution of CO_2 in brine are processes that will eventually fix the

CO_2 in place, but these act over periods of hundreds to thousands of years and are not relevant for the short term. Free CO_2 can be trapped by anticlinal (dome shaped) structures or in fault traps, similar to the case of natural gas. It has been estimated that the trapped volume in deep formations is of the order of a few per cent of the total formation volume (Bradshaw et al., 2007*)*. It is also possible to store CO_2 in deep saline formations that are nearly horizontal, utilising the slow migration of CO_2 and relying on dissolution for long-term secure storage. The Sleipner project is one such example (Arts et al., 2008).

The threshold for trap volume is that the volume should be large enough to contain the injected volume of CO_2. Reservoir storage capacity, especially for saline formations, can be limited by either the volume of the total formation (accommodating the pressure increase, as explained above), or the trap volume.

1.1.4 Reservoir Depth

Reservoir depth must be greater than about 800 m, to ensure that CO_2 is stored in a dense phase, optimising the use of storage space. At these depths, CO_2 has a density of the order of 700 kg/m^3. The phase change from gas phase to dense phase occurs at a pressure near 80 bar, corresponding to depths around 800 m. Lindeberg et al. (2008) show that the local temperature gradient controls the depth at which the phase change occurs.

1.1.5 Permeability and Formation Thickness

The injection rate is controlled by the product of injection interval and formation permeability, and the pressure difference between well and reservoir. A minimum value for reservoir permeability of 200 mD (milliDarcy) has been proposed as a target to ensure injection rates of the order of several Mt/yr for realistic formation thickness (van der Meer, 1993; Dynamis, 2007*)*. Such rates are comparable to the volume of CO_2 produced annually by the Moneypoint power plant.

The allowed pressure increase near the injection well also affects the injection rate, but is not considered here. Formation permeability can be lower for gas fields, which are generally at a lower pressure after production. Injection rates can be predicted from the production history of the field (see, e.g. van der Velde et al., 2008).

1.1.6 Seal

The storage site must be able to retain the injected CO_2 indefinitely. An impervious formation on top of the reservoir should prevent the CO_2 from migrating upward. Evaporites (e.g. salt) and shale are examples of seals. Gas fields have a proven seal, but the capacity of the seal to also trap CO_2 must be tested. The extent of the seal must be at least as large as the expected size of the plume of free CO_2 in the reservoir. This can be the area of a structural trap, but if the CO_2 is stored in a large, nearly horizontal reservoir the seal must be present over a much larger area. Other parameters, such as presence of wells, regional stress field and seismicity also affect confinement

1.1.7 Presence of Faults

The ideal CO_2 storage reservoir contains no faults. Faults can impede the flow of CO_2 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 CO_2 storage.

A storage site must, of course, meet many other requirements, for example those dealing with regulations and health and safety, but these are not considered as part of this study. Site selection procedures have been proposed (e.g. Chadwick et al*.,* 2007; Kaldi and Gibson-Poole, 2008; GeoCapacity, 2009), and site selection and characterisation procedures that can be quality controlled are currently being developed (Aarnes et al., 2009).

2 Methodology

In order to examine the potential for reservoirs in the Clare Basin and assess these features, the project was undertaken using these modules[6]:

1 Data capture;

2 Interpretative processing;

3 Project borehole programme;

4 Rock characterisation studies;

5 3D geological modelling;

6 Assessment of CO_2 storage potential.

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

The extensive data-gathering exercise encompassed compilation of all available geological data held by the GSI into a relational project database using a combination of various software packages, primarily MapInfo, ArcGIS and Geosoft. Amongst other elements of the interpretation module, a detailed re-logging programme of deep historical boreholes was started in an effort to maximise the subsurface data available to the project. Once available, all data arising from the reinterpretation exercises were incorporated into the 3D Petrel 2009[7] geological model and the 3D model revised accordingly. Based on observations from the interim Petrel 2009 model and local reconnaissance geological mapping, two boreholes were completed at key sites in the eastern and western margins of the project area. Additionally, downhole petrophysical surveys were conducted at both drill sites. A primary objective of the drilling programme was to provide fresh material for rock characterisation studies. Samples were taken from the project boreholes and historical boreholes for this purpose. On receipt of results from the rock characterisation analyses, all data from the drilling campaign was integrated into Petrel 2009 and a final 3D geological model produced. Thereafter, a final assessment of the potential storage volume and suitability of the onshore portion of the Clare Basin was undertaken. Additionally, a review of various CO_2 storage options within Ireland and a subsequent frequency, events and processes analysis (FEP) was completed.

6 The original concept made provision for an intermediate phase of new seismic data acquisition, as well as deep drilling. These were not advanced due to budgetary constraints.

7 Unified seismic interpretation, geological modeling, and reservoir engineering software

3 Study Area

The geographical limits to the area in which data capture was undertaken are shown in Fig. 3.1 This boundary was determined by reference to both the density and perceived usefulness and/or quality of the compiled information. While much of the compiled information lies within the data capture limits, it should be noted that information outside the boundary, which was recognised by project geologists as being important, was also captured. As such, the data capture boundary was viewed as being indicative rather than proscriptive in terms of the information compilation programme.

