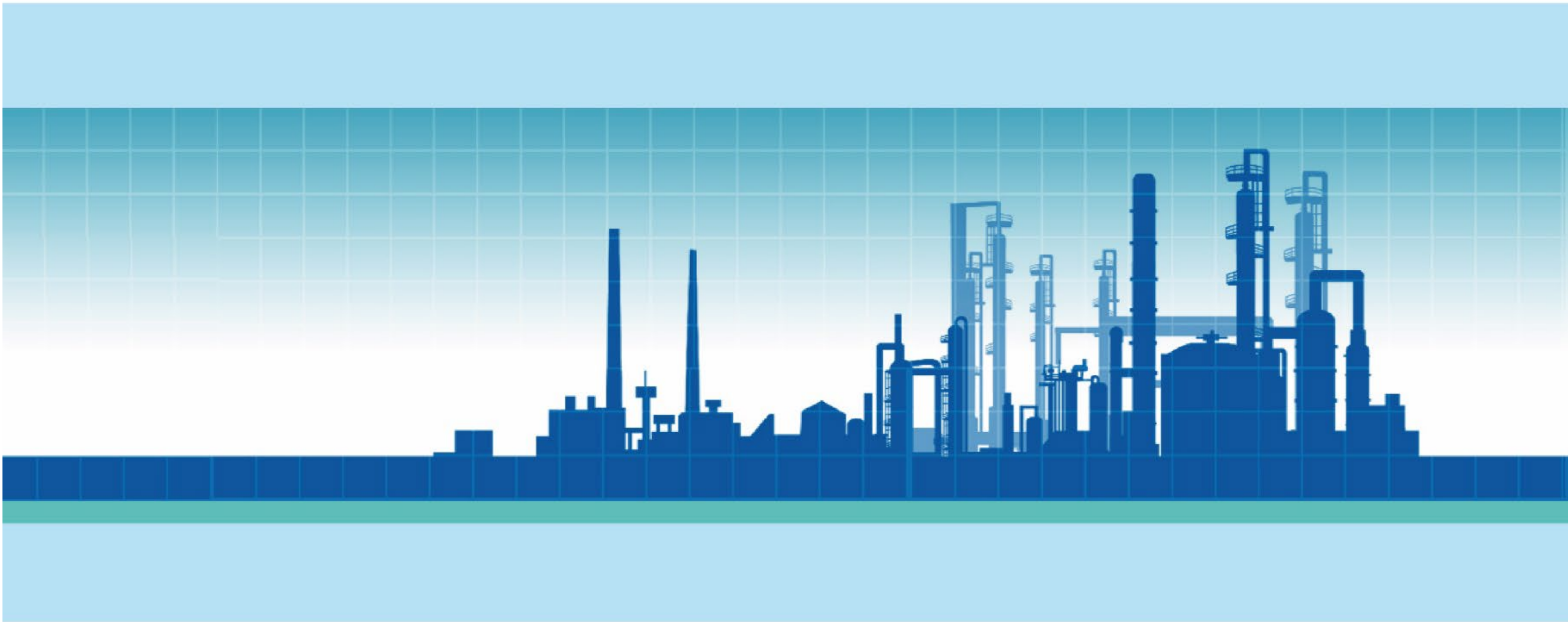
REALISE CCUS

Call ID: LC-SC3-NZE-5-2019-2020

Demonstrating a Refinery-adapted cluster-integrated strategy
to enable full-chain CCUS implementation - REALISE

D3.9 Synthesis report on full CCUS chain assessment for the CORK cluster

Ragnhild Skagestad (SINTEF), Kristian Aas (SINTEF)



18-10-2023

Dissemination Level (Public)

@realise-ccus | www.realiseccus.eu

Document History

Revision History

This document has been through the following revisions:

Version No.	Revision Date	Brief Summary of Changes	Name
Draft V1	13.10.2023	First version of report	Ragnhild Skagestad
Draft V2	15.10.2023	Second version of the report	Des McCabe
Final V3	18.10.2023	Final draft version of the report	Ragnhild Skagestad

Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP Leader or QA	Des McCabe	Des McCabe	18.10.2023
Project Coordinator	Inna Kim	Inna Kim	19.10.2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 884266

