National Heat Study

Carbon Capture Utilisation and Storage (CCUS)

Suitability, Costs and Deployment Options in Ireland

seai SUSTAINABLE ENERGY AUTHORITY OF IRELAND

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Report 6 of the National Heat Study

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February 2022

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The National Heat Study and associated reports were commissioned by a project team across the SEAI Research and Policy Insights Directorate and developed with the assistance of Element Energy and Ricardo Energy and Environment.

Sustainable Energy Authority of Ireland

SEAI is Ireland's national energy authority investing in, and delivering, appropriate, effective and sustainable solutions to help Ireland's transition to a clean energy future. We work with the public, businesses, communities and the Government to achieve this, through expertise, funding, educational programmes, policy advice, research and the development of new technologies.

SEAI is funded by the Government of Ireland through the Department of the Environment, Climate and Communication.

Key insights

- **Carbon capture, utilisation and storage (CCUS) is an important decarbonisation technology option globally.** Energy system decarbonisation scenarios aligned with Ireland's objectives suggest that CCS and greenhouse gas removal technologies, such as bioenergy with carbon capture and storage (BECCS), will need to be deployed.
- **Global deployment of CCS technology is gaining momentum.** Several on-site CO_2 capture technologies are already commercialised (e.g. amine scrubbing) and demonstration projects are ongoing across Europe at industrial sites (e.g. cement). Other European countries (e.g. United Kingdom, Norway, Netherlands) have active projects that are aiming to begin commercial operations as early as 2024-2025.
- **While international deployment is foreseen from 2025, Ireland is unlikely to see CCS deployed until the late 2020's at the earliest.** CO_2 transport and storage infrastructure have long-lead times and are at early stages of development in Ireland.
- **International CO_2 shipping is likely to be available before any domestic CO_2 storage development begins.** The depleted Kinsale gas field is being explored as a potential option for domestic CO_2 storage with the earliest date for potential operation in the mid-2030s.
- **CCUS is a critical decarbonisation option for industrial sectors with process emissions that cannot be abated via low-carbon fuel switching**. In Ireland, the cement and lime sectors are the largest source of industrial process emissions.
- **Carbon capture and utilisation (CCU) routes have high uncertainty around their techno-economics and deployment timeframes;** however, there may be viable CCU options for Ireland to reduce emissions in the cement sector or transition to synthetic fuel production in the existing refining sector.
- **BECCS is not limited to large-scale power generation in Ireland.** Opportunities for BECCS exist in both the industrial (primarily cement sites) and energy-from-waste (EfW) sectors which can achieve considerable scales of negative emissions in high-deployment scenarios (approximately 1 $MtCO_2$/y).
- **Advanced planning around the role of CCUS and BECCS in Ireland is needed,** particularly around clustering of sites and infrastructure, if policy seeks to encourage deployment of the technology. This can provide confidence to infrastructure developers about the scale of CO_2 volumes to be transported and aid the development of business models for long-term operation. With the late 2020s likely the earliest opportunity for CO_2 shipping exports, early investigations could focus on the development of port infrastructure and supporting regulatory frameworks.
- **In a high-deployment scenario, CCUS could abate nearly 17 $MtCO_2$/y by 2050, including up to 9 $MtCO_2$/y of negative emissions potential from BECCS –** in 2019, Ireland emitted a total of 59.79 $MtCO_{2eq}$. The largest industrial and power sites are likely most suitable for CCS and BECCS given the economies of scale achievable for both CO_2 capture at individual sites and CO_2 transport and storage infrastructure but careful consideration of the role of imported biomass fuels is required.
- **Future scenarios with lower amounts of BECCS would need either increased negative emissions** from other technologies (land–based solutions or engineered removals), or higher levels of effort in other economy sectors to reach the same levels of net emissions.

Acknowledgements

SEAI, Element Energy and Ricardo Energy and Environment would like to convey our thanks to the following bodies for their valuable inputs to the study:

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Contents

Executive summary

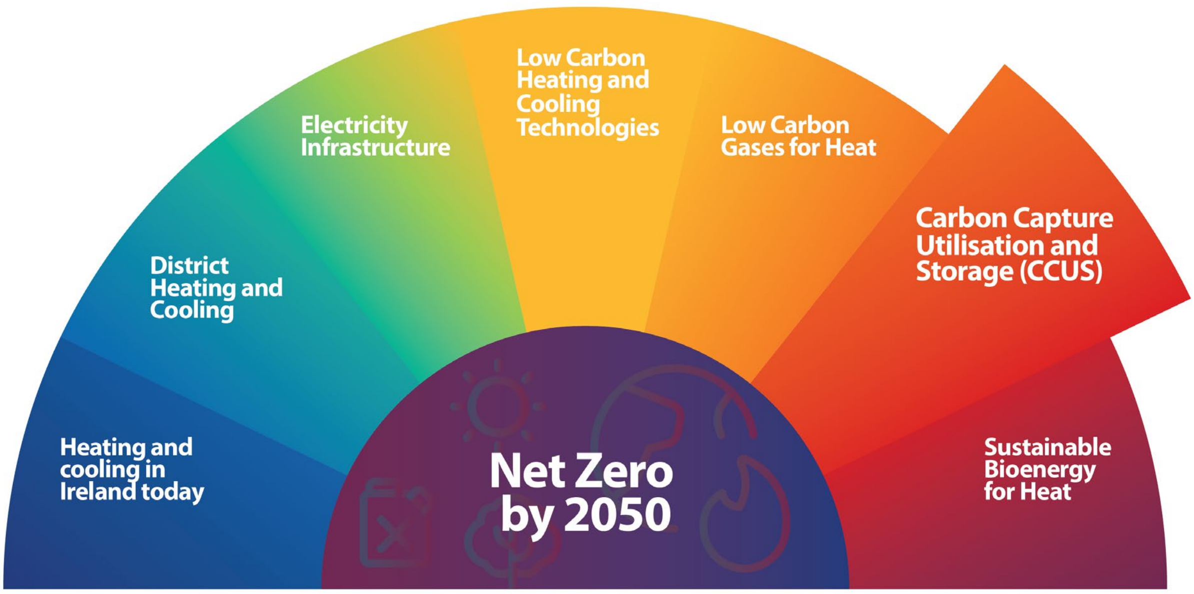
Ireland's 2021 Climate Action and Low Carbon Development (Amendment) Act commits Ireland to reducing greenhouse gas emissions by 51% by 2030 and to achieving economy-wide carbon neutrality by 2050. This requires immediate emissions reductions in every sector. Energy used for heating and cooling accounts for 24% of Ireland's greenhouse gas emissions, but the current pace of decarbonisation falls short of the cuts required. Almost every sector of Ireland's economy uses heat energy, and decarbonisation efforts will need to be implemented by industry, businesses, and households. This requires a comprehensive, robust and actionable evidence base that policymakers and other stakeholders can use to make decisions.

The Sustainable Energy Authority of Ireland (SEAI) commissioned Element Energy and Ricardo Energy and Environment to work with SEAI on the National Heat Study to provide this evidence base. The study evaluates the costs and benefits of various pathways that reach net zero by 2050. We based the evaluation on a comprehensive understanding of heating and cooling demand in Ireland and the deployment costs, potential and suitability of technologies, infrastructure and fuels to reduce emissions.

We have separated the insights and analysis from the study into eight reports (outlined in Figure 1)[1]. These reports provide a rigorous and comprehensive analysis of options for decarbonising heating and cooling in Ireland up to 2050. The findings support Ireland's second submission to the EU of a national comprehensive assessment of the potential for efficient heating and cooling, as required by Article 14 of the Energy Efficiency Directive.[2] There are seven major technical reports, each focusing on topics that form the overall analysis. The concluding report is called *Net-Zero by 2050: Exploring Decarbonisation Options for Heating and Colling in Ireland*[3]. It outlines the study's key insights across scenarios that achieve net-zero emissions from heating and cooling.

As shown in *Figure 1*, this report serves as a standalone document detailing the analysis carried out to determine the potential for carbon, capture, utilisation and storage (CCUS), including bioenergy with carbon capture and storage (BECCS), in Ireland.

Figure 1: Overview of the reports contributing to the National Heat Study



[1] All reports and supporting materials published as part of the National Heat Study are available from www.seai.ie/NationalHeatStudy/

[2] SEAI, 'Comprehensive Assessment of the Potential for Efficient Heating and Cooling in Ireland, report to the European Commission'. 2021 [Online]. Available: https://www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/#

[3] SEAI, 'Net-Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'. 2022 [Online]. Available: www.seai.ie/publications/Net-Zero-by-2050.pdf

Carbon capture, utilisation and storage (CCUS) is likely to be an important decarbonisation technology option globally. Scenarios aligned with Ireland's objectives suggest that CCS and greenhouse gas removal technologies, such as bioenergy carbon capture and storage (BECCS), are likely to be needed for Ireland to meet its decarbonisation aims.

This report examines and quantifies the potential for CCUS (including BECCS) in the Irish context from literature review, analysis and stakeholder engagement on the potential, costs and challenges associated with CCUS in Ireland. We determined the suitability of industrial sites for CCUS and incorporated these into the study's final outputs. This study also considers wider energy system context scenarios that utilise BECCS in Ireland and how these align with pathways focused on the heat sector.

This analysis led to the following outputs:

- Characterisation of the sources of carbon emissions and options for CO_2 transport and storage in Ireland and abroad, with an overview of CCUS projects currently under way.
- Assessment of the status of CCUS (including BECCS) in Ireland and internationally.
- Technical potential scenarios for the deployment of CCUS to 2050 and the potential for negative emissions from BECCS.
- Identification of the challenges and barriers to CCUS deployment in Ireland and enabling policies and actions that may mitigate these.

The potential for CCUS deployment across Ireland depends on several important factors that influence the technology's viability in a net-zero emissions future:

- Many industrial sectors (e.g. cement or refining) have process-based emissions which cannot be decarbonised by low/zero-carbon fuel switching alone, thus they likely require the adoption of CCUS technology for deep / net-zero decarbonisation
- Infrastructure development will be a key constraint for adopting CCUS at both industrial and power sites, particularly more dispersed sites, which will need assurance from infrastructure developers about downstream CO_2 transport and storage options before they deploy CO_2 capture.
- The deployment of CCUS and BECCS technologies is most suitable for large point source emitters of carbon. Sites in or near to 'clusters' potentially have easier access to shared infrastructure (e.g. near shoreline terminals), helping to achieve economies of scale for build-out of infrastructure such as pipelines and shipping.

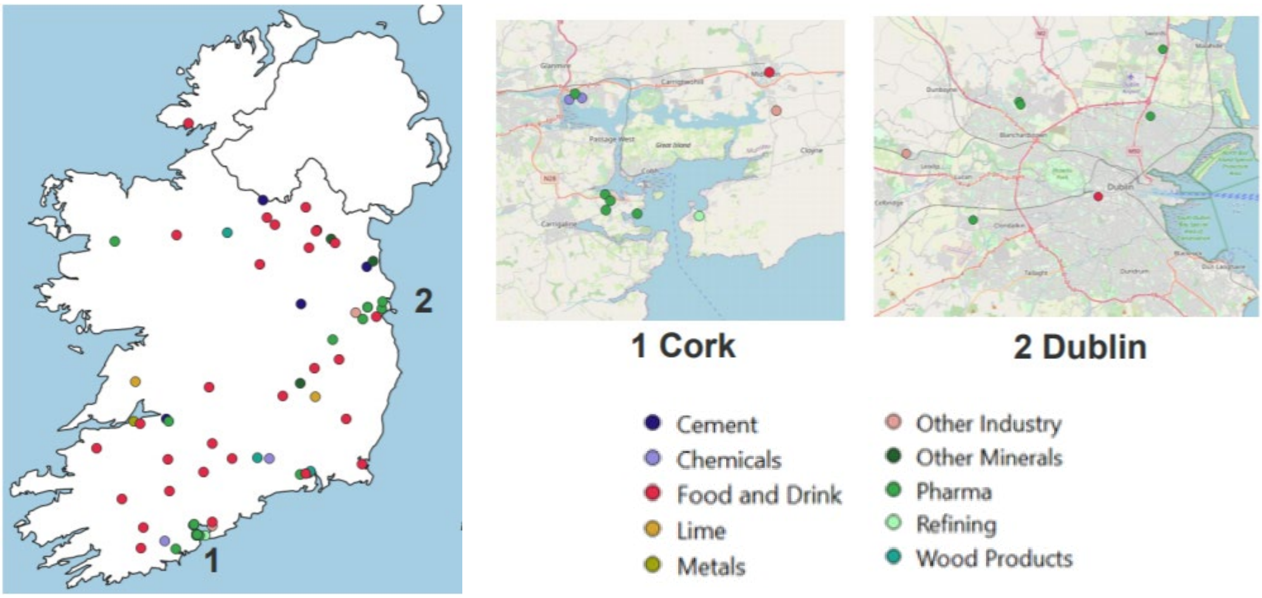
For that reason, the focus of this work is on the application of CCUS and BECCS in industry and power generation settings. The spatial distribution of these sites is an important consideration. The more closely 'clustered' the sites are, the lower the overall cost of the CO_2 transportation and shipping infrastructure. We examined the spatial distribution of these sites in Ireland to estimate these costs.