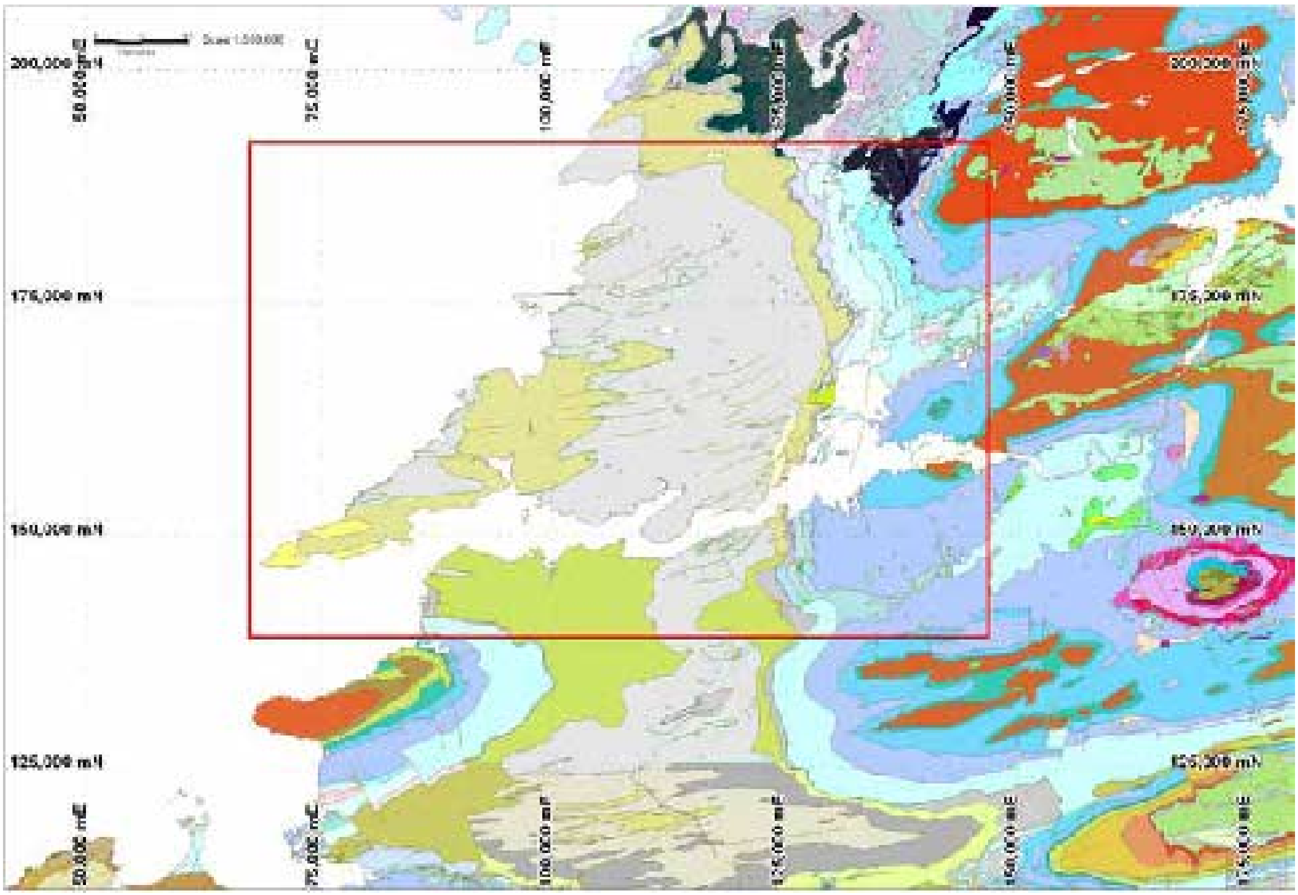

Figure 3.1. Geological map of the Clare region outlining the project area data compilation boundaries (Geological Survey of Ireland 1:100,000 Bedrock Map Series).

4 Data Compilation

A critical component of the overall project methodology was the compilation and digital capture of relevant geological information pertaining to the project area. It was recognised from the outset that provision of an accurate, validated geological data set would underpin many aspects of the project, including critical elements such as the design of proposed seismic surveys and location sites for boreholes. For this reason, the data capture module of the project was prioritised at the project initiation. The primary information sources can be broadly subdivided into three groupings: geological, borehole and geophysical information.

4.1 Geological Information

The available geological information largely consists of historical field sheets derived from GSI mapping programmes conducted during the 19th century. These historical maps are an important data source as they show a complete outcrop distribution prior to the sometimes widespread burial of bedrock occurrences by modern farming and building practices.

A secondary source of geological map information consists of field sheets relating to 20th-century mapping programmes undertaken by the GSI and various workers, including academic studies.

In all cases, the base maps were sourced either as hard copies or scanned images. All hard copies were subsequently scanned and the resultant images rectified where necessary and geo-referenced in preparation for digitisation. Thereafter, key information such as outcrop, dip-strike measurements, lithological descriptions, geological boundaries and structures were digitally captured and assimilated into a relational GIS database. In total 14,376 individual outcrop polygons and 12,278 dip-strike measurements were digitised from the 19th- and 20th-century maps.

A number of bedrock mapping suites published by the GSI were also acquired as part of the data compilation process. These include an all-Ireland 1:500,000-scale map, a series of 1:100,000-scale maps covering the project area and also a limited number of 1:25,000-scale compilation maps which cover a portion of the project area. These maps were acquired in both ArcGIS and AutoCad format and were integrated into the project GIS database.

4.2 Borehole Information

The primary data source for subsurface information was derived from historical drilling records. This borehole information for the project area was compiled from a number of sources. These included the Department of Communications, Energy and Natural Resources' Petroleum Affairs Division for onshore hydrocarbon-well logs and also the Exploration and Mining Division's Open File archive for borehole information relating to mineral exploration. A total of 361 holes were identified within the study area and relevant information such as header location, downhole lithology, survey information etc. was compiled in each case. It should be noted that log information for a number of short holes drilled within the project area by the GSI was found to be unavailable. All borehole data sets were cross-verified using MapInfo Discover and Datamine borehole procedures and any identified issues resolved.

4.3 Geophysical Information

Data covering the project area for a number of regional geophysical surveys was also acquired. These include regional gravity information held by the Dublin Institute of Advanced Studies (DIAS) and Huntings Aeromagnetic data held by the GSI. Both data sets were made available in digital format to the project through the auspices of the GSI.

Additional data sources relating to historical seismic surveys and downhole petrophysical surveys were acquired from the Petroleum Affairs Division. Information from a number of offshore and onshore seismic surveys was also reviewed. However, owing to the poor quality of these historical surveys (pre-1980s), it was considered that digital capture and additional processing of this information was not warranted.