Disclaimer

1 Executive summary

The refining industry is a highly energy intensive sector, with direct CO_2 emissions typically ranging from 100 to 200 kg CO_2/tonne crude oil, requiring urgent solutions for reducing CO_2 emissions. REALISE (Demonstrating a **Re**finery-**A**dapted C**l**uster-**I**ntegrated **S**trategy to **E**nable Full-Chain CCUS Implementation) is a three and a half -year research project funded by the European Union's Horizon 2020 program. It commenced in May 2020 and was completed at the end of October 2023.The REALISE project targeted this sector by enabling integration of CO_2 capture in current refineries, for rapid implementation of CCUS to the oil refinery sector.

The overall objective of REALISE was to develop a refinery-centred sector-coupling strategy to enable full-chain CCUS implementation, by demonstrating technologies to lower the cost of CO_2 capture by at least 30% and increase the overall rate of CO2 capture to 90% by solving technical barriers, as well as developing recommendations for policy and regulatory changes to overcome societal, political, and socio-economic barriers.

This synthesis report presents, at a high level, the results and conclusions of a full chain assessment of CCUS at a cluster refinery in Cork Ireland including two power generation plants BGE Whitegate Powerplant, the ESB Aghada Powerplant and Irving Oil Whitegate Refinery. The overarching objective was to undertake a real-world assessment of the potential for CCUS at this cluster and the implications for capturing, transporting utilising, and storing CO_2 from the oil refinery.

Key sub-objectives of the work included.

- The assessment of the economically feasible percentage of carbon capture at an oil refinery.
- A review of the potential process implications of post combustion carbon capture from stacks.
- An assessment of plot size for CC plant, source of associated utilities and auxiliaries for reference locations.
- An impact assessment of the potential cost and operational efficiencies achievable from cluster approach.
- Build an open access simulation tool that can be used to design CO_2 capture units for refineries of different complexities.
- A review of the transportation, utilisation and storage options required for industrial clusters.
- An assessment of the appropriate storage options for the identified CCUS cluster
- A high-level assessment of societal and refinery readiness for a full chain CCUS cluster at Cork

The REALISE project team examined a scenario of post combustion carbon capture from the three largest industrial emitters in the Cork area, consisting of two natural gas fired power plants and the refinery, where they are treated as a carbon capture cluster.

The Cork cluster; with these three major emitters operating within a small geographical radius; offers a creditable potential for a cost effective CCUS Project. Their combined annual emissions are in the order of 2.48 MT with the refinery emitting approximately 0.32 MT.

The potential development of the cluster was assessed including capture at the refinery using amine-based absorption technology, utilising the options for CO_2 export and/or indigenous permanent storage while sharing common CO_2 transport infrastructure, and the potential for ancillary services.

Several studies assessed the technical and economic aspects of capture at the refinery. Using the Aspen Plus V11.0 HS3 model developed within WP1 as the modelling tool, the integration technical study concluded that:

- a single-absorber configuration was preferential for the refinery, given the flowrates and composition of the stacks to be treated.
- regarding the impact on energy integration for capturing CO2, thermal coupling between hot flue gas and water can provide a significant portion of the steam needed for solvent regeneration.
- Dedicated heat recovery for each of the stacks to be treated in the capture plant was recommended in terms of total costs reduction.
- An integrated capture approach can achieve similar CO2 capture rates, electricity output, and slightly lower steam consumption, with reduced investment costs.

Another important contribution from the Project on the topic of integration was the development of an open access capture tool, The OCTOPUS tool (**O**nline **C**alculator **T**o **O**ptimise CO_2 capture **P**rocesses for m**U**ltiple **S**tacks) is a web-based open access application (https://octopus.sensorlab.tno.nl/), The tool is designed in such a way that it is user friendly and is able to give high-level design and cost estimations for carbon capture processes within a few clicks, using relevant process data from the user. The tool is additionally able to evaluate the integration of multiple process stacks into a single carbon capture process.