As shown in *Figure 2*, industrial emissions sources are widely dispersed across Ireland. There are some clusters of industrial sites around Cork and Dublin, along with some shoreline clustering around Drogheda and East Cork. The most likely sites for CCUS adoption include those in cement and refining sectors, where CO_2 capture is potentially the only solution to abate process-based emissions[4] and achieve cost-effective economies of scale. Other industrial sectors also have the potential to utilise CO_2 capture as an abatement

[4] 'By-product' emissions of CO_2 from chemical reactions within the industrial process, which are unable to be abated by low carbon fuel switching.

measure. These sectors include lime, chemicals, food and drink, metals (i.e. alumina), other minerals and wood products.

Figure 2: Map of industrial fossil-based emissions sources in Ireland by sector[5]



For the industry sector, the potential at a given site is based on technical and economic suitability. We used the 2019 EU ETS dataset to determine site level emissions. Using this information, sites with annual emissions greater than 20ktCO_2/y were then selected as sites with potential for CCS. Below this cut off point, CCS is unlikely to be commercially viable and likely to face additional technical challenges. Using data on the CO_2 concentration at each site, the location of the site relative to potential shoreline terminals in Ireland, and costs for transportation and storage infrastructure, we estimated an initial levelised cost of CCS at each site. We excluded all sites above 180 €/tCO_2 on the basis of our judgement that other more cost-effective abatement options are likely available to those sites. This method led to the identification of 16 industrial sites with the potential for CCS adoption.

In this study, we also undertook a high-level assessment of electricity generation sites to investigate the potential application of CCUS. This enabled consideration of these additional volumes of CO_2 and their impact on the economies of scale of transport and storage infrastructure deployment. This included both fossil-fuelled power stations (i.e. peat, coal, natural gas) and energy from waste (EfW) facilities. In addition to CCUS in industry and power, this study also examined the role of BECCS in Ireland. We undertook a quantitative assessment of the potential uptake of BECCS across the sectors outlined in *Table 1*.

Table 1: Description of potential Irish BECCS sectors and their focus of assessment in this study

Sector	BECCS description	Assessment focus
Power Generation	Biomass-fuelled power stations which participate in the electricity market	Considered power BECCS in Ireland as potential for new build dedicated biomass generators with CCUS

[5] This map does not show all industrial sites in Ireland, only those included in the EU-ETS dataset (2019).

Energy from Waste	Sites which are principally responsible for waste management as a service (e.g. combustion of municipal solid waste), but also sell electricity	Considered EfW BECCS in Ireland for both new build plants and retrofits of existing plants with CCUS
Industry	Includes a range of potential industrial sites and sectors (with a focus in this study on the cement, wood products, and food and drink sectors)	Considered industrial BECCS in Ireland for existing industrial plants for CCUS retrofits

These findings allowed a range of deployment scenarios to be developed. *Table 2* provides a description of the role of CCS and BECCS across various energy system decarbonisation scenarios. The scenarios shown were developed across all work streams in the National Heat study. The scenarios represent four ways of reaching net-zero emissions by 2050 and the underlying scenario narrative guides the technology deployment choices in each.

The amount of CCUS deployed varies considerably across the scenarios, reflecting a range of probable levels for the development of CCUS in Ireland. These deployment trajectories are an output of this work and act as a deterministic input into the full scenario modelling presented in the report: *'Net Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'*[6]. The CCUS trajectories are constructed with the aim of exploring the impact of varying CCUS and BECCS deployment. The deployment choices aim to be consistent with the overall scenario narratives. For example, the High Electrification scenario represents the lowest level of CCUS deployment based on the limited adoption across key industrial sectors and limited CCUS uptake in the power sector. In a high electrification scenario, many industrial sites that electrify no longer have onsite emissions to capture. Decarbonised Gas represents the highest level of CCUS deployment. CCUS is deployed across industrial and power sites that are suitable for CCUS and hydrogen and other renewable gases are used more widely. Further work can build on these trajectories and link to economy wide decarbonisation strategies in Ireland.

Table 2: CCUS and BECCS deployment in each scenario

Scenario	Decarbonised Gas	High Electrification	Balanced	Rapid Progress
Number of industrial sites with CCS	16 sites	3 sites	8 sites	11 sites
Industrial emissions captured	4.5 MtCO2	2.4 MtCO2	3.7 MtCO2	4.3 MtCO2
Number of EfW and power BECCS Sites	4 sites	1 site	6 sites	4 sites
EfW and BECCS power emissions captured	9.2 MtCO2	0.3 MtCO2	5.4 MtCO2	5.4 MtCO2

[6] SEAI, 'Net-Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'. 2022 [Online]. Available: www.seai.ie/publications/Net-Zero-by-2050.pdf

Number of gas power sites with CCS	5 sites	0 sites	2 sites	1 site
Gas power emissions captured	3.2 MtCO2	0 MtCO2	1.3 MtCO2	0.9 MtCO2
Total emissions captured	**16.9 MtCO2**	**2.7 MtCO2**	**10.4 MtCO2**	**10.5 MtCO2**
Total negative emissions (portion of captured emissions)[7]	**9.0 MtCO2**	**0.8 MtCO2**	**5.1 MtCO2**	**6.0 MtCO2**

Across all scenarios, we assume that any large-scale deployment of CCUS (i.e. greater than 0.5 $MtCO_2$) will begin in the 2030's, due to the nascent state of planning for CCUS infrastructure in Ireland, coupled with the long lead times to develop new CCUS infrastructure, particularly around the availability of CO_2 shipping either domestically or internationally. As several on-site CO_2 capture technologies are already fully commercialised (e.g. amine scrubbing), along with novel demonstration projects ongoing across Europe at industrial sites (e.g. cement), we do not assume adoption of this technology to be a barrier for CCUS deployment should Ireland have CCUS infrastructure capacities available in the late 2020s.

These four scenarios include differences in the levels of negative emissions provided, to reflect the range of estimates of negative emissions that might be needed and can be provided through BECCS. As shown in *Figure 3*, by the early 2040s, negative emissions can offset all remaining emissions from industrial and power sites which select CCUS or BECCS abatement. Remaining emissions come from the unabated portion of fossil/process emissions after applying CO_2 capture. It is important to note that this figure only shows the pathways for the relevant sites (i.e. those sites which adopt CCUS technology in each scenario) and does not portray an economy-wide net zero analysis which was outside the scope of this study. This work has been guided by published research work in Ireland supplemented with feedback provided directly by stakeholders. To highlight this, the figure shows the varying number of industrial CCUS, power BECCS and gas power CCUS sites that were assumed in each scenario. We have not included industrial sites where CCUS is not applied as these will have selected other abatement options. (e.g. industrial sites selecting hydrogen or electrification abatement technologies). We explain this in greater detail in the National Heat Study report: *Low Carbon Heating and Cooling Technologies*[8]. Remaining emissions come from the unabated portion of fossil/process emissions after applying CO_2 capture.

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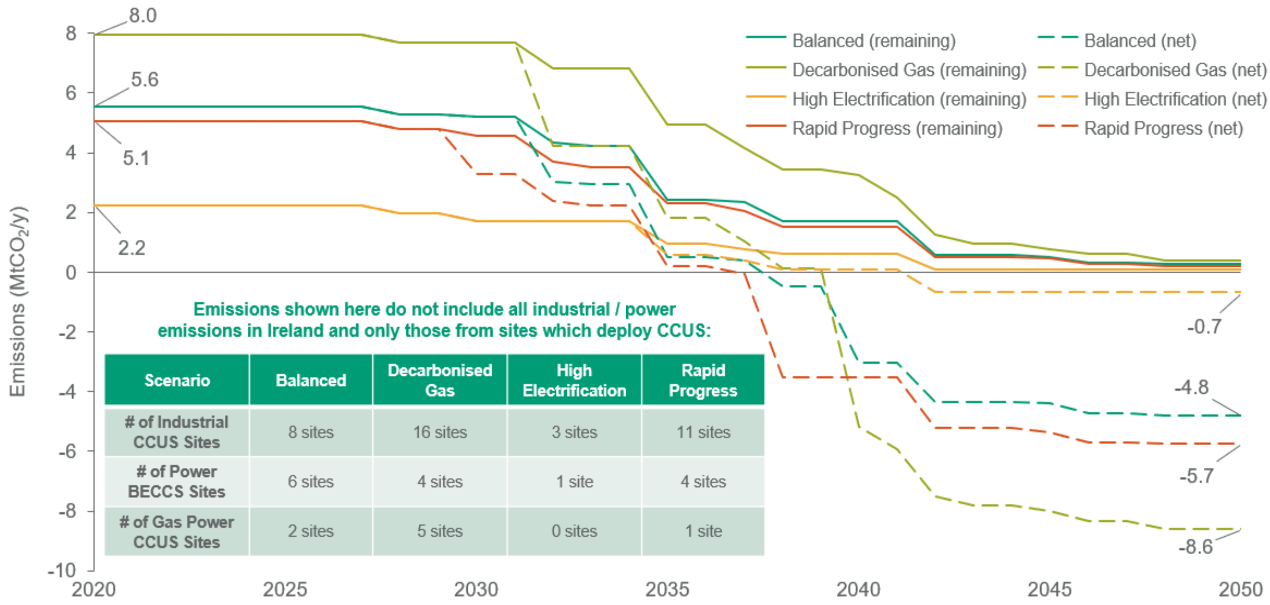
[7] Negative emissions from BECCS. These are derived from the biogenic portion of emissions which are captured from power BECCS, industrial BECCS (e.g. cement) and EfW BECCS plants.

[8] SEAI, 'Low Carbon Heating and Cooling Technologies'. 2022 [Online]. Available: www.seai.ie/publications/Low-Carbon-Heating-and-Cooling-Technologies.pdf

Figure 3: Remaining and net emissions from all industrial and power sites abated by CCUS or BECCS



Scenario	Balanced	Decarbonised Gas	High Electrification	Rapid Progress
# of Industrial CCUS Sites	8 sites	16 sites	3 sites	11 sites
# of Power BECCS Sites	6 sites	4 sites	1 site	4 sites
# of Gas Power CCUS Sites	2 sites	5 sites	0 sites	1 site

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To overcome these challenges, the following actions present plausible options for facilitating the deployment of CCUS in Ireland:

- **Development of a clear plan for offshore CO_2 transport and storage.** Development of CO_2 shipping infrastructure could accelerate the deployment of CCUS ahead of domestic offshore CO_2 transport and storage using the Kinsale gas field. Policy can steer the planning around interregional and international CO_2 shipping. This would provide greater certainty on the timeframes for infrastructure deployment, which can help reduce the costs and help speed deployment of CCUS.
- **Drive full-scale CCUS projects in core industries (e.g. cement, EfW).** With several CCUS demonstration projects currently underway across Europe in the industrial and power sectors, the private and public sector in Ireland could seek to work together to leverage key technologies and learnings into full-scale projects or similar demonstration/pilot projects that seek to close the financial viability gap of CCUS.
- **Develop CO_2 transport and storage infrastructure.** policy that aims to identify the most likely clusters to support early deployment of CCUS and that begins strategic initiatives to drive economies of scale in infrastructure deployment in the medium to long term can bring about development. Other European countries have commenced similar initiatives.
- **Facilitate connections between CO_2 sources and sinks.** Policy can facilitate cooperation between industrial/power sites exploring CO_2 capture and CO_2 transport and storage infrastructure. By engaging with stakeholders exploring CCUS, policy can facilitate regional cluster-based or dispersed site projects, progressing investment decisions and aligning timeframes for infrastructure deployment.
- **Begin investigating frameworks and market mechanisms to incentivise CCUS and negative emissions.** This includes planning for the regulatory frameworks required to address cross-chain risks with CO_2 transport and storage infrastructure (e.g. CO_2 storage liabilities). Policy could also consider the mechanisms needed to support the additional operational costs of CCUS or remunerations aimed at awarding negative emissions from BECCS. The role of imported biomass and the associated sustainability requires careful consideration as part of this.

1 Introduction

Ireland's 2021 Climate Action and Low Carbon Development (Amendment) Act commits Ireland to reducing greenhouse gas emissions by 51% by 2030 and to achieving economy-wide carbon neutrality by 2050. This requires immediate emissions reductions in every sector. Energy used for heating and cooling accounts for 24% of Ireland's greenhouse gas emissions, but the current pace of decarbonisation falls short of the cuts required. Almost every sector of Ireland's economy uses heat energy, and decarbonisation efforts will need to be implemented by industry, businesses, and households. This requires a comprehensive, robust and actionable evidence base that policymakers and other stakeholders can use to make decisions.