4.4 Other Data Sources

Topographic and remote sensing information were also compiled from a number of different sources. These include Shuttle Radar Tomography Mission (SRTM) data for elevation data, and Landsat imagery for structural geology interpretation purposes, in addition to a number of other freely available satellite photographic sources (e.g. Google Earth and Virtual Earth). Topographic maps were acquired from the Ordnance Survey of Ireland.

Information from a number of publications including geological papers, academic studies and historical reports was also compiled. Close links to academic groups with interests in the Clare Basin were maintained throughout the project lifespan. These include the Marine and Petroleum Geology Research Group at University College Dublin (UCD), and the Seismic and Basin Analysis Group at Trinity College Dublin (TCD), in addition to other individuals with wider but related research interests.

All data capture activities were conducted using a series of quality control/quality assurance (QC/QA) control checks to ensure production of a fully validated GIS database. All scanned maps were rectified and geo-referenced to the highest precision to ensure accurate digitisation of compiled features.

5 Potential Saline Aquifers

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. These principal target horizons remained constant throughout the project lifespan and the subsequent analysis was focused primarily on their assessment.

The geology of the project area is dominated by a subcrop of post–Dinantian age, namely the Namurian. Therefore, 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. Although the Viséan succession in the boreholes is distinct to that seen elsewhere there was inadequate information to subdivide it or recognise units that would be particularly favourable for CCS. Therefore a decision was made to apply the general term of 'Dinantian Limestone' to describe this sequence and is herein interpreted as including all sub-Namurian carbonates within the project area.

The stratigraphy of the Namurian within the Clare Basin has been described by various workers. As discussed by Sleeman and Pracht (1999), much of this work was based on a 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 based on the goniatite fauna of marine bands (Hodson and Lewarne, 1961), sedimentology (Pulham, 1989) and sequence stratigraphy (Davies and Elliott, 1996). For the purposes of this report, the stratigraphic subdivision of the Namurian used by the GSI (Sleeman and Pracht, 1999) and supported by Pyles (2008) and others has been adopted. This involves a tripartite subdivision of the Namurian into the Clare Shale Formation, Shannon Group and Central Clare Group (Fig. 5.1). The Shannon Group includes the Ross Sandstone Formation and the overlying Gull Island Formation. The Central Clare Group consists of five cyclothemic sequences, three of which are named (Tullig, Kilkee and Doonlicky cyclothems).

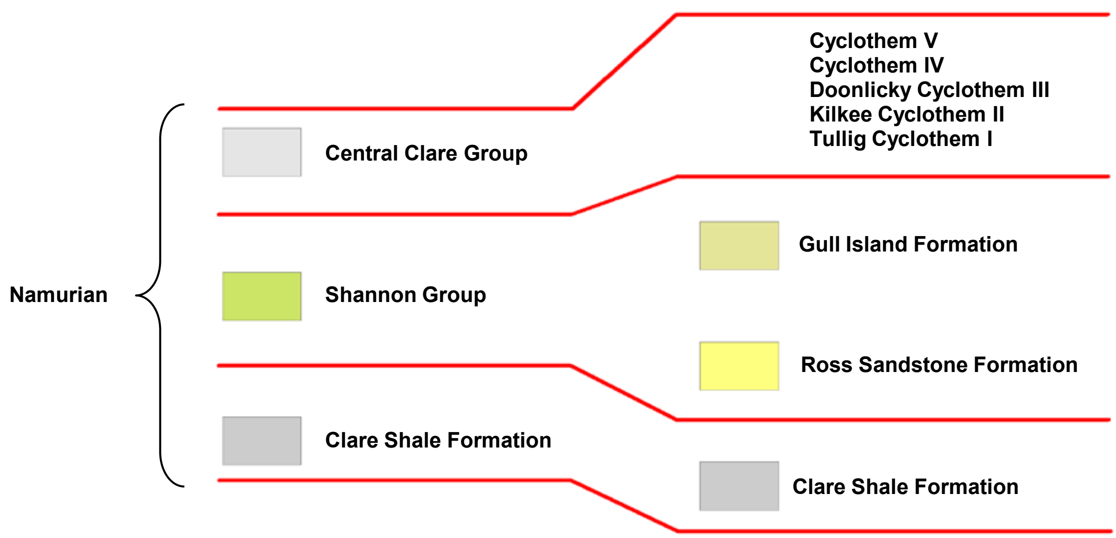

Figure 5.1. Stratigraphic subdivision of the Namurian for the Clare area.

It should be noted that while this stratigraphic framework is underpinned by biostratigraphic age determinations, the presence of goniatite/marine bands are not uniform throughout the project area. Therefore, the assignation of outcrop and borehole successions to individual formations is often based on lithological and/or sedimentological observations as opposed to biostratigaphy. For the purpose of the project, lithological correlation has been accepted in the absence of biostratigraphic control for some of the major subdivisions and does not always indicate temporal equivalence (e.g. Ross Sandstone Formation).

6 Borehole Programme

At an early stage in the project it became apparent that suitable samples of the target formations were required for analysis. A two-borehole programme was undertaken as part of the project using the GSI's drill rig: this provision was made as a substitute for a programme of deep drilling (c.1500 m), which was not possible due to budgetary limitations. The following were the objectives of the borehole programme:

- To provide core samples from the Ross Sandstone Formation;
- To provide some estimates of porosity and permeability from unweathered material;
- To provide information on the seal qualities of the Gull Island Formation;
- To provide key information on the geological stratigraphy and information on formation thickness and lithologies;
- To provide gamma, sonic, resistivity, dip meter and temperature information;
- To aid interpretation and refinement of the 3D Petrel 2009 geological model.