A separate techno-economic assessment (TEA) of capture at the refinery estimated the CO_2 capture cost from using the benchmark MEA solvent in the region of 78-82 €/t and for the new solvent HS3 around 93 €/t. It must be stressed however that since the HS3 solvent is not fully commercialised at the time of performing this study it is not possible to obtain a reliable vendor price quotation so the price assumption made for HS3 is extremely conservative.

The potential OPEX savings of nonlinear model-based predictive control (NMPC) was evaluated with respect to optimized control against lowest possible steam use at any given time and against intensifying capture rates when energy prices are lower and vice versa. The calculated payback time of using NMPC in each individual scenario was evaluated to range from 4 to 25 weeks.

The use of plastics as material for elements of the columns and for the packings for the column was compared to the conventional use of metal. For the columns, metal was still the lowest cost material to use, whereas plastics had the lowest cost for the packing.

Following this comprehensive review of capture at the refinery the focus turned to the design options for conditioning and compression, transportation and storage. Detailed design studies including detailed PFDs from emitter to storage were completed taking into account pressure, flexibility and injection technical criteria. The Cork cluster offered a creditable potential for a cost effective CCUS project by sharing common CO_2 transport infrastructure.

Regarding transportation possibilities, the study recommends extending the existing jetty at the oil refinery for CO_2 export to Norway, due to cost-effectiveness and proximity to the water. Repurposing existing pipelines and offshore infrastructure is limited.

The indigenous storage section of the study established that the KHGF has a total storage capacity of up to 300 Mt. The Cork cluster based on this study would involve injecting about

2.2 Mt/p.a. over 25 years equal to 55 Mt in the base case scenario. Therefore, there is significant flexibility to accommodate CO_2 from other emitters in Ireland or elsewhere.

However permanent indigenous storage as an option is much more complex to develop whereas the export option is much easier to implement when considering a single CCUS cluster in Cork.

On the other hand, the cost-benefit analysis favoured indigenous storage over export, with lower cost per tonne of CO_2 abatement. The levelised cost of abatement in the Indigenous Storage case was estimated at €84 per tonne of CO_2 captured for the power plants. For the export case the levelised cost of abatement was €113 per tonne of CO_2 captured.

The utilisation study reviewed the Irish CO2 market, identified current demand and supply and explored potential new CCU markets such as building materials, polymers, and methanol. It concluded that there is currently no significant demand for CO_2 in Ireland (only 45,000 tonnes per annum) and so therefore a new source of captured CO_2 would not significantly impact market prices in Ireland. It was noted that the new CCU markets did not currently exist in Ireland.

A study on societal acceptance and refinery readiness for Ireland was carried out based on literature review of previous CCS projects and the development of a refinery readiness indicator. It concluded that the successful execution of a CCS project requires a robust and effective risk management process that includes socio-political risk. Incorporating lessons learnt from previous experience coupled with robust risk management processes is critical to ensuring projects proceed successfully.

The most important socio-political barriers included public resistance, policy uncertainty and lack of regulation and infrastructure.

In summary, the studies carried out in this full chain analysis provided a significant contribution in terms of improving our understanding and knowledge of the technical and economic challenges of implementing CCUS to a refinery as part of a cluster. It emphasized the potential for cost-effective CCUS in the Cork cluster, with a focus on solvent selection, the benefits of integration of the capture facility, transport options, storage, and economic considerations including cost saving opportunities across the chain.

2 Table of Contents

3 Project Outline

3.1 Carbon Capture Utilisation and Storage

CCUS is being assessed for utilisation in Ireland as part of the overall goal to move Ireland towards a cleaner energy future by reducing CO_2 emissions from the electricity, heating, industry, agriculture, and transport sectors.

This study is focused on the feasibility of developing a CCUS project located in the lower Cork harbour area, serving two large Combined Cycle Gas Turbine (CCGT) power generation plants and the Irving Oil Whitegate refinery.

Cork is the second largest city of Ireland with a population more than 300,000. It is planned that this Cork cluster could be expanded over time to bring in other industries located in the greater Cork area. The city is contained within the county of Cork which has a population of just over 540,000, an area of 7,500 km² and contains Cork Harbour, the second largest natural harbour in the world after Sydney, Australia.