The Sustainable Energy Authority of Ireland (SEAI) commissioned Element Energy and Ricardo Energy and Environment to work with SEAI on the National Heat Study to provide this evidence base. The study evaluates the costs and benefits of various pathways that reach net zero by 2050. We based the evaluation on a comprehensive understanding of heating and cooling demand in Ireland and the deployment costs, potential and suitability of technologies, infrastructure and fuels to reduce emissions.

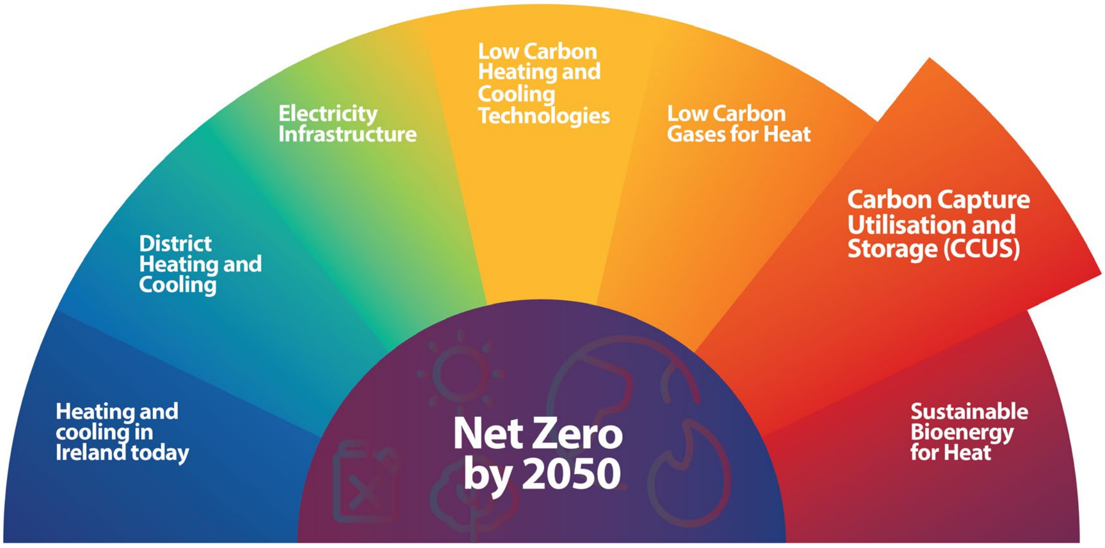
We have separated the insights and analysis from the study into eight reports (outlined in Figure 1). These reports provide a rigorous and comprehensive analysis of options for decarbonising heating and cooling in Ireland up to 2050. The findings support Ireland's second submission to the EU of a national comprehensive assessment of the potential for efficient heating and cooling, as required by Article 14 of the Energy Efficiency Directive.[9] There are seven major technical reports, each focusing on topics that form the overall analysis. The concluding report is called *Net-Zero by 2050: Exploring Decarbonisation Options for Heating and Colling in Ireland*[10]. It outlines the study's key insights across scenarios that achieve net-zero emissions from heating and cooling.

As shown in Figure 4 this report serves as a standalone document detailing the analysis carried out to determine the potential for carbon, capture, utilisation and storage (CCUS), including bioenergy with carbon capture and storage (BECCS), in Ireland.

[9] SEAI, 'Comprehensive Assessment of the Potential for Efficient Heating and Cooling in Ireland, report to the European Commission'. 2021 [Online]. Available: https://www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/#

[10] SEAI, 'Net-Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'. 2022 [Online]. Available: www.seai.ie/publications/Net-Zero-by-2050.pdf

Figure 4: Overview of the reports contributing to the National Heat Study



1.1 Objectives and scope of this report

This report provides an examination and quantification of the potential for CCUS in the Irish context. The report presents information gathered through literature review and stakeholder engagement on the potential, costs and challenges associated with CCUS in Ireland. Previous work carried out by SEAI in 2009 explored the potential and costs of CCS in Ireland [3]. We have gathered more recent data for this study to provide an updated analysis of CCUS (including BECCS).

The primary objectives of this portion of the National Heat Study are to:

- Characterise the sources of carbon emissions and options for storage and utilisation in Ireland and abroad.
- Understand CCUS projects currently under way.
- Develop technical potential scenarios for deployment of CCUS for use in the scenario modelling as described in the *Net Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland*[11] concluding report.
- Assess the status of BECCS in Ireland and internationally, evaluate its negative emissions potential and develop technical potential scenarios for its deployment to 2050.
- Discuss challenges and barriers to CCUS deployment in Ireland, and enabling policies and actions to mitigate these.

A detailed analysis of the role of CCS in the power sector is out of the scope of this study, which focuses primarily on heat demand. We included power sector assumptions at an appropriate level because of the influence that captured power sector emissions have on CO_2 transport and storage infrastructure costs. Power CCS sites may be located in or nearby shoreline clusters with offshore transport and storage networks, thereby contributing significant CO_2 volumes to achieve economies of scale for infrastructure deployment.

[11] SEAI, 'Net-Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'. 2022 [Online]. Available: www.seai.ie/publications/Net-Zero-by-2050.pdf

1.2 Relationship to overall modelling

This work feeds into the overall modelling work we are conducting as part of the National Heat Study. The modelling work examines four scenarios that reach net-zero emissions in the heat sector by 2050 and a business as usual baseline. The outputs from this work adds the detail on CCUS and BECCS deployment in each of the scenarios examined using SEAI's National Energy Modelling Framework (NEMF).

Each alternative scenario seeks to reflect a plausible pathway to a decarbonised heat supply to 2050, considering a variety of relevant factors including, but not limited to, the speed of transition, energy efficiency, heat networks, gas grid extent, level of CCUS/BECCS deployment, renewables deployment, power system considerations, transport system considerations and a mix of low-carbon technology uptake. The High Electrification and Decarbonised Gas scenarios intend to capture the two ends of the fuel switching options spectrum, in terms of the different potential pathways to heat decarbonisation. The Balanced scenario aims at a middle ground between these two, accounting for a technology mix that achieves an outcome that is cost-effective, feasible to implement, and aims to minimise the risk of over-dependence on any single technology. Finally, the Rapid Progress scenario reflects a future in which decarbonisation measures are achieved earlier (with a particular focus in the next ten years), allowing net zero to be achieved prior to 2050.

The deployment of CCUS and BECCS in each is a deterministic input to the NEMF model based on the outputs of the work and deployment trajectories described in this report. These trajectories apply CCUS to individual existing industrial sites along with consideration of potential power sector CCS deployment. The analysis assesses energy/fuel requirements, costs and emissions reductions from CO_2 capture on the relevant industrial sites, including costs related to CO_2 transport and storage. The deployment of CCUS and BECCS in each scenario aims to be consistent with the wider technology deployment choices in each scenario. For example, in the high electrification scenario more industrial sites switch to electricity so they no longer have on-site emissions to capture. Similarly, in the decarbonised gas scenario, sites that switch to hydrogen fuel also cease emitting greenhouse gases onsite.

Relationship to Overall Modelling

Scenario	Details
Baseline	Business-as-usual scenario where all sectors continue to use carbon-intensive practices.
	Limited deployment of heat networks, new technologies or fuel switching.
	Includes policy measures from the 2019 Climate Action Plan that had existing implementing measures such as funding and planning or legislation in place by the end of 2020.
	It does not achieve net zero by 2050.
High Electrification	Weighted towards electrification, coupled with minimal amounts of bio-derived gases, CCUS and green hydrogen.
	High levels of heat networks deployment and significant efficiency uptake.
	Achieves net zero by 2050.
Decarbonised Gas	Weighted towards green hydrogen use, CCUS infrastructure or bio-derived gases, or both, coupled with domestic and commercial fuel switching to green hydrogen or bio-derived gases, or both.
	Low levels of heat networks deployment and efficiency uptake.
	Achieves net zero by 2050.
Balanced	Progresses steadily and comprises a mix of cost-effective deployment of low-carbon technologies (electricity, bio-derived gases, green hydrogen).
	Medium level of industrial CCUS, heat networks and efficiency deployed.
	Achieves net zero by 2050.
Rapid Progress	Accelerated progress, driven by policy targets; all low-temperature applications are quickly electrified, while bio-derived gases are prioritised for industry sites.
	High levels of heat networks deployment and energy efficiency uptake.
	Achieves net zero by 2050.

High-level details of the Baseline and Scenarios examined

2 CCUS and BECCS potential in Ireland

2.1 Overview of key viability factors for CCUS

The potential for CCUS deployment across Ireland depends on several important factors that influence the technology's viability in a net-zero emissions future:

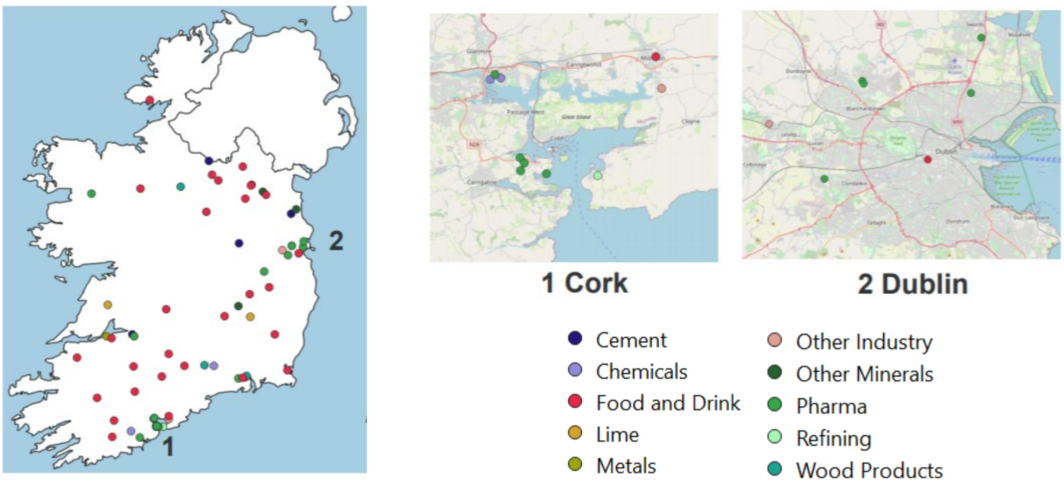
- Many industrial sectors (e.g. cement or refining) have process-based emissions which cannot be decarbonised by low-carbon fuel switching alone, requiring the adoption of CCUS technology for deep decarbonisation at sites within these sectors.
- Infrastructure development will be a key constraint for adopting CCUS at both industrial and power sites, particularly more dispersed sites, which will need assurance from infrastructure developers about downstream CO_2 transport and storage before committing to deploying CO_2 capture.
- Sites in or near to 'clusters' potentially have easier access to shared infrastructure (e.g. near shoreline terminals), helping to achieve economies of scale for build-out of infrastructure such as pipelines and shipping.

2.2 Potential CO_2 sources in the industrial and power generation sectors

In first defining the CCUS potential in Ireland, this study considered the industrial and power sector CO_2 sources for which CCUS may be suitable. Due to economies of scale involved in carbon capture technology, these are very likely to be restricted to the largest industrial sites within Ireland (0.1 to 1.2 $MtCO_2$/y emitted), which are included within the EU emissions trading scheme (EU ETS). We also assessed biogenic emission sources as opportunities for BECCS adoption, discussed in greater detail in the next section.

As shown in *Figure 5*, industrial emissions sources are widely dispersed across Ireland, which leads to challenges in developing CCUS infrastructure (explained further in *Section 2.5*). There are some clusters of industrial sites around Cork and Dublin, along with some shoreline clustering around Drogheda and at the Cork / Waterford border.

Figure 5: Map of industrial fossil-based emissions sources in Ireland by sector[12]



The most likely sites for CCUS adoption include those in cement and refining sectors, where CO_2 capture is one of the key technologies available to abate process-based emissions[13] and to achieve cost-effective economies

[12] This map does not show all industrial sites in Ireland, only those included in the EU ETS dataset (2019).
[13] 'By-product' emissions of CO_2 from chemical reactions within the industrial process which are unable to be abated by low carbon fuel switching.

of scale. Ireland has one refinery - Irving Oil Whitegate Refinery in the Cork cluster. There are also currently four cement plants across Ireland, three of which use partially biogenic fuel mixes, offering the potential for negative emissions via BECCS. These cement plants are largely dispersed, although one is near the Shannon Estuary and one near Drogheda, both of which offer the potential for reduced CO_2 transport costs due to their proximity to a potential shoreline terminal. While less likely, other industrial sectors have the potential to utilise CO_2 capture as an abatement measure. These sectors include lime, chemicals, food and drink, metals (alumina[14]), other minerals and wood products.