A limited programme of reconnaissance mapping and field checking was undertaken in the Inishcorker area to identify the presence of the Ross Sandstone Formation. The objective of this exercise was to visit key outcrops in the area to help with the planning of the project boreholes. A number of drill-site options were considered during a technical review and a number of potential sites were selected. A final decision was made to drill two boreholes as follows:

- At Killadysert, to test the nature and thickness of the Ross Sandstone Formation in east Clare;
- In the townland of Faha, Co. Kerry, to help increase the geographical distribution of samples from the target Ross Sandstone Formation for permeability and porosity testing.

7 Rock Characterisation

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 horizon, the Ross Sandstone Formation, from selected areas within the study area. A secondary objective was to provide porosity/permeability measurements from the Doonbeg 1 borehole, against which historical downhole survey data could be reassessed.

Table 7.1. Ranges for porosity/permeability results.

Sample no.	Hole ID/ Location	Depth (m)	Type	Easting (ING)	Northing (ING)	Comment	Depth (m)	Gas permeability @ 400 psig (mD)	Porosity (%)	Grain density (g/cc)
AX9601	Kilcredaun	N/A	Outcrop	83012	149401	Upper Ross Sandstone	N/A	0.006	0.6	2.68
AX9602	Doonbeg 1	1476.1	Core	96370	163820	Asbian/ Brigantian	1476.1	0.006	1.1	2.70
AX9603	Doonbeg 1	1477.8	Core	96370	163820	Asbian/ Brigantian	1477.8	0.006	0.5	2.78
AX9604	Doonbeg 1	1883.7	Core	96370	163820	Rathkeale Beds/ Durnish Lst (Holkerian / Asbian)	1883.7	0.006	0.8	2.71
AX9605	Doonbeg 1	2496.3	Core	96370	163820	Fine calcarenite	2496.3	0.004	0.3	2.71
AX9606	Doonbeg 1	2717.3	Core	96370	163820	Late Tournasian	2717.3	0.005	0.2	2.73
AX9607	Doonbeg 1	3084.1	Core	96370	163820	Ballyvergin Shale	3084.1	Frac	0.7	2.77
AX9608	Doonbeg 1	3085.8	Core	96370	163820	Ballyvergin Shale	3085.8	0.009	0.2	2.72
AX9609	IPP-1	814.0	Core	110000	170000	Asbian Reef	814.0	0.006	0.7	2.71
AX9610	IPP-1	1173.2	Core	110000	170000	Ramp Facies A	1173.2	0.003	0.7	2.71
AX9611	IPP-1	878.4	Core	110000	170000	Ramp Facies A	878.4	0.006	0.9	2.71
AX9612	IPP-1	1186.3	Core	110000	170000	Ramp Facies B	1186.3	0.003	0.7	2.72
AX9613	IPP-2	183.0	Core	117680	176020	Gull Island Fmn	183.0	0.005	0.4	2.73
AX9614	IPP-2	312.1	Core	117680	176020	Ross Sandstone	312.1	0.006	1.2	2.70
AX9615	IPP-2	331.0	Core	117680	176020	Ross Sandstone	331.0	0.003	1.0	2.70
AX9616	IPP-2	352.7	Core	117680	176020	Ross Sandstone	352.7	0.005	0.5	2.69
AX9617	IPP-2	355.1	Core	117680	176020	Ross Sandstone	355.1	0.007	1.2	2.69
AX9618	IPP-2	444.6	Core	117680	176020	Burren Limestone	444.6	0.003	1.5	2.72
AX9619	IPP-2	919.4	Core	117680	176020	Burren Limestone	919.4	0.007	1.1	2.71
AX9620	Inishcorker	N/A	Outcrop	126004	157625	Ross Sandstone Unit 14	N/A	0.011	9.4	2.69
AX9621	Inishcorker	N/A	Outcrop	126048	157621	Ross Sandstone Unit 8	N/A	0.007	0.3	2.72
AX9622	Inishcorker	N/A	Outcrop	126126	157629	Ross Sandstone Unit 2	N/A	0.005	2.6	2.70
AX9623	GSI/09/04	29.5	Core	126517	158683	Gull Island Fmn (sandstone)	29.5	0.004	0.6	2.67
AX9624	GSI/09/04	59.9	Core	126517	158683	Gull Island Fmn (sandstone)	59.9	0.006	0.4	2.68
AX9625	GSI/09/05	41	Core	87405	145406	Ross Sandstone	41	0.005	0.1	2.68

Sample no.	Hole ID/ Location	Depth (m)	Type	Easting (ING)	Northing (ING)	Comment	Depth (m)	Gas permeability @ 400 psig (mD)	Porosity (%)	Grain density (g/cc)
AX9626	GSI/09/05	53.9	Core	87405	145406	Ross Sandstone	53.9	0.006	0.1	2.68
AX9627	GSI/09/05	114.7	Core	87405	145406	Ross Sandstone	114.7	0.005	0.1	2.69
AX9628	GSI/09/05	134.5	Core	87405	145406	Ross Sandstone	134.5	0.006	0.5	2.70
AX9629	GSI/09/05	150	Core	87405	145406	Ross Sandstone	150	0.008	<0.1	2.69
AX9630	GSI/09/04	50.9	Core	126517	158683	Gull Island Fmn (siltstone)	50.9	0.003	0.8	2.71

N/A: No depth given, outcrop sample.

Frac: No permeability measurement possible due to fracturing.

Abbreviations and units in table: Fmn = formation; Lst = limestone; psig = pound force per square inch gauge; cc = cubic centimetre.

A total of 30 samples was taken from both historical and project boreholes (GSI 09/04 and GSI 09/05) in addition to a number of outcrop samples. The samples were analysed by Corex Laboratories in Aberdeen, Scotland. These samples were plugged and cleaned, with subsequent gas permeability, porosity and grain density measurements being undertaken. The results are presented in Table 7.1.

It should be noted that the 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 range for samples from the Ross Sandstone Formation is as in Table 7.2.

The results show low-order porosity and permeability ranges for both the Ross Sandstone Formation and underlying Dinantian Limestone succession. The porosity/permeability results for the Ross Sandstone Formation are similar to those received from a parallel study undertaken by UCD on core from their Loop Head drilling programme. Integrated results from both sampling programmes are presented in Fig. 7.1.