Other industrial clusters in Dublin (the capital city), Limerick (the third city) and Drogheda (port town with a large Liquefied Petroleum Gas (LPG) shipping facility and cement plant) are also either under consideration or could be considered in the future.

The focus of the Cork CCUS project is to utilise the depleted Kinsale Head Gas Field (KHGF) as a long-term storage facility, coupled with marine infrastructure that would facilitate the transportation of CO_2 to other long-term below ground storage facilities in Europe.

3.2 About REALISE

As part of the CCUS development process, the REALISE (Demonstrating a Refinery-Adapted Cluster-Integrated Strategy to Enable Full-Chain CCUS Implementation) project will develop carbon capture, utilisation and storage strategies for oil refineries centred in industrial clusters and demonstrate in a pilot scale an absorption technology based on novel solvent for cost-efficient and environmentally sustainable CO_2 capture from multiple flue gas sources.

REALISE further addresses the full CCUS chain including CO_2 transport, storage and utilisation options for the specific business cases to be developed in the project for Ireland, South Korea and China, as well as assessment of the financial, political and regulatory barriers and opportunities in these countries.

3.3 Description of the Deliverable and Purpose

The purpose of this deliverable is to consolidate the results of the Cork refinery cluster case including capture, utilisation, transport, storage and societal readiness for the Cork cluster.

This synthesis report is a summary assessment of the various considerations associated with CO_2 capture at the Irving Oil refinery, drawing from the detailed reports under Work package 3 in the project. It summarizes, in one coherent report, the major findings and conclusions reported. The basis for the synthesis report are the following individual assessments that are contained in deliverables:

- D3.1 Cluster transportation of CO_2 and storage assessment.
- D3.2 Integration of CO_2 capture plant in refineries.
- D3.3 Techno Economical Assessment (TEA) of CO_2 capture from Irving Oil Refinery
- D3.4 Carbon Dioxide (CO_2) Utilisation Assessment.
- D3.5 Assessment of injection profile and infrastructure requirements to control & monitor of transportation pipelines and intermediate storage vessels.
- D3.6 Assessment of options to provide flexibility in the design and operation of transport and storage network.
- D3.7 High Level schematics (process flow diagrams) from Emitter to Storage
- D3.8 Open access CO_2 capture tool for refineries
- D4.3 Analysis of socio-political considerations of CCS

Report D3.1 and D3.4 are project internal reports, and not publicly available.

4 Cork CCUS chain introduction

4.1 Introduction

This chapter provides background information to the full chain assessment, beginning with an introduction to the Cork cluster and then moving on to describe the CO2 capture technology, CO2 transport routes, CO2 utilisation potential and CO2 storage options to be assessed.

4.2 The Cork cluster

There are several reasons why the Cork cluster has been chosen as one of the main clusters in this project. From an Irish (and European) perspective, the Cork cluster combines 4 key aspects to be considered as a potential region to accommodate a CCUS project:

1. The city of Cork is surrounded by several industry plants either in the pharmaceutical, distilleries or in the food ingredients sectors. However, the main emissions of carbon in Cork come from the two power generation plants BGE Whitegate Powerplant, the ESB Aghada Powerplant and the Whitegate oil refinery.
2. The city is located on Cork Harbour, served by the large Port of Cork and the nearby ports of Cobh and Ringaskiddy.
3. The area is very well served by all main infrastructure and the pipeline network is widely developed.
4. The depleted Kinsale Head **Gas Field** (**KHGF**) may potentially serve as a long-term storage facility and is located within 50 kms of the oil refinery and power plant cluster. At time of writing the field is being decommissioned.