From the complete list of industrial sites shown in *Figure 5*, we made further assumptions to identify which sites were most suitable for CCUS:

1. We only took forward industrial sites emitting above 20 $ktCO_2$/y into the CCUS suitability assessment (based on emissions taken from the 2019 EU ETS dataset). This cut-off represents a minimum scale for which we assumed a full-scale CCUS plant would be potentially commercially viable.
2. We estimated the cost of carbon capture at each site based on the flue gas stream's concentration of CO_2 and the scale of the emissions at the site.
3. We calculated the cost of CO_2 transport and storage for each site, dependent on scale of emissions and site distance from shoreline terminals.
4. After arriving at an initial estimate for the levelised cost[15] of CCUS for each site, we excluded all industrial sites with levelised costs greater than €180/tCO_2 stored. Above this cost, we assumed other abatement options were more cost-effective than CCUS.[16]

These assumptions led to a final count of 16 industrial sites deemed potentially suitable for CCUS adoption.[17] We aligned CCUS adoption at these sites to each of the four different scenarios, which is discussed further in *section 3*.

In this study, we also assessed power sector sites for their potential application of CCUS. This included both fossil-fuelled power stations (i.e. peat, coal, natural gas) and energy-from-waste (EfW) facilities, shown in *Figure 6*. The scope of this study does not include a detailed focus on the power sector (i.e. no detailed abatement archetypes, site-specific assessment or cost breakdowns) and the analysis focuses on developing a representation of the additional volumes of CO_2 for transport and storage. We selected the power sector CCUS sites to achieve the approximate MWh of gas CCUS seen in literature [4], using the assumption that load factors do not change.[18]

[14] For the alumina sector, the calciners were assessed as the piece of equipment most likely to use carbon capture. However, carbon capture is potentially not the only abatement option as electrification or hydrogen technologies under development may offer a similar decarbonisation potential.

[15] A levelised cost is the average cost of the lifetime of the plant per MWh of electricity generated.

[16] Sites with significant process emissions of CO_2 were below this cut-off point.

[17] For reference, were the cut-off to have been €200/tCO_2 or €250/tCO_2, then 22 or 37 sites would have been considered for CCUS, respectively.

[18] If load factors were to decrease, additional power CCUS plants may be needed, but as this did not impact CO_2 volumes this was beyond the scope of the study.

Figure 6: Map of power stations and EfW facilities in Ireland

This resulted in five existing gas-fired power stations in Ireland which we deemed as potentially suitable for CCUS adoption. This included the Whitegate and Aghada Combined Cycle Gas Turbines (CCGTs), both situated in the Cork cluster, which we are also considering for CCUS adoption within the Cork CCS project. *Section 2.4* discusses the selection of power plants for BECCS (including EfW plants).

2.3 Industrial and power sector CO_2 capture

We based the technology and cost assumptions used in this study for industrial and EfW carbon capture plants on a UK study which has investigated the potential for CO_2 capture across different industrial sectors [5]. We took performance and costs parameters for biomass combustion with carbon capture from a recent study conducted for the UK Government's Department for Business Energy and Industrial Strategy (BEIS) [6].

The cost of carbon capture can vary widely depending on the technology used and a plant's specific operational factors. One of the most important considerations is the CO_2 content in the flue gas. Sites with a higher CO_2 content in their flue gas can typically be equipped with lower-cost technology to capture the CO_2. In addition, sites with large emissions sources can achieve greater economies of scale with CCUS, further reducing the cost of capture unit on site. This work also assumed a constant 95% capture rate based on recent studies from the International Energy Agency (IEA) which suggest that capture rates of 95% (and greater) are achievable [7] [8].

Table 3 shows a sample of carbon capture costs for the cement sector. This report's accompanying Excel spreadsheet provides the full set of carbon capture costs and technical parameters.

Table 3: Costs and energy requirements for carbon capture in the cement sector[19]

Technology	Capex (€/tCO_2)	Non-fuel opex (€/tCO_2)	Heating required[20] (kWh/tCO_2)	Electricity required[20] (kWh/tCO_2)
Calcium looping	17.2	16.6	122	92
First generation amines	21.4	33.0	1056	56

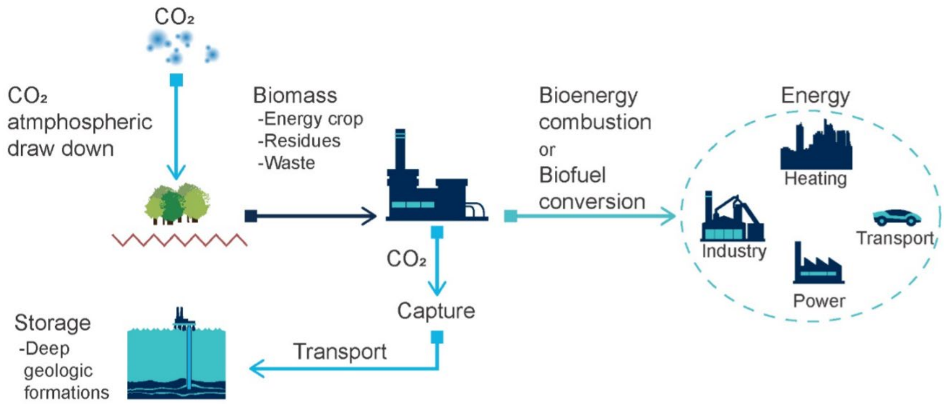
[19] Costs are in 2019 €. More information is provided in the accompanying Annex excel file. Capex and opex are levelised values (3.5% discount rate). Opex excludes fuel costs.
[20] Carbon capture plants require additional heating and electricity inputs due to the additional energy requirements for compressing flue gas streams, regenerating solvents, and running auxiliary equipment.

We incorporated post-combustion amine scrubbing technology (i.e. first-generation amines) into the analysis as the incumbent carbon capture technology.[21] We assumed the first year of availability to be 2025 across all sectors. Within the scenarios explored, the early adoption of CCUS was assumed to use/apply amine scrubbing We then selected calcium looping as a representative future carbon capture technology option, considering its potential to have lower pre-treatment, capex and heat requirements compared to first generation amine solvents across most sectors. We assumed that by 2035 calcium looping technologies begin operation and that they see the highest deployment across the scenarios out to 2050.

2.4 Opportunities for BECCS

Bioenergy with carbon capture and storage (BECCS belongs to a suite of technologies referred to as greenhouse gas removal (GGR) technologies.[22] Such technologies can remove carbon directly from the atmosphere and sequester it for a long time. Other prominent GGR options include biochar, direct air capture (DAC) and nature-based options such as enhanced weathering and afforestation [10]. BECCS is likely to be driven by the need to abate certain sectors which use biogenic fuels (e.g. cement or EfW plants) and to deliver verifiable, large-scale volumes of negative emissions.

Figure 7: Overview of BECCS process [9]



Opportunities to deploy BECCS exist across a range of applications. Sustainable biomass sources are derived from a variety of biological origins such as biogenic portions of organic waste, by-products and residues from forestry, and perennial energy crops such as short rotation coppice willow. These biomass fuels can be used in an array of applications which replace fossil-fuelled sources, from traditional thermal power generation to hydrogen production via gasification, EfW plants and industrial sites. BECCS results in negative emissions when downstream biogenic CO_2 originally captured from the atmosphere via plants is permanently stored in geological formations or utilised in processes which prevent it from re-entering the atmosphere over the long term.

A key driver for BECCS across the energy sector is to support the need to roll out negative emissions technologies. For Ireland to reach net zero emissions, it is likely that GGRs will be required to balance residual emissions from some of the most difficult to decarbonise sectors (e.g. agriculture, aviation, heavy industry). In the Irish context, up to 17.4 TWh of BECCS electricity generation have been deployed in whole systems energy models which achieve net zero by 2050 [4] [10]. While Ireland has the potential to scale up and deploy BECCS in the future, other GGR options are also potentially available.

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[21] Currently deployed in the Boundary Dam and Petra Nova CCS demonstration plants.
[22] Also referred to as negative emission technologies (NETs) or carbon dioxide removal (CDR) technologies.

The analysis completed in this study focuses on BECCS to generate negative emissions due to its higher potential for large-scale deployment in the industrial and power sectors. It has implications for CCUS on industrial emissions in Ireland, as it requires transport and storage of additional CO_2, leading to economies of scale in CO_2 transport and storage infrastructure development. For this study, we examined five key sectors for the potential application of BECCS technologies. *Table 4* summarises each sector along with the completed BECCS assessment (quantitative or qualitative).

Table 4: Description of potential BECCS sectors and their focus of assessment in this study

Sector	BECCS description	Assessment focus
Power Generation	• Biomass-fuelled power stations participating in the electricity market • Sources of biomass feedstocks can vary (e.g. combustion of wood pellets or biomethane) and be either produced in Ireland or imported	**Quantitative:** Considered power BECCS in Ireland as potential for new build dedicated biomass power generation with CCS
Energy from Waste (EfW)	• Incinerators which are principally responsible for waste management as a service (e.g. combustion of municipal solid waste), but also sell electricity produced • EfW plants typically have biogenic emissions due to the biogenic fractions of organic waste used as a feedstock	**Quantitative:** Considered EfW BECCS in Ireland for both new build plants and retrofits of existing plants with CCS
Industry	• Includes a range of potential industrial sites and sectors (with a focus in this study on the cement, wood products and food and drink sectors in Ireland) • Industrial biofuels include biogas, biogenic portions of waste feedstocks, and solid biomass fuels	**Quantitative:** Considered industrial BECCS in Ireland as existing industrial plants for CCS retrofits
Biogas Upgrading	• Anaerobic digestion facilities with biogas upgrading processes for biomethane production • CO2 volumes at biogas processing facilities are likely to be small scale compared with industry and power	**Qualitative:** Considering the low volumes and distributed nature of CO_2 from biogas upgrading, this CO_2 could be a potential candidate for CO_2 utilisation (qualitatively assessed)
Hydrogen Production	• Low-carbon hydrogen production via waste/biomass gasification technologies or biogas used in reforming • Future potential exists to apply CCS to the flue gas to achieve BECCS	**Qualitative:** We further assess hydrogen production methods in the *Low Carbon Gases for Heat*[23] report

For this study, we quantitatively assessed existing sites as part of the BECCS scenario development:

- **Power generation** - One new full-scale dedicated BECCS plant. Assumed to be sited in the Shannon Estuary in a similar location to the Moneypoint coal power plant closing in 2025.[24] We estimated total annual CO_2 emissions to be 8.1 $MtCO_2$/y, which is scaled down in select scenarios.[25]

[23] SEAI, 'Low Carbon Gases for Heat'. 2022 [Online]. Available: www.seai.ie/publications/Low-Carbon-Gases-for-Heat.pdf
[24] Recent plans announced at the end of this study have outlined that the Moneypoint generating station site is set to be transformed into a green energy hub [11].
[25] Based on Ricardo's previous analysis for BECCS at the Shannon Estuary.

- **Energy from waste** – Two existing EfW plants retrofitted with CCUS technology[26] and one additional new build EfW plant with scale and location similar to the proposed Ringaskiddy incinerator.
- **Industry** – All four of the currently operational cement plants which were analysed, along with five plants in the wood processing and food and drink sectors.

In the Irish cement industry, there is likely potential for increased biogenic fuel uptake. High levels of biogenic fuels are based on current testing ongoing in UK and Germany for fuel switching in cement kilns. This approach varied across each scenario (see *section 3.1*).

2.5 CO_2 transport and storage

Following the capture of CO_2 from industrial and power sites, CO_2 must be transported to CO_2 storage or utilisation locations. *Table 5* highlights the distinct options for onshore and offshore CO_2 transport and storage identified and considered in this study with the potential to develop across Ireland.

Table 5: Onshore transport options (left) and offshore transport and storage options (right) for Ireland

Onshore transport options (site to cluster point / terminal)		Offshore travel and storage options			
Trailer	Dedicated pipelines (onshore)	Dedicated pipelines (offshore) including repurposing	Shipping	Offshore storage (Ireland)	Offshore storage (International)

Recent UK studies investigating CCUS deployment at dispersed industrial sites and modelled CO_2 shipping costs informed assumptions for CO_2 transport, including trailer, pipeline and shipping [12] [13]. Transport costs are particularly sensitive to two key factors: CO_2 demand and location. The amount of CO_2 demand (typically referred to in megatonnes of CO_2 per annum or $MtCO_2/y$) plays an important role in determining the size requirement of CO_2 pipelines. The project team estimated the location of the CO_2 source relative to its final storage or utilisation destination with straight-line transport distances in kilometres.

It is unlikely that the development of onshore transport options will be the constraining factor for deployment of CCUS in Ireland. While permitting onshore pipelines can be a long process, trailers can be available in reasonable lead times (i.e. less than 4 years). Rather, the technology readiness of carbon capture and the availability of downstream transport and storage infrastructure at a site will be the key constraints for adoption of CCUS abatement. For instance, previous studies have estimated lead times for CO_2 shipping infrastructure to be around 5 to 7 years [14]. This has informed assumptions in this study around the earliest availability of offshore transport and storage to the late 2020s or early 2030s. In practice, cost and geographical constraints will play a key role in determining which options are most likely for each site (e.g. potential to repurpose existing assets such as natural gas pipelines and depleted gas fields). For instance, a previous study informed an estimate of €12/tCO_2 storage cost for the offshore Kinsale gas field with a total potential storage capacity of 330 Mt [15]. In addition, there would be approximately 50 km of offshore pipeline required from Cork to Kinsale [3], at an additional estimated €2/tCO_2.