The results for the Ross Sandstone Formation appear consistent with recent petrographic observations undertaken by the UCD group, which show that the sandstones contain a quartz cement that serves to anneal the internal porosity and permeability. Similarly poor porosity and permeability results for the Dinantian Limestone succession are considered representative of tight limestones in which the porosity has been filled by carbonate cements.

Table 7.2. Ranges for porosity/permeability results (project data sets – unweathered samples only).

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

Units: cc = cubic centimetre; psig = pound force per square inch gauge.

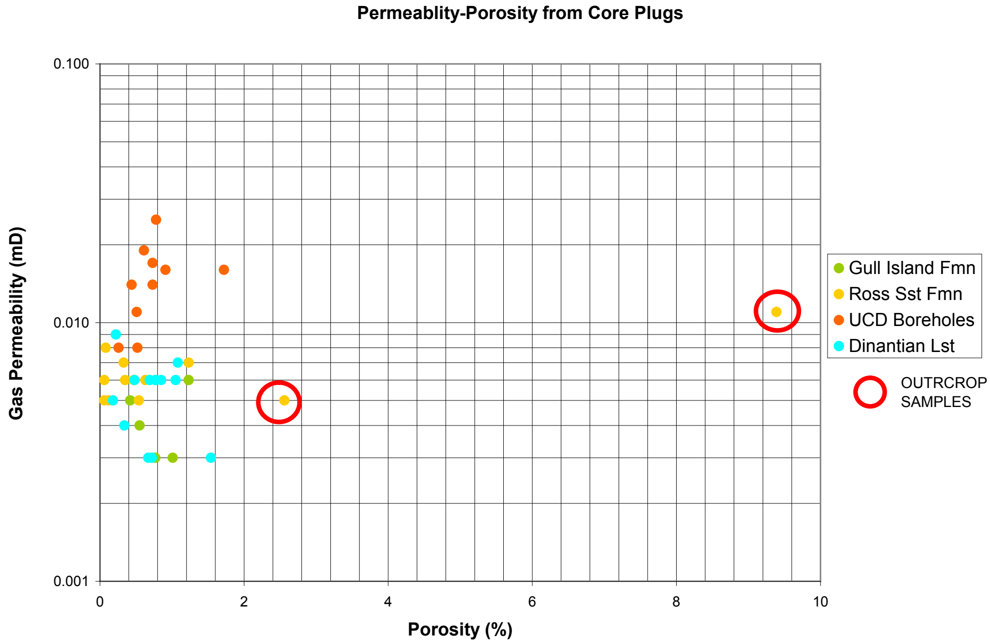

Figure 7.1. Permeability versus porosity plot for project and UCD data sets (outcrop samples highlighted). Fmn (formation), Sst (sandstone), Lst (limestone).

7.1 Critical Criteria in the Clare Basin

A number of critical criteria have been investigated with respect to potential CO_2 storage within the onshore portion of the Clare Basin. While not exhaustive, these factors are considered to be the most important factors for assessment of a saline aquifer in terms of a pre-feasibility study. It should be noted, however, that failure to meet any one of these criteria would effectively militate against CO_2 storage at a potential site. A listing of the criteria is given in Table 7.3.

Table 7.3. Discriminatory criteria and thresholds for CO_2 storage within a saline aquifer.

	Criterion	Comment, threshold
1	Seal	Required
2	Aquifer depth	Must be >800 m
3	Trap	Required
4	Reservoir quality/ injection rate	Higher permeability is better Higher than about 200 mD
5	Presence of faults	Fewer is better – less compartmentalisation
6	Size – storage capacity	Larger is better Amount to store is of the order of 200 Mt CO_2

7.2 Seal

An adequate seal for a potential aquifer is essential to prevent upward migration of injected CO_2. 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 180 m 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 the 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_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.

7.3 Aquifer Depth

An aquifer depth of greater than 800 m is required to ensure that any injected CO_2 will remain in dense form. Due to the high proportion of sand content within the turbidites of the Ross Sandstone Formation, this sequence was considered to be the primary potential saline aquifer. Based on analysis of various data sources, the volume of the Ross Sandstone Formation below the critical depth is low (132 km^3). Owing to the good seal properties of the Clare Shale Formation, the Dinantian Limestone succession was considered as a potential secondary aquifer. Given the depth setting of the Dinantian Limestone 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.

7.4 Traps

The volume estimates presented above are for a 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 prerequisite for site selection. Suitable traps include anticlinal dome structures or fault traps. A full analysis of the structural setting for the Clare Basin has been undertaken. This examination suggests that a ‘basin’ geometry has developed in response to local and regional tectonic stress. Structural elements in west Co. 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.

7.5 Reservoir Quality and 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 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 interpreted as being consistent with recent petrographic observations undertaken by the UCD group (personal communication), showing that the sandstones contain a quartz cement which serves to anneal the internal porosity and permeability. Similarly poor porosity and permeability results for the Dinantian Limestone succession are considered representative of tight limestones in which the porosity has been filled by carbonate cements. These results are orders of magnitude lower than those required for successful carbon storage, and effectively militate against the potential saline aquifers considered within this study: the Ross Sandstone Formation and the Dinantian Limestone.

7.6 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 the Dinantian Limestone succession occurs and that multiple injection sites would be required to access individual compartments of any potential reservoir.

Table 7.4. Volumetric and storage capacity estimates for potential saline aquifers in the onshore portion of the Clare Basin.

Potential aquifer	Bulk formation at depths >800 m	Theoretical storage capacity in entire aquifer volume	Bulk formation in traps (estimated)	Theoretical storage capacity in traps
Ross Sandstone Formation	132 km^3	18 Mt CO_2	1.5 km^3	4 Mt CO_2
Dinantian Limestone succession	300 km^3	42 Mt CO_2	4 km^3	11 Mt CO_2

7.7 Storage Capacity

In spite of the poor rock characterisation results, 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 converted to CO_2 storage capacity. The results are detailed in Table 7.4.