As this area has numerous CO_2 emitters, it could have been a very large cluster with several industries. The project has decided that only the largest emitters should be included, and three sources have been chosen and presented below:

Table 1 Emitter details and CO_2 emissions per year

Site / Location	Sector	Owner/Operator	Capacity (MWe)	CO_2 Emissions (Mt/y) As per C02 Cork cluster proposed annual production base case scenario
Whitegate Refinery	Oil Refining	Irving Oil	N/A	.32
Aghada CCGT	Power Generation	ESB	430	1.08
Whitegate CCGT	Power Generation	BGE	450	1.08

An overview of the location of the sources are presented in figure 1:

Figure 1 Overhead view of the Cork industrial cluster

A description of the sources is presented below:

- Whitegate Oil Refinery
Irving Oil is a privately owned, Canadian energy company founded in 1924 with a history of long-term partnerships and relationships. In 2016, Irving Oil expanded operations to Ireland at the Whitegate Refinery, situated on a scenic 330-acre site on the outskirts of Whitegate village. Since opening in 1959, the Whitegate refinery has played a critical role in Ireland's energy infrastructure. With a capacity of 75,000 barrels a day, Whitegate is Ireland's sole refinery, serving commercial and wholesale customers. Ten continuous flow flue gas streams characterized by different CO_2 content, temperature and flowrate are generated at the Irving Oil Whitegate refinery site. Ten continuous flow flue gas streams characterized by different CO_2 content, temperature and flowrate are generated at the Irving Oil Whitegate refinery site.

- Aghada CCGT Power Station
Aghada power station was built in 1980s and originally worked with a capacity of 577 MW, produced in a single conventional steam turbine with a capacity of 270 MW and three 85 MW open-cycle gas turbines. A significant upgrade to the site was finalized in 2010 through the realization of a natural gas combined cycle (NGCC), which provided a new baseload generating capacity to meet rising power demand in Ireland. With a capacity of 435 MW the new NGCC unit was able to increase the total capacity of the power plant from 528 MW to 963 MW. Nowadays, the station generates enough power to meet the electricity needs of around 450,000 homes. NGCC cycle is known to significantly improve the efficiency of electric power generation with respect to the single gas and steam turbine cycles.

- Whitegate CCGT Power Station
Whitegate power station is a 445 MW combined cycle gas turbine (CCGT) electricity generating station near Whitegate in Cork in Ireland. It was built in 2010 and can supply approx. 10 % of the electricity demand in Ireland. The station comprises two 280 MW gas turbines. The gas turbines can be fired with natural gas or light distillate fuel. The turbine exhaust generates steam in the heat recovery steam generator (HRSG). Additional firing is available in the inlet duct of the HRSG, using refinery off gas or natural gas. The thermal efficiency of the station is 58.5%, making it the most efficient station in Ireland.

Cluster growth opportunities exist, including smaller industrial emitters in the Cork area and the planned Indaver Waste to Energy project in Ringaskiddy.
There is also potential for ancillary services such as hydrogen production utilising CCUS.

4.3 CO_2 Capture technology

The CO_2 capture technology that has been used in the analysis is post combustion absorption method. The solvents used have been MEA, which is well known and utilised world – wide today, and HS3 which is a new and promising solvent. There are many configurations possible, with splitting the streams as one of the possibilities.

Amine absorption is a well-known technology used for natural gas and in refineries. The technology is also used for capturing CO_2 from flue gas for use in food processing or enhanced oil recovery (EOR). Furthermore, the amine process is showed in figure 2 and described as follows:

The flue gas coming from an industrial plant is cooled in a direct-contact cooler before entering the absorption column at approximately 40°C. In the absorption column, the flue gas comes into contact with the absorbent, typically an amine-based solution. CO_2 in the flue gas reacts with the amine and exits the bottom of the column in what is called a 'rich amine solution' (rich in CO_2), while the purified flue gas exits from the top of the column via a water wash section.

The purpose of this wash is to limit amine emissions to the atmosphere. The rich amine solution is then heat-exchanged (heated) and pumped into a packed stripper column. Here, CO_2 is removed from the amine solution through further heating. The heat is supplied by a stripper boiler that typically uses 120°C steam. CO_2 released from the amine solution exits at the top of the stripper and flows on to a condenser where it is cooled to between 20 and 30°C before proceeding to a liquefaction facility. The now 'lean amine solution' (lean in CO_2) exits at the bottom of the stripper column, heat-exchanges with the rich amine solution on its way into the stripper (as mentioned above) and is further cooled to approximately 40°C before flowing back into the absorber for a new absorption cycle.