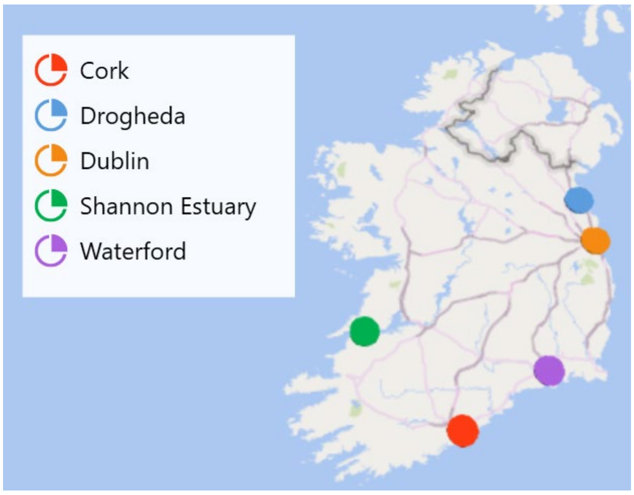
[26] Dublin and Meath sites with total CO_2 emissions of approximately 1.3 $MtCO_2/y$ based on 2019 EU ETS data.

In this study, we considered the storage of CO_2 internationally, particularly in nearby European states. Examples include the Northern Lights project in Norway [16], Acorn project in Scotland [17], HyNet project in Merseyside (England) [18] and the Porthos project in the Port of Rotterdam (Netherlands) [19]. Commercialisation horizons for these international projects are aiming for operations to begin as early as 2024-2025. We also assume the timeline for offshore transport and storage operation at the Cork cluster could be in the mid-2030s, but export of CO_2 internationally may begin prior to this.[27] Therefore, the development of Irish CO_2 T&S port infrastructure is likely to be a constraining factor for international shipping.

Offshore transport and storage costs for international storage are highly uncertain due to the range of storage cost estimates from the project developers mentioned previously. These range from as low as € 21/tCO_2 for Acorn's first shipping imports [20] and as high as €87/tCO_2 for Northern Lights' demonstration phase [21]. For this study, we assumed a central cost estimate, starting with costs of €45/tCO_2 in 2025 and reducing to €30/tCO_2 by 2050.[28]

This study has identified five key shoreline terminals which could receive CO_2 for further offshore transport and storage (shown in Figure 8). The Cork terminal serves as a potential strategic location as it offers direct access to an Irish CO_2 storage reservoir. The Cork CCS project aims to repurpose existing infrastructure in the area to connect a pipeline from the Inch Terminal to the offshore Kinsale gas field. The other four shoreline terminals could utilise CO_2 shipping to Cork or internationally, which we define under each scenario in *section 3*. We selected each of the cluster points based on their existing potential to upgrade port infrastructure and the clustering of industrial and power sites close to the terminals themselves.

Figure 8: Location of five potential CO_2 shoreline terminals in Ireland



2.6 CO_2 utilisation

This study also examines at a high level the potential for CO_2 utilisation (CCU) in Ireland. We consider two CCU options which offer the potential for large-scale deployment – synthetic fuel production and CO_2 curing in the refining and cement sectors, respectively. *Table 6* provides brief descriptions of each option, their potential timeframe for deployment in Ireland and the assumptions for integrating each CCU option into the scenario analysis.

Note that this study does not investigate the costs of each CCU option in detail. Current costs are highly uncertain and variable across sources, with some CCU options achieving market cost-competitiveness today

[27] Assumption supported by stakeholder engagement in this study.
[28] These cost assumptions were also benchmarked against international shipping cost estimates provided by stakeholders in this study.

(e.g. CO_2 curing), whereas others come at a significant cost premium to conventional fossil-based products (e.g. synthetic aviation fuel production relative to current-day jet fuel production).

Table 6: CO_2 utilisation options considered for large-scale deployment in Ireland

Sector	Description	Timeframe[29]	Analysis assumptions
Refining	**Synthetic fuel production:** using Fischer-Tropsch (F-T) synthesis for the production of aviation fuels	Late 2030s or early 2040s due to low TRL	• Synthetic fuel production volumes assumed to vary across scenarios, benchmarked against current Irish demand for aviation fuels[30] • CCU volumes assumed to be sourced from the Cork terminal to be used at the Whitegate Refinery
Cement	**CO_2 curing:** to accelerate carbonation in conventional concrete production, allowing less cement to be used in the process	Late 2020s or early 2030s due to high TRL[31]	• Concrete curing volumes to vary across scenarios, benchmarked against current Irish cement production volumes[32] • Calculations determined the reduction in cement production required as a result of concrete production material efficiency gains

There are other CCU opportunities which offer potential in Ireland that we do not investigate in detail in this study (classification of potential CCU pathways shown in *Figure 9*). Small-scale methods could, for instance, link to existing CO_2 uses in industry, such as in the food and drink, chemicals and pharmaceuticals sectors. Another opportunity exists in the construction sector for producing aggregates and other building materials. For example, technology is available that can convert waste materials into carbonate aggregates.[33] We would need to investigate the CCU options in Ireland in more detail to better understand the full potential of its uptake across the country.

[29] Timeframe for deployment based on assumptions of a CO_2 utilisation option's technology readiness level (TRL), which defines the technical maturity of a technology throughout its development lifecycle

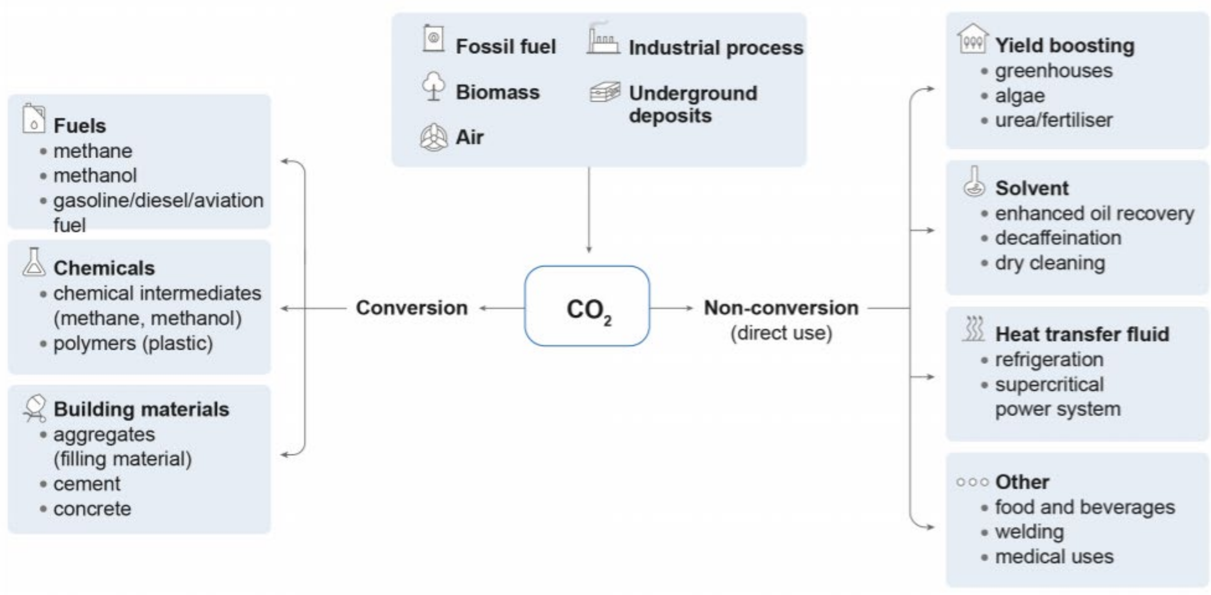
[30] Aviation fuel demand in Ireland is approximately 1Mt/annum [22].

[31] For example, CarbonCure is one start-up which has already successfully commercialised this technology. Other organisations active in this space include Solidia, Carbicrete and Carbstone Innovation.

[32] Current cement production volumes in Ireland were estimated to be 6.1 Mt/annum. This was calculated based on current ETS emissions and an assumed emissions intensity of concrete [23].

[33] Carbon8 is a UK-based company which has developed an accelerated carbonation process [24].

Figure 9: Classification of potential CCU pathways [25]



3 Deployment scenarios

3.1 Methodology

We developed the four scenarios for this study across all workstreams to align with a possible future pathway to net zero by 2050. *Table 7* provides a qualitative description of the differences between the role of CCUS and BECCS across each scenario. The table also provides additional descriptions of the power and industrial sector as reference for the implications of the CCUS and BECCS adoption. The last row describes the assumptions that were incorporated into fuel switching in the cement sector in Ireland.

Table 7: Qualitative description of the differences between CCS, BECCS and fuel switching deployment in each scenario

Category	Decarbonised Gas	High Electrification	Balanced	Rapid Progress
BECCS	• High BECCS in power • Medium-high BECCS in industry	• Limited BECCS in power • Limited/no BECCS in industry	• Medium BECCS in power • Medium BECCS in industry	• Medium BECCS in power • High BECCS in industry
Fossil CCUS	• Highest level of industrial CCUS • High CCUS in power	• Later & limited scale industrial CCUS • Very limited CCUS in power	• Core large industrial sites • Small amount of power CCUS	• Medium industrial CCUS (and earlier) • Limited CCUS in power
Power (reference for power CCUS implications)	• Comparatively lower renewables deployment (still high, but lowest of scenarios) • Largest role for thermal generation • Some baseload biomass/BECCS	• High renewables deployment, with minimal role of thermal generation in power	• Balanced, middle ground for renewables/thermal • High renewables deployment • Some role for thermal peaking generation	• Rapid renewables deployment in line with High Electrification • Medium role for BECCS in power
Industry (reference for industrial CCUS implication)	• High share of industrial processes using low-carbon gas • Lower efficiency improvements	• Low-temperature applications nearly all electrified • Some H_2/CCS for high-temperature applications • High efficiency improvements	• Low-temperature applications mostly electric • Biomethane or H_2 at core sites (high-temp, non-CCS), or both • Medium efficiency improvements	• Low-temperature applications nearly all electrified (low cost electricity) • H_2 used for rapid retrofit and targeted • High efficiency improvements

Fuel switching in cement sector	• Continue with current fuel mixes	• Increase to a high level of biogenic fuel	• Increased to a medium level of biogenic fuel[34]	• Increase to a high level of biogenic fuel[35]

The scenarios vary considerably in the amount of CCUS deployed, reflecting a range of probable levels for the development of CCUS in Ireland. The High Electrification scenario represents the lowest level of CCUS deployment based on adoption across key industrial sectors and limited CCUS uptake in the power sector. Conversely, Decarbonised Gas represents the highest level of CCUS deployment, with ambition to roll out CCUS across a wider range of industrial and power sites. In this analysis, the Decarbonised Gas scenario does not represent a necessary upper range of CCUS for deployment for Ireland to decarbonise the industrial or power sectors, as many of the sites which select CCUS in this scenario could decarbonise through alternative low-carbon fuel switching options. For example, you could assume levels of CCUS similar to the Decarbonised Gas scenario in a scenario with greater electrification of heat.

Assumptions for the breakdown of CCUS and BECCS deployment by 2050 in each scenario are in *Table 8* and CO_2 utilisation assumptions in *Table 9*. The scenarios contain significant differences in the levels of negative emissions provided. This reflects the range of estimates of negative emissions potentially needed via BECCS in Ireland. Scenarios with lower BECCS would need either increased negative emissions from other technologies (land-based solutions or engineered removals), or higher levels of effort in other economy sectors to reach the same levels of net emissions.

Table 8: Breakdown of CCUS and BECCS deployment by 2050 in each scenario

Scenario	Decarbonised Gas	High Electrification	Balanced	Rapid Progress
Number of industrial sites with CCUS	16 sites	3 sites	8 sites	11 sites
Industrial emissions captured	4.5 $MtCO_2$	2.4 $MtCO_2$	3.7 $MtCO_2$	4.3 $MtCO_2$
Number of EfW and power BECCS Sites	4 sites	1 site	6 sites	4 sites
EfW and BECCS power emissions captured	9.2 $MtCO_2$	0.3 $MtCO_2$	5.4 $MtCO_2$	5.4 $MtCO_2$
Number of gas power sites with CCUS	5 sites	0 sites	2 sites	1 site
Gas power emissions captured	3.2 $MtCO_2$	0 $MtCO_2$	1.3 $MtCO_2$	0.9 $MtCO_2$

[34] Fuel consumption becomes: 40% biowaste, non-biowaste increased to 20% (or remains the same if already higher), remainder solid fossil fuels.
[35] Fuel consumption becomes: 50% biowaste, 25% non-biowaste and 25% other biomass.