For the calculation of the storage capacity within aquifer volume, a storage efficiency factor of 2% was used. As the hydraulically connected reservoir volume cannot 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 the total available pore volume in the potential reservoirs, is 18 Mt and 42 Mt, for the Ross Sandstone Formation and the Dinantian Limestone succession, respectively.

Storage capacity can also be limited by the volume in the traps. Table 7.4 shows that this is the case for both potential reservoirs. The storage capacity of the traps in these formations was computed by assuming a CO_2 saturation of 40% in the trap, which is a value that follows from modelling CO_2 flow in homogeneous formations (Pruess, 2003). It should be noted that similar work for heterogeneous reservoirs resulted in lower values, in the range 1–10% (van der Meer, 1995; Doughty et al., 2003; USDoE, 2009). Therefore the values reported here should be regarded as an upper limit of trap capacity.

In summary, the storage capacity (theoretical) for the trapped portion of the Ross Sandstone Formation is in the order 4 Mt CO_2, while the traps in the Dinantian Limestone are estimated at 11 Mt CO_2.

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

8 Summary

A summary of the critical criteria with respect to the potential CO_2 storage within the onshore portion of the Clare Basin is presented in Table 8.1. This study has demonstrated that certain key parameters 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 information suggests that the reservoir lithologies are tight and are orders of magnitude below the accepted thresholds for injection and successful storage of CO_2. 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 the 'failed criteria' listed above militates against carbon storage in the Clare Basin.

Table 8.1. Summary of assessment criteria for the onshore portion of the Clare Basin.

Basin	Clare onshore		Clare onshore	
Type	Saline aquifer		Saline aquifer	
Target horizon	Ross Sandstone Formation		Dinantian Limestone	
Seal	Gull Island Formation		Clare Shale Formation	
Aquifer size	Small	✘	Small	✘
Depth	Limited areas below 800 m	?	800+ m	✔
Permeability	0.003–0.008	✘	0.003–0.009	✘
Seal	Moderate	?	Good	✔
Porosity	0.06–1.23%	✘	0.18–1.54%	✘
Traps	Structural (anticline)	✔	Structural	✔
Thickness	460 m (max.)	✔	1000+ m	✔
Presence of faults	Faults may penetrate seal, compartmentalisation likely	?	Faults may penetrate seal, compartmentalisation likely	?

✔ Criterion passed
✘ Criterion failed
? Uncertain

For comparative purposes, the project results have been placed in context against a 'hypothetical situation', whereby carbon storage in the Clare Basin would be permissible, in Table 8.2. The parameters documented under the 'hypothetical situation' reflect the criteria required for storage of total emissions of 200 Mt CO_2 with injection rates in the order of 5 Mt CO_2 per annum.

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 CO_2 within saline aquifers.

Table 8.2. Required parameters for successful carbon storage in Clare (hypothetical situation) listed against actual situation determined by this study.

Parameter	Hypothetical situation	Actual situation
Aquifer size	900 km^2	Small
Depth	800+ m	Limited area below 800 m
Permeability	200+ mD	Poor (<0.009 mD)
Seal	Impermeable/Tested	Gull Island Formation – moderate seal/Clare Shales – good seal
Aquifer/Reservoir	Ross Sandstone/Dinantian Limestone	Ross Sandstone/Dinantian Limestone
Porosity	20%+	Poor (<1.54%)
Traps	Well developed	Limited
Thickness	80+ m	0–200 m
Basin architecture	Unfaulted with structural traps	Steep-sided basin, potential spill points, limited traps
Risks		Ross Sandstone sub-crops at eastern margin of basin (spill points)
		Poor injectivity rates (permeability parameter unfulfilled)
		Poor porosity not compensated by reservoir horizon thickness
		Gull Island Formation is a questionable seal
		Dinantian Limestone has low porosity/permeability
		Fracture porosity in the Dinantian Limestone likely to be filled/tight
		Facies variation in Ross Sandstone unfavourable (eastward thinning of sandstones)

9 Criteria for Assessment of Alternative Sites

An analysis of the potential for CO_2 storage in Ireland, onshore and offshore, was performed recently (Bentham et al., 2008). As storing CO_2 in the subsurface of County Clare appears not to be feasible, this recent all-Ireland inventory has been screened for alternative sites.

Bentham et al. (2008) screened for storage potential in both onshore and offshore Ireland, in both hydrocarbon fields and saline aquifers. The authors present brief descriptions of each storage option, which allows a prioritisation of the sites. The sites assessed have been re-examined, using the results and conclusions from the Clare Basin.

A CO_2 storage site must meet a large number of requirements, ranging from geological and economical to regulatory and technical, that are addressed as a site is developed from first exploration to actual injection of CO_2. Bentham et al. (2008) performed a screening study, addressing only those geological requirements that could be assessed from existing data with limited data processing.

These geological requirements describe the suitability of a geological structure for CO_2 storage at a high level and can be used to quickly identify a number of key features. In revisiting the sites in Bentham et al. (2008), the points addressed above and summarised in Table 7.3 were used.

These requirements were used in a prioritisation of the sites described in Bentham et al. (2008). With the available data and descriptions, only a first-order screening of the sites was done. A colour code was used for the properties addressed in Table 9.1 and Table 9.2:

- Red indicates that a property poses serious difficulties. Examples include shallow depth (inefficient CO_2 storage), low permeability (low injection rates) or small size (relatively expensive storage);
- Yellow indicates a storage site where CO_2 storage will be challenging. Examples include strongly faulted reservoirs (possibly many wells needed to access all of the compartmentalised space) or an unproven seal. These properties are likely to lead to higher costs when developing the site;
- Green indicates that, based on current data, few problems are expected. Examples include proper depth, few faults and sufficient permeability.