Total emissions captured	**16.9 $MtCO_2$**	**2.7 $MtCO_2$**	**10.4 $MtCO_2$**	**10.5 $MtCO_2$**
Total negative emissions (portion of captured emissions)[36]	**9.0 $MtCO_2$**	**0.8 $MtCO_2$**	**5.1 $MtCO_2$**	**6.0 $MtCO_2$**

Table 9: Assumptions for CO_2 utilisation across the four scenarios

CO_2 utilisation method	Benchmark / Metric	Decarbonised Gas	High Electrification	Rapid Progress	Balanced
Synthetic fuel production	% current aviation fuel demand	30%	0%	20%	10%
	CO_2 utilisation volumes (Mt/y)	0.98	0	0.65	0.33
CO_2 curing	% cement production	30%	0%	20%	10%
	% reduction in cement emissions	1.8%	0%	1.2%	0.6%

Rationales for key assumptions under each scenario are as follows:

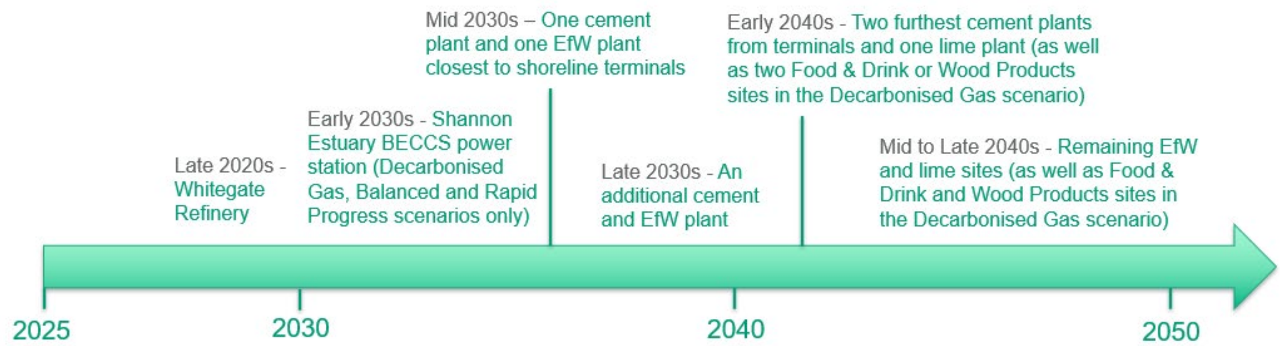
- **Balanced:** Steady build-out of CCUS and BECCS across the Irish economy. Industrial sites select a greater portion of abatement via electrification and hydrogen options, particularly in the alumina, wood products and food and drink sectors, which do not have the potential to adopt CCUS due to limited infrastructure availability. BECCS in the power sector plays a concentrated role in three EfW plants and a moderate build-out of dedicated biomass generation at one location.
- **Decarbonised Gas:** This scenario has the lowest level of renewables deployment for electricity generation. This leads to a greater dependency on baseload power generation, particularly from BECCS but also CCUS deployed as retrofits on existing gas-fired stations. The large-scale deployment of CCUS and BECCS in the power sector results in the expansive roll-out and cost reductions of CO_2 transport and storage infrastructure. This also enables the greatest roll out of CCUS/BECCS across the industrial sector of all four scenarios.
- **High Electrification:** CCUS plays a limited role in this scenario. Renewables and storage dominate the power sector, with no gas CCUS and BECCS limited to a single EfW plant. We assume that other EfW plants could still exist in 2050 in this scenario with their remaining emissions offset by negative emissions sources. The industrial sector sees no activity in CO_2 utilisation due to limited infrastructure availability and CCUS is limited to only a few plants in the cement sector.
- **Rapid Progress:** Similar in the scale of the roll out of CCUS/BECCS in the Balanced scenario, although at an accelerated/earlier pace. Innovation drives further deployment of CO_2 utilisation than

[36] Negative emissions from BECCS. These are derived from the biogenic portion of emissions which are captured from power BECCS, industrial BECCS (e.g. cement) and EfW BECCS plants.

the Balanced scenario, and the earlier development of CO_2 T&S infrastructure enables a few more industrial sites to adopt cost-effective CCUS abatement.

Figure 10 outlines likely relative timing of CCUS deployment at key industrial and power sites. The exact timing of deployment varies across each scenario. CCUS deployment is likely to begin with the largest sites to drive down economies of scale for CO_2 transport and storage. The assumptions for the roll out of CCUS start with the possibility of deployment in the refining sector in the late 2020s, then driven by deployment of large-scale power BECCS and CCUS retrofits on cement and EfW plants in the 2030s. Note that this timeline is illustrative and reflects only one possibility of deploying CCUS in the coming decades.

Figure 10: Relative timing of assumed CCUS deployment at industrial and power sites in Ireland

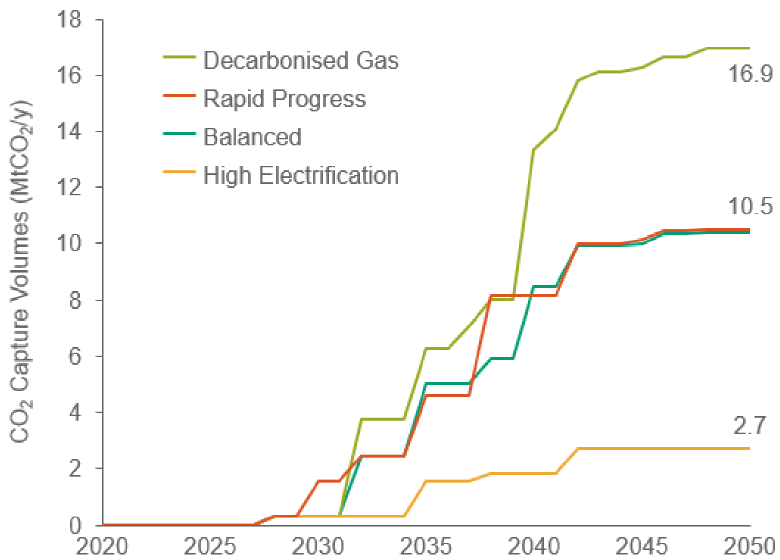


3.2 Deployment scenarios

3.2.1 Overview of CCUS deployment

Figure 11 indicates the scale of CCUS deployment across each scenario, showing CO_2 capture volumes from all sites which utilise CCUS (including BECCS) in the power and industrial sectors. This includes CO_2 captured from both fossil and biogenic emission sources.

Figure 11: CO_2 capture volumes in each scenario over time



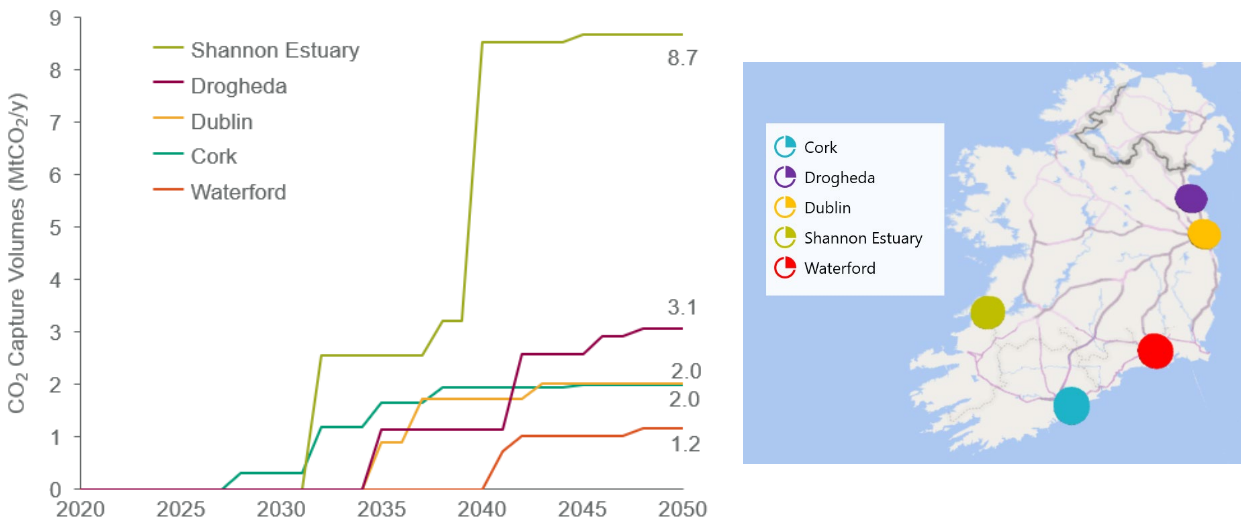
Across all scenarios, we assume that any large-scale deployment of CCUS (i.e. greater than 0.5 $MtCO_2/y$) will begin in the 2030s. This is due to the early stage of planning of CCUS infrastructure in Ireland, coupled with the long lead times to develop new CCUS infrastructure, particularly around the availability of CO_2 shipping, either domestically or internationally. In addition, domestic offshore storage sites (i.e. Kinsale gas field) are unlikely to be available before 2030.[37] Carbon capture adoption constrains the roll out of CCUS at sites. We assume the majority of the increase in CCUS uptake will occur in the mid-to-late 2030s as larger sites (i.e. refining, cement) initiate build-out of the transport and storage network. By the 2040s, smaller sites, which are mainly industrial users in the wood products, lime, and food and drink sectors, can connect to this network and adopt carbon capture.

The largest increase in CCUS deployment occurs due to an assumed dedicated BECCS plant in the Shannon Estuary. For example, in the Decarbonised Gas scenario, we assume it to be a full-scale plant (approximately 8 $MtCO_2$/y) which has CCUS deployed on one out of three boilers in 2032 and the remaining two boilers in 2040.[38] We attribute additional large increases in CCUS deployment to full-scale adoption at cement and EfW plants (approximately 1 $MtCO_2$/y for the largest plants).

3.2.2 Results for shoreline terminals

In a high-CCUS scenario, we assume that all proposed terminals could source significant CO_2 volumes. *Figure 12* displays the results of the Decarbonised Gas scenario's amounts of CO_2 received at each of Ireland’s shoreline terminals defined in this study. These volumes represent the captured volumes of CO_2 from all industrial and power plants in Ireland, broken down by the terminal which receives CO_2 from onshore sources. Across all scenarios, sites select CO_2 transport to the nearest distance available terminals.

Figure 12: CO_2travel and storage volumes at each Irish shoreline terminal (Decarbonised Gas scenario)



Given the scale of the dedicated BECCS plant assumed at the Shannon Estuary, this terminal would see the greatest transport and storage volumes. The CO_2 from the Shannon Estuary terminal would either be shipped internationally or to the Cork terminal for offshore storage in Ireland (if available). By 2050, we assume all other terminals will have volumes of 1-3 $MtCO_2$/y, significant scales which will help reduce the costs of offshore transport and storage. The deployment of CCUS begins at the Cork terminal, with the Whitegate Refinery assumed to adopt CCUS in 2028.

3.2.3 Negative emissions and net emissions

The scenarios include differences in the levels of negative emissions provided to reflect the range of estimates of negative emissions that BECCS could deliver. Scenarios with lower BECCS would need either increased negative emissions from other technologies (i.e. land-based solutions such as afforestation, or

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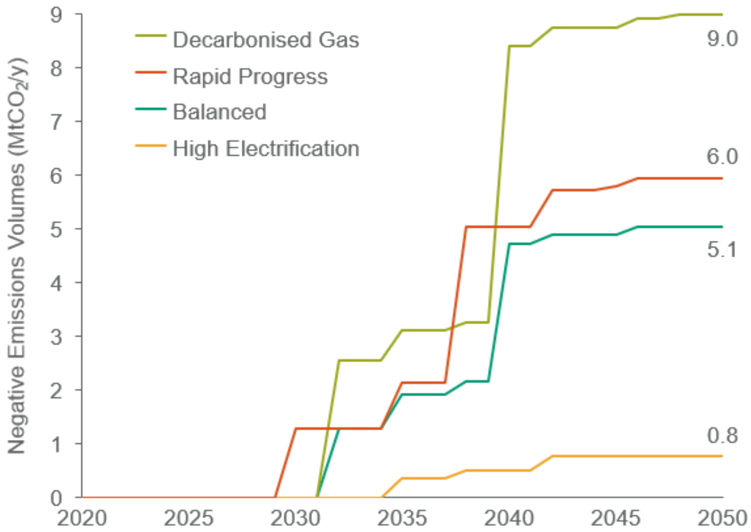
[37] Year informed from stakeholder discussions and Cork CCS Project Overview [26].

[38] This is assumed to be a 50% at-scale plant (approximately 4 $MtCO_2$/y) in the Rapid Progress and Balanced scenarios. Estimates for the Shannon Estuary BECCS plant are based on Ricardo's 2020 analysis of a dedicated BECCS plant at the current location of the Moneypoint generating station.

other engineered removals such as DAC), or higher effort in other economy sectors to reach the same levels of net emissions.