In Bentham et al. (2008), an optimistic storage efficiency factor of 40% was used in the calculation of storage capacity for saline aquifers. As aquifer storage is limited by the amount the average pressure in the aquifer can be increased, realistic storage capacities are of the order of 1–2% of the total available pore space, as noted above. A revised storage capacity estimate within saline aquifers of approximately 1600 Mt CO_2 for the island of Ireland has been calculated using this revised storage efficiency factor.

Based on the revised estimates for saline aquifers, analysis of data for hydrocarbon fields and subsequent FEP analysis, the following target areas have been identified as the most attractive for potential CO_2 storage in the all-Ireland context:

- Peel Basin (saline aquifer);
- Lough Neagh Basin (saline aquifer);
- Kinsale Head (gas field).

The most likely alternative for storing CO_2 from Moneypoint is the Kinsale Head gas field. Its location, storage capacity and the fact that it has the advantage of being an (almost) depleted gas field render it much more attractive than saline aquifers in basins at similar distances from Moneypoint.

Saline aquifers that appear most attractive from the currently available data include the Peel Basin and the Lough Neagh Basin. Data presented by Bentham et al. (2008) suggest that challenges exist for both basins, to be resolved by collecting more data on the subsurface structures.

The secondary conclusion of this study is that the Kinsale Head gas field represents the best potential CO_2 storage option for emissions from the Moneypoint power station.

Table 9.1. Shortlist of aquifer storage sites considered in the all-Ireland study.

Basin	Name	Seal	Depth (m)	Trap	Permeability (mD)	Storage capacity (Mt)	Presence of faults	Limiting factors
Portpatrick Basin	Sherwood Sst structures	Mudstones, halites	750	Fault traps	45	20–10	Many faults present, possible compartmentalisation	Shallow depth; small capacity; structural traps at depths >750 m exist
Central Irish Sea	Sherwood Sst structures	Mudstone; seal quality lower near edges basin; gas seepage observed on sea floor	1200	Tilted fault blocks	0.04–0.41	625	Basin likely to be compartmentalised	Tight reservoir
Lough Neagh Basin	Enler Group structures	Evaporites and mudstones; seal thickness may not be sufficient	<700	Fault trap	50–100	90	Faults may compartmentalise the reservoir; fault extent not known	Seal to be studied; permeability is an issue; no traps identified at proper depths.
East Irish Sea	Ormskirk structures	Seal expected to be good (halite), but some questions remain	556	Tilted fault blocks	0.02–2100	32	Faulted aquifer	Too shallow; capacity small
Kish Bank Basin	Sherwood Sst structures	Seal may be breached by faults; gas seepage observed on sea floor	1200	Dome structures are present	No data	14	Faults are present, but their density is not clear	Seal to be studied; no permeability data; capacity small
Celtic Sea	Cretaceous A sand	Claystone; faults may compromise seal quality	750	Dome structure	2.49–429	29	Faults may penetrate seal	Seal to be studied; capacity small
Peel Basin	Sherwood Sst whole basin	Mudstone; seal quality unsure; shallow gas is observed	800	Fault traps	No data	670	Many faults present	Seal to be studied; no permeability data
North-West Carboniferous Basin	Dowra whole basin	Proven seal (natural gas pockets)	1200		0.02–0.22	19	Little data	Small capacity; tight reservoir

The colour code indicates whether sites meet criteria for the different properties. Red: criteria not met and site probably not suitable for CO_2 storage. Yellow: storage will be challenging. Green: site meets the criteria. The better sites in this list are the Peel Basin and Lough Neagh Basin. Sst = Sandstone.

Table 9.2. Shortlist of gas field storage sites considered in the all-Ireland study.

Basin	Name	Seal	Depth (m)	Trap	Permeability (mD)	Presence of faults	Size (Mt)	Limiting factors
East Irish Sea	South Morecambe	Shallow gas in formations overlying gas fields	670	Fault blocks	0.3–1000	No data	734	Seal quality
	North Morecambe	Integrity seal to be studied	899	Fault roll-over	0.2–180	No data	139	Seal quality
	Hamilton	Good seal	701	Structural	300–2100	No data	66	Shallow depth
	Other	Integrity seal to be studied				No data	120	Seal quality
North Celtic Basin	Kinsale Head, South-West Kinsale	Shallow gas; faults through reservoir may reach seabed	800–900	Structural	280–420	Faults may cut through overburden	336	Seal quality
Porcupine Basin	Spanish Point	Gas chimneys; pock marks observed on sea floor	3971	Fault block	2–20	Faults may cut through overburden	115	Seal quality

The colour code indicates whether sites meet criteria for the different properties. Red: criteria not met and site probably not suitable for CO_2 storage. Yellow: storage will be challenging. Green: site meets the criteria.

References

Aarnes, J.E., S. Selmer-Olsen, M.E. Carpenter and T.A. Flach (2009) *Towards guidelines for selection, characterisation and qualification of sites and projects for geological storage of CO_2*, Energy Proc., 1, 1735–1742.

Arts, R.J., Chadwick, A., Eiken, O., Thibeau, S. and S. Nooner (2008), *Ten years of experience with CO_2 injection in the Utsira Sand at Sleipner (offshore Norway)*. In Goulty, N. and Arts, R.J., Special topic on underground CO_2 storage, First Break Vol. 26, 2008.

Bentham, M.S., K.L. Kirk and J. Williams (2008) *Basin-by-basin analysis of CO_2 storage potential of all-island Ireland* (BGS report CR/08/036, Annexe 1 to CSA Group (2008) Assessment of the Potential for Geological Storage of CO_2 for the Island of Ireland). Available at www.sei.ie.

Bradshaw, J., S. Bachu, D. Bonijoly, R. Burrus, S. Holloway, N.P. Christensen, and O.M. Mathiasen (2007). *CO_2 storage capacity estimation: Issues and development of standards*, Int. J. of Greenhouse Gas Control, 1, 62–68.

CSA Group (2008) *Assessment of the potential for geological storage of CO_2 for the island of Ireland*. Available at www.sei.ie.