Figure 13 shows the negative emissions from all industrial and power plants in Ireland. The dedicated BECCS plant at the Shannon Estuary accounts for most of these emissions – approximately 8 $MtCO_2/y$ in the Decarbonised Gas scenario, and approximately 4 $MtCO_2/y$ in the Rapid Progress and Balanced scenarios by 2050. Other significant sources of negative emissions include Cement and EfW plants; however, there are fewer negative emissions from these sources which have less CCUS deployed in High Electrification.

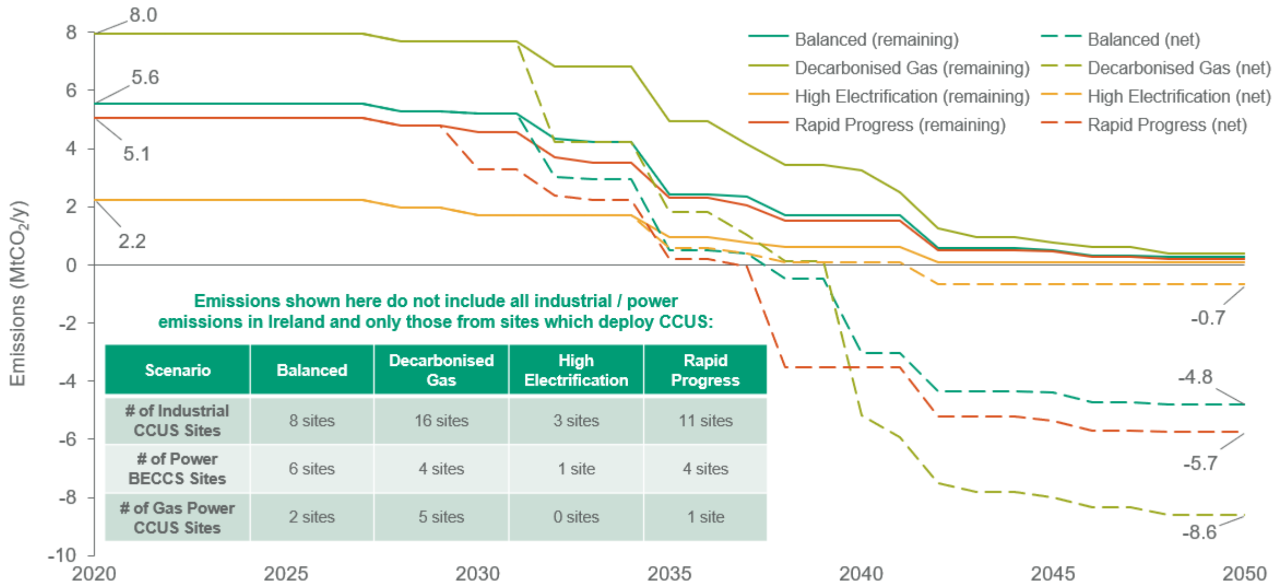
Figure 13: Negative emissions volumes (from industrial and power BECCS) across each scenario



All remaining emissions from industrial and power sites which select CCUS or BECCS abatement we assume to be offset by negative emissions by the early 2040s, as shown in *Figure 14*. In these scenarios, remaining emissions will come from the unabated portion of fossil/process emissions after applying CO_2 capture (95% capture rate assumed in this study, refer to *section 2.3* for further justification). We calculate net emissions by accounting for the negative emissions from industrial and power BECCS (i.e. subtracting negative emissions from the remaining emissions in each year). Each scenario reaches net zero emissions by the mid-2030s to early 2040s. In this case, this is just for the relevant sites (i.e. those where CCUS is applied in each scenario)[39] and not a sector- or economy-wide net zero analysis.

[39] Sites where CCUS is not applied are not included in this analysis, as these will be selecting other abatement options (e.g. industrial sites selecting hydrogen or electrification abatement technologies).

Figure 14: Remaining and net emissions from all industrial and power sites abated by CCUS or BECCS



Scenario	Balanced	Decarbonised Gas	High Electrification	Rapid Progress
# of Industrial CCUS Sites	8 sites	16 sites	3 sites	11 sites
# of Power BECCS Sites	6 sites	4 sites	1 site	4 sites
# of Gas Power CCUS Sites	2 sites	5 sites	0 sites	1 site

4 Challenges and opportunities

4.1 Challenges

The deployment of CCUS and BECCS in Ireland currently faces several technical, commercial and economic challenges. While CO_2 capture technologies are technically feasible today (e.g. amine absorption systems) and could achieve the necessary capture rates for deep decarbonisation, hurdles still exist in key sectors. For instance, further trials in industrial sectors (e.g. cement or lime) or in EfW plants are still needed to ensure developer and investor confidence in CCUS/BECCS technologies. Globally, across the industry and EfW sectors, there are promising developments underway. Norway's Northern Lights project aims to have a full-scale CCUS equipped EfW and cement plant by 2024 [27]. However, there are only a few operational EfW demonstration plants worldwide (e.g. Japan) with several under development in the Netherlands [28]. Should Ireland seek to develop a domestic CCUS capability, there are opportunities to learn from these demonstrations and to consider similar demonstrations or trials in Ireland.

In the power sector, similar momentum is building around the deployment of large-scale BECCS facilities. Currently the largest power BECCS plant globally, the demonstration-scale BECCS Mikawa Power Plant (50 MW) in Japan began operations in late 2020, now capturing 500 tons of CO_2 a day [29]. In the UK, the Drax power plant has been operating a pilot BECCS project with C-Capture since early 2019 and started a second pilot project with Mitsubishi Heavy Industries in late 2020. Drax envisions a full-scale BECCS plant is achievable by 2027. If Irish policy considers power BECCS as a pivotal option for both delivering baseload low-carbon power generation and significant quantities of negative emissions, then early investigation into the optimal deployment timescales and siting of a plant should begin in the 2020s.

The deployment of CCUS and BECCS in Ireland is further shaped by several Irish-specific factors. These include:

- **Large industrial sites in Ireland are relatively dispersed.** For example, this study identified that sites in the cement sector were typically greater than 50 km away from the nearest shoreline terminal.[40] This dispersed nature of industrial sites (including some power sites) increases the costs of the full-scale CCUS or BECCS chain. The onshore transport of CO_2 via pipeline or trailer delivery, while technically feasible at such large distances, faces challenges around planning and permitting processes. Recent studies for deploying CCUS at dispersed sites in the UK suggest these challenges are not insurmountable, but require early planning and coordination between the Government, project developers and infrastructure operators [12].
- **Ireland has limited accessible domestic CO_2 storage sites.** The Cork CCS project has proposed to utilise the Kinsale gas field for CO_2 storage; however, uncertainty still exists around the plans for the development of offshore transport and storage infrastructure in this region. Investigations are also underway to develop CO_2 shipping infrastructure from the Cork terminal. This would enable Ireland to export CO_2 internationally, most likely to Europe as the market for transboundary CO_2 shipping develops (e.g. projects underway across Norway, Netherlands or UK). If prioritised as Ireland's preferred offshore CO_2 transport and storage option, this could be available before any domestic development begins.
- **Ireland has yet to develop business models or regulatory frameworks to support the deployment of CCUS or BECCS**. In particular, careful consideration could be given to the regulatory framework that could be designed for CO_2 transport and storage. Addressing the viability gap will also need to be considered for the deployment of CO_2 capture at sites. One example is the UK's proposed contract-for-difference (CfD) model for industrial CCUS, which is discussed further in *Box 1*.

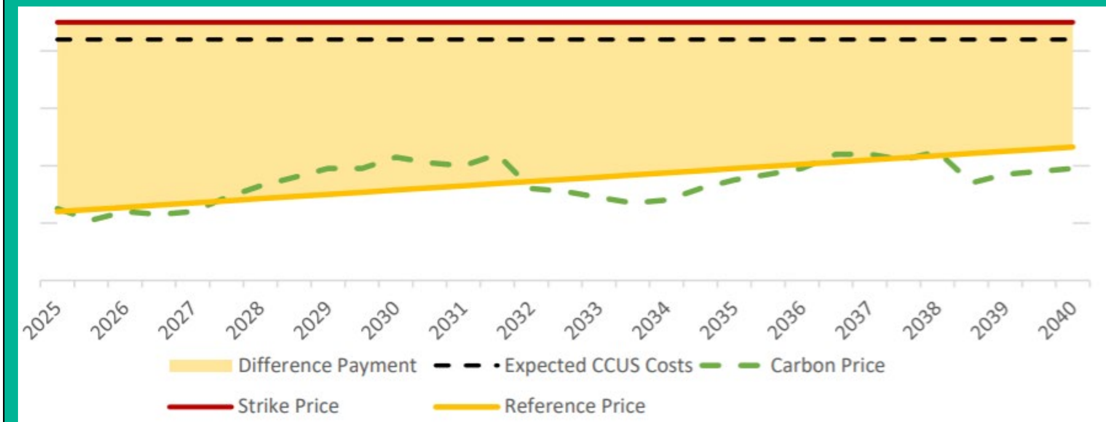
[40] In the Decarbonised Gas and Rapid Progress scenarios, only one cement site was approximately 6km from the nearest shoreline terminal.

Box 1: CCUS business models in the UK (focus on industrial CfD)

In December 2020, the UK Government provided updates on business models for CCUS [30]. This update included details on the CO_2 transport and storage regulatory model, the dispatchable power agreement for gas power CCUS, and the contract-for-difference (CfD) for industrial CCUS.

For industrial CCUS, the UK Government is aiming to implement a CfD financing mechanism combined with an upfront grant in 2022. The upfront Government co-funding would help finance the capital costs of constructing the CO_2 capture plant, along with a CfD to provide revenue support over an agreed operational duration of the capture plant. The Government selected the CfD based on its potential to provide high revenue certainty for the industrial site, along with value of taxpayer money spent. A contractually agreed-upon strike price per tonne of CO_2 abated would be defined, however further investigations are ongoing to determine appropriate reference prices and benchmark emissions. The CfD financing would cover the project's operational capture costs (this will include fuel costs), the capex investment for the project and CO_2 T&S infrastructure costs. Figure 15 depicts the payment mechanism from the UK's industrial CfD.

Figure 15: Industrial CCUS business model [30]



There are also sector-specific risks faced by the development of CCUS/BECCS in both the power and industrial sectors. This report has discussed some, including CO_2 transport and storage availability and costs, CCUS costs for dispersed sites, and the high capital costs and immature technology deployment of carbon capture. Within specific sectors there are important risks that need to be considered for any future policy support for CCUS or BECCS. *Table 10* outlines these risks for the three key sectors that were quantitatively assessed as part of this study.

Table 10: Risks and challenges impacting the key CCS/BECCS sectors in Ireland identified in this study

Sector	Risks and challenges
Power Generation	• Biomass-fueled power stations participate in the wholesale electricity market and are subject to the risks associated with revenue from this market over time. • There is a high range of uncertainty for biomass costs, due to a wide range of feedstocks and suppliers, varying between imports versus domestic production. The sustainability of imported biomass requires careful consideration, with robust lifecycle emissions reporting and regulations in place to limit unsustainable biomass sources from being imported (described further in the *Sustainable Bioenergy for Heat*[41] report). • Uncertainty of plant dispatch could be a key risk. Ideally, a BECCS power station should run baseload to maximise the negative emissions potential of the plant (if deemed the most valuable service to society). However, this load profile could vary considerably in a high renewables' grid.
Energy from Waste	• Waste feedstock availability and variability are key risks for the long-term operation of EfW facilities in various regions. Planning around the required levels of waste removal in Ireland and guarantees around the gate fees[42] associated with the collection of waste are possible strategies to provide greater revenue certainty to mitigate this risk. • Public acceptability concerns, particularly around air pollution, may hinder the investment in, and development of, new EfW plants.
Industry	• Carbon leakage is the most salient risk associated with decarbonisation of industry. Carbon leakage refers to the situation that may occur if, due to costs related to climate policies, businesses were to transfer production to other countries with lower emission constraints, thereby leading to an increase in their emissions. • Investments in new industrial sites or abatement technologies may also face greater difficulty financing due to the shorter payback periods required.

4.2 Options for developing CCUS in Ireland

Overcoming the challenges posed in the previous section may require a suite of policy, market and regulatory measures across the full CCUS chain. This section provides a high level outline of the options available for supporting a nascent and growing CCUS sector in Ireland. We have also included examples which cover some of the existing and potential CCUS policies and business models being explored worldwide, such as capital support, carbon pricing, operational subsidies and market-based mechanisms.

Driving CCUS adoption with carbon pricing or market-based mechanisms

Carbon pricing aims to incentivise abatement across various sectors of the economy. The EU ETS in Ireland covers both industrial and power sectors in this manner. However, carbon pricing schemes do not inherently incentivise CCUS specifically. If CCUS is the only or most cost-effective abatement option, emitters may still require other avenues of support to reduce the burden of capital costs for adopting retrofit CCUS technology and the additional operational costs associated with CO_2 capture. These operational costs primarily include fuel costs (or reduction in plant energy outputs) as well as CO_2 transport and storage fees.

In the future, carbon pricing schemes could similarly incentivise negative emissions technology deployment, such as BECCS. In its current form, the EU ETS Directive does not contain any legal basis for generating CO_2

[41] SEAI, 'Sustainable Bioenergy for Heat'. 2022 [Online]. Available: www.seai.ie/publications/Sustainable-Bioenergy-for-Heat.pdf
[42] A gate fee is the charge levied upon a given quantity of waste received at a waste processing facility (e.g. in € per tonne waste).

removal credits. Integrating CO_2 removal into the EU ETS is likely to require challenging fundamental amendments of the ETS Directive, waiving the currently mandatory association of emitting activities to the adoption of emission abatement technologies. For this reason, implementation of the evolution of carbon pricing markets with negative emissions is unlikely to be within the next decade. As such, the Government could consider other policy mechanisms to incentivise deployment of BECCS in the 2020s and early 2030s.

Ongoing work is investigating different market-based mechanisms for their potential to incentivise CCUS or BECCS; however, to date, no such functioning markets exist (excluding carbon pricing markets which indirectly support adoption of CCUS or BECCS). One prominent example is a compliance market with obligations to purchase negative emissions credits (e.g. from BECCS plants). Regulatory mandates can require certain emitters to offset their emissions, such as upstream fossil fuel producers to dispose of a fixed percentage of the CO_2 contained within their fuel sales, or large emitters from other sectors such as aviation or maritime. Supply and demand would drive a market-based emissions price (in €/tCO_2). Initial entrants selling credits are likely to be engineered removals (e.g. BECCS) or land-based options (e.g. afforestation, habitat restoration) which have reliable accounting methods for the amount of CO_2 removed. Over time, the market liquidity could increase with the inclusion of other greenhouse gas removal options.

Addressing the near-term financial viability gap of CCUS

Tools which governments can use to help reduce risk associated with CCUS and BECCS development include providing capital grants or other financial support to lower the cost of capital. In addition, grant funding could drive advances in research and innovation for CO_2 capture technologies, or be used to support pilot and demonstration projects in sectors with nascent development to date (e.g. cement or EfW). Another similar support mechanism is the provision of loan guarantees, which reduce the risk to debt providers and lower the cost of capital for new build plants.

Directing funds to initiate strategic deployment of CCUS in clusters may achieve economies of scale in the medium to long term by driving down initial costs of transport and storage infrastructure. For example, the UK's new CCS Infrastructure Fund (£1 billion) plans to deliver on the promise of deploying CCUS in at least two industrial clusters, with the aim to have one in the mid-2020s and a second by 2030.

Operational subsidies are another tool which aim to drive down costs of low-carbon technologies and are being increasingly considered for their inclusion or adaptation to CCUS technologies. As discussed in*Box 1*, the UK's CfD scheme is being developed for industrial CCUS, which plans to use a benchmark price following the carbon price trajectory over time, with the subsidy paid above this amount to cover the additional costs of adopting CCUS.

Another prominent example in Europe is the SDE++ mechanism in the Netherlands, which applies to a range of CO_2 reducing options including CCUS [31]. For each technology option, the 'operating shortfall' is subsidised. This shortfall is calculated as the difference between the cost price of the technique that reduces the CO_2 (the 'base amount') and the market value of the product giving rise to the technique (the 'correction amount'). The base amount is fixed for the entire duration of the subsidy, and the correction amount is determined annually. If the market value rises, the operating shortfall decreases, thus decreasing the subsidy as well. Phased tender rounds also drive the subsidy costs, with technologies such as CCUS separated into separate pools, to stimulate market parties to submit project bids for a lower price.

Governments could use tax incentives to address the financial viability of CCUS, most likely as tax credits to CCUS or BECCS plant operators, enabling businesses to receive emissions credits on their tax statements. This could be applied in euros per tonne of CO_2 captured, to take advantage of a wide range of sectors which could capture CO_2. In addition, governments could also consider tax incentives for the initial capital investment in the CO_2 capture plant. A prominent example of a national CCUS tax credit is the USA's Section 45Q Tax Credit for Carbon Dioxide Sequestration. As shown in Figure 16, the value of the 45Q credit varies under different cases whether the CO_2 is utilised or stored in permanent geological storage.

Figure 16: Overview of the USA's 45Q tax credit [32]

TYPE OF CO_2 STORAGE/USE	MINIMUM SIZE OF ELIGIBLE CARBON CAPTURE PLANT BY SIZE ($KtCO_2$/YR)			RELEVANT LEVEL OF TAX CREDIT GIVEN IN OPERATIONAL YEAR (USD/tCO_2)									
	POWER PLANT	OTHER INDUSTRIAL FACILITY	DIRECT AIR CAPTURE	2018	2019	2020	2021	2022	2023	2024	2025	2026	LATER
DEDICATED GEOLOGICAL STORAGE	500	100	100	28	31	34	36	39	42	45	47	50	
STORAGE VIA EOR	500	100	100	17	19	22	24	26	28	31	33	35	INDEX LINKED
OTHER UTILISATION PROCESSES*	25	25	25	17	19	22	24	26	28	31	33	35	

Supporting CCUS growth with supplementary actions

The previous sections highlight some of the more prominent proposed or currently implemented policies and government support mechanisms for supporting CCUS and BECCS. However, this was not an exhaustive list and other enabling actions include:

- Regulatory measures to manage the CO_2 transport and storage networks, particularly for offshore domestic storage and linkages with international shipping.
- Programmes to encourage technology development and innovation as well as developing the skills necessary to support the CCUS supply chain in Ireland.
- Procurement mechanisms to support the production of low-carbon goods (e.g. cement production).
- Carbon border tax adjustments to maintain industrial competitiveness by accounting for the price of manufactured goods produced in countries or regions with less stringent carbon pricing policies.

If Ireland determines CCUS or BECCS, or both, to be of strategic importance for reaching net zero, it is likely that a mix of policy measures could ensure development keeps pace with emissions reduction targets.

5 Summary and next steps

5.1 Key findings

This study identified several key findings on the potential for CCUS and BECCS in Ireland:

- **Carbon capture, utilisation and storage (CCUS) is a critical decarbonisation option for industrial sectors with process emissions** that cannot be abated via low-carbon fuel switching, most notably the cement and lime sectors in Ireland. While more limited in scale, CCUS can also play a role in other sectors using fossil or waste fuels such as refining, food and drink, and wood products.
- **CO_2 transport and storage infrastructure is at early stages of development in Ireland** compared to other European countries (e.g. United Kingdom, Norway, Netherlands). Further investigation is required into both domestic and international CO_2 shipping opportunities. This study has identified the potential for international CO_2 shipping to be available before any domestic CO_2 storage development begins.
- **Advanced planning on the role of CCUS and bioenergy with carbon capture and storage** (BECCS) in Ireland, particularly around clustering of sites and infrastructure, is needed if policy seeks to encourage deployment of the technology. This can provide confidence to infrastructure developers about the scale of CO_2 volumes to be transported and to aid the development of business models for long-term operation. As it is likely the late 2020s will be the earliest opportunity for CO_2 shipping exports, early investigations could focus on the development of port infrastructure and supporting regulatory frameworks.
- **CCU routes have high uncertainty in relation to their techno-economics and deployment** timeframes; however, there may be viable CCU options for Ireland to reduce emissions in the cement sector or transition to synthetic fuel production in the existing refining sector.
- **BECCS is not limited to large-scale power generation in Ireland.** Opportunities for BECCS exist in both the industrial (primarily cement sites) and energy-from-waste (EfW) sectors which can achieve considerable scales of negative emissions in high-deployment scenarios (approximately 1 $MtCO_2$/y).
- **In a high-deployment scenario, CCUS could abate nearly 17 $MtCO_2$/y**, including up to 9 $MtCO_2$/y of negative emissions potential from BECCS. Of this potential, the largest industrial and power sites are likely most suitable for CCUS given the economies of scale achievable for both CO_2 capture at individual sites and CO_2 transport and storage infrastructure.
- **Future scenarios with lower amounts of BECCS would need either increased negative emissions** from other technologies (land-based solutions or engineered removals), or higher levels of effort in other economy sectors to reach the same levels of net emissions.

5.2 Potential next steps for developing CCUS in Ireland

In this section we describe some potential next steps and actions that can support the deployment scenarios presented in this work and to support the deployment of CCUS and BECCS in Ireland.

Develop a plan for offshore CO_2 transport and storage

Uncertainty exists around the route and timing for development of offshore CO_2 transport and storage in Ireland. Further engagement with stakeholders in Ireland investigating the options for domestic offshore storage or international CO_2 shipping will be crucial to understand the most cost-effective and feasible pathway forward for Ireland's downstream management of CO_2. Irish policy could lead further detailed work to investigate the CO_2 unit costs (i.e. €/tCO_2) required for interregional and international CO_2 shipping. Development of CO_2 shipping infrastructure could accelerate the deployment of CCUS ahead of domestic offshore CO_2 transport and storage to the Kinsale gas field. With a holistic plan in place, this would provide greater certainty on the timeframes for infrastructure deployment, which can help reduce the costs and speed deployment of CCUS.

Drive full-scale projects in core CCUS sectors

Closing the financial viability gap of CCUS could be achieved by utilising tools such as direct capital funding for CO_2 capture (possibly matched by the private sector) or funds geared towards investments in transport and storage infrastructure. Regulation and fiscal tools may also have a role. The Irish cement sector is a potential candidate for the Government to consider focusing CCUS early development activities on. Refining and energy-from-waste plants in the power sector may also provide promising options. With an array of CCUS demonstration projects currently underway across Europe in the industrial and power sectors, the private and public sector in Ireland could seek to work together to leverage key technologies and learnings into full-scale projects or similar demonstration/pilot projects.

Develop CO_2 transport and storage infrastructure in clusters

This work has shown that Ireland has the potential to develop several CO_2 transport and storage clusters, typically associated with shoreline terminal access and the congregation of nearby larger emissions sources. For example, the UK has geared substantial focus of CCUS support towards planning, sequencing and developing industrial clusters [33] (including power BECCS and hydrogen generation via gasification which may utilise CO_2 infrastructure). Similar to the UK and EU, the Irish Government could begin strategic initiatives geared towards identifying the most likely clusters to support early deployment of CCUS and BECCS to drive economies of scale in infrastructure deployment in the medium to long term.

Facilitate connections between CO_2 sources and sinks

The potential to decarbonise industrial and power CO_2 sources with CCUS hinges on the ability to coordinate the downstream transport and storage of captured CO_2. Irish policy can play the important role of facilitator between CO_2 sources (i.e. industrial/power sites with CO_2 capture) and CO_2 sinks (i.e. infrastructure developers, both domestically and internationally). Creating alliances with companies and private developers to explore the full value chain of CCUS integration is a fundamental building block of this. By engaging with stakeholders exploring CCUS and BECCS, the Irish Government could facilitate different regional cluster-based or dispersed site projects to progress development of investment decisions and ensure alignment of timeframes for infrastructure deployment.

Investigate the potential of CCU routes in greater depth

This study provides a high-level investigation into the potential for CCU in Ireland, focusing on two key opportunities: CO_2 curing for concrete production in the cement sector and synthetic fuel production in the refining sector. Both these technologies (and other CCU options more broadly) greatly vary in their commercialisation and technology readiness level. Follow-on studies and research on the technical and economic barriers, emissions mitigation potential, and policy options, for CCU routes are required to understand the value to Ireland. For example, Ireland could investigate the prospects for CO_2 captured from biogas processing facilities and its potential utilisation in smaller-scale applications. Ireland could complete this in tandem with further planning and support for the wider economy adoption of CCUS and BECCS, given the inherent linkages between all three technologies (e.g. sharing transport infrastructure, overlapping policy incentives, etc.).

Glossary

Term / Acronym	Description
BECCS	Bioenergy with carbon capture and storage
Capex	Capital costs
CCGT	Combined cycle gas turbines
CCUS	Carbon capture, utilisation and storage (CCS or CCU used where a specific discussion or project name does not focus on broader CCUS deployment)
CfD	Contract for difference (low-carbon subsidies in the UK used for power generation and proposed for industrial CCUS)
EfW	Energy from waste (plants which incinerate waste and generate electricity)
ETS	Emissions Trading Scheme (regarding the EU Emissions Trading Scheme)
GGR	Greenhouse gas removal (typically referring to technologies which sequester carbon from the atmosphere with the potential for negative emissions)
$MtCO_2/y$	Megatonnes of CO_2 per annum
Opex	Operational costs (non-fuel)
T&S	Transport and storage (typically regarding CO_2 infrastructure)

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