Davies, S.J., and T. Elliott (1996) *Spectral gamma ray characterization of high resolution sequence stratigraphy: Examples from Upper Carboniferous fluvio-deltaic systems, County Clare, Ireland*. In J.A. Howell and J.F. Aitken (eds), High resolution sequence stratigraphy: Innovations and applications. Geological Society, London, Special Publication, 104, 999–1999.

Doughty, C., S.M. Benson, and K. Pruess. (2003) *Capacity investigations of brine-bearing sands for geologic sequestration of CO_2*. In J. Gale and Y. Kaya (eds), Greenhouse Gas Control Technologies, vol. II. Elsevier Ltd., pp.1645–1648.

Dynamis (2007) *Shortlist of potential CO_2 storage sites*, EU Dynamis deliverable D4.1.1, 26pp., EU Dynamis consortium, Brussels.

GeoCapacity (2009) WP 4 Report, *Capacity standards and site selection criteria*, EU GeoCapacity deliverable D26, 45pp., EU GeoCapacity Consortium, Brussels.

Hodson, F. and G.C. Lewarne (1961): *A Mid-Carboniferous (Namurian) basin in parts of the counties of Limerick and Clare, Ireland*, Quarterly Journal of the Geological Society of London, 117, 307–333.

Kaldi, J.G. and C.M. Gibson-Poole (eds.) (2008) *Storage capacity estimation, site selection and characterization for CO_2 storage projects*, CO2CRC report RPT08-1001, Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Canberra, Australia.

Lindeberg, E., J.F. Vuillaume and A. Ghaderi, (2009) *Determination of the CO_2 storage capacity of the Utsira formation*, Energy Proc., 1, 2777–2784.

Metz, B., O. Davidson, H. de Coninck, M. Loos and L. Meyer (eds) (2005) *Carbon dioxide capture and storage*, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Monaghan, R., M. Brazilian and G. Brennan (2006) *Carbon dioxide capture and storage in Ireland: Costs, benefits and future potential*, Sustainable Energy Ireland, Dublin. Available at www.sei.ie.

Pruess, K., T. Xu, J. Apps and J. Garcia (2003) *Numerical modeling of aquifer disposal of CO_2*, SPE Journal, pp.49–60.

Pulham, A.J. (1989) *Controls on internal structure and architecture of sandstone bodies within the Upper Carboniferous fluvial-dominated deltas, County Clare western Ireland*. In M.K.G. Whately and K.T. Pickering (eds), Deltas: Sites and traps for fossil fuels. Geological Society of London, Special Publication, 41, 170–203.

Pyles, D.R. (2008): *Multiscale stratigraphic analysis of a structurally confined submarine fan: Carboniferous Ross sandstone, Ireland*. AAPG Bulletin, vol. 92, no. 5, pp.557–587.

Sleeman, A.G. and M. Pracht (1999) *Geology of the Shannon Estuary: A geological description of the Shannon Estuary region including parts of Clare, Limerick and Kerry*, to accompany the Bedrock Geology 1:100,000 Scale Map Series, Sheet 17, Shannon Estuary. Geological Survey of Ireland, Dublin, 77pp.

USDoE (United States Department of Energy) (2008) *Methodology for development for geological storage estimates for carbon dioxide*. Available at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/methodology2008.pdf.

Van der Meer, B. and P.J.P. Egberts, (2008) *A general method for calculating subsurface CO_2 storage capacity*, SPE- OTC 19309, Offshore Technology Conference held in Houston, Texas, May 2008.

Van der Meer, L.G.H. (1995) *The CO_2 storage efficiency in aquifers*, Energy Convers. Mgmt., 36(6–9), 513–518.

Van der Meer, L.G.H. (1993) *The conditions limiting CO_2 storage in aquifers*, Energy Convers. Mgmt 34(9–11), 959–966.

Van der Meer, L.G.H. and F. Yavuz, (2009) *CO_2 storage capacity calculations for the Dutch subsurface,* Energy Proc., 1, 2615–2622.

Van der Velde, R., J. Mieog, J. Breunese and G. Remmelts (2008) *Potential for CO_2 storage in depleted gas fields at the Dutch continental shelf*. Available at http://www.nlog.nl/resources/StorageCO_2.

Acronyms and Annotations

cc	Cubic centimetre
CCS	CO_2 capture and storage
DIAS	Dublin Institute of Advanced Studies
FEP	Features, events and processes
Fmn	Formation
GIS	Geographic information system
GSI	Geological Survey of Ireland
IDCSSTI	Interdepartmental Committee for the Strategy for Science Technology and Innovation
IPCC	International Panel on Climate Change
Lst	Limestone
psig	Pound force per square inch gauge
QA	Quality assurance
QC	Quality control
SRTM	Shuttle Radar Tomography Mission
Sst	Sandstone
TCD	Trinity College Dublin
UCD	University College Dublin
UNFCCC	United Nations Framework Convention on Climate Change

Appendix: Steering Committee

Frank McGovern (Environmental Protection Agency)

Maria Martin (Environmental Protection Agency)

Ger Hussey (Environmental Protection Agency)

John Morris (Geological Survey of Ireland)

Peter Croker (Department of Communications, Energy and Natural Resources)

Bob Hanna (Department of Communications, Energy and Natural Resources)

Graham Brennan (Sustainable Energy Ireland)

Michael Young (Department of the Environment, Heritage and Local Government)

Chris Bean (University College Dublin)

Pat Naughton (Electricity Supply Board)

Owen Wilson (Electricity Supply Board)

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.
- Scardadh dramhuisce

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Climate Change Research Programme (CCRP) 2007-2013

The EPA has taken a leading role in the development of the CCRP structure with the co-operation of key state agencies and government departments. The programme is structured according to four linked thematic areas with a strong cross cutting emphasis. Research being carried out ranges from fundamental process studies to the provision of high-level analysis of policy options.

For further information see www.epa.ie/whatwedo/climate/climatechangeresearch

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