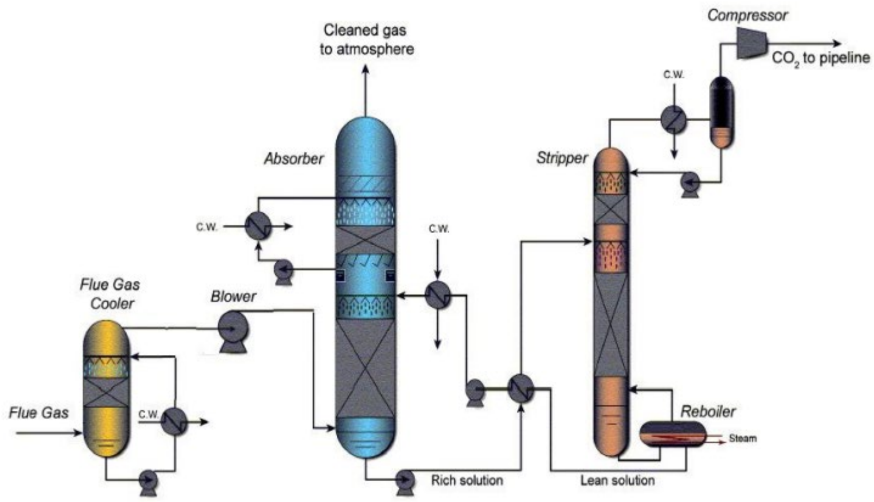


Figure 2 Overview of the amine process (Dept. Process technology, SINTEF)

Some of the key areas relating to capture technology that require assessment include:

- The optimal integration of a carbon capture plant within the refinery and as part of the cluster under consideration,
- The potential process implications of post combustion carbon capture from stacks
- The economically feasible rate of carbon capture at the refinery taking into account steam availability within the cluster.
- the available plot size, taking into account associated utilities and auxiliaries.
- A techno economic assessment of the proposed optimum carbon capture plant design – CAPEX and OPEX costs

- An impact assessment of the potential cost and operational efficiencies achievable from cluster approach
- Assessment of the most cost-effective source of utilities for cluster
- Assessment of how the application of NMPC based control system will contribute to reducing operating costs for the integrated capture plant.

- The value derived from the development and use of simulation software with technical and cost inputs to assist in deciding on an optimal capture design.
- Costs and risks associated with the technologies selected throughout the capture process.

4.4 Transport routes

CO_2 can be transported alone or through a combination of four modes; pipelines, rail, road, and waterways. Of these modes of transportation, pipelines are the most versatile, used extensively worldwide to distribute and transport oil and gas. Using roads or rail to transport CO_2 requires additional capacity planning and potential debottlenecking since these modes are also used to transport people, freight, and other types of cargo.

The transport of CO_2 through waterways, especially international waterways, has unique requirements. Planning for staged deployment of capture projects at a refinery is essential, and transport design should be considered in unison to ensure the most suitable transport design and method selected. It is likely in Europe that a combination of transport methods will be applied for refinery, and other CO_2 sources, to transport CO_2 to s suitable storage location.

The transport routes are determined based on the location of the sources and the storage options. The two main options for the Cork cluster are pipeline to an Inch terminal and then pipeline to the reservoir or pipeline/ trucks to a liquefaction and intermediate storage hub before ship transport to another CO_2 storage facility.

Some of the key areas relating to pipeline transport that require assessment include:

- The potential for repurposing existing pipelines and other appropriate infrastructure where available at the clusters to minimise cost.
- The potential for expanding the clusters with a view to determining the viable limit of a build out of infrastructure to be correlated with captured CO_2 quantities.
- CO_2 compression and conditioning technology for CO_2 lean and dense phases.
- Ship transportation is considered as a solution for longer distances and early-stage development of relevant storage sites.
- Safety related to this mode of transportation.
- Hubs for intermediate storage of collected CO_2 from various sources as well as closer to the storage site, taking into account impurities identified.
- The requirements for a jetty or dock (existing or otherwise) for the exportation of CO_2.

The pressure and temperature of the CO_2 is of importance when it comes to transport and injection as the CO_2 changes phases between liquid, solid and gas depending on the pressure /temperature. The figure below shows the phase diagram for pure CO_2 and typical conditions in pipeline and injection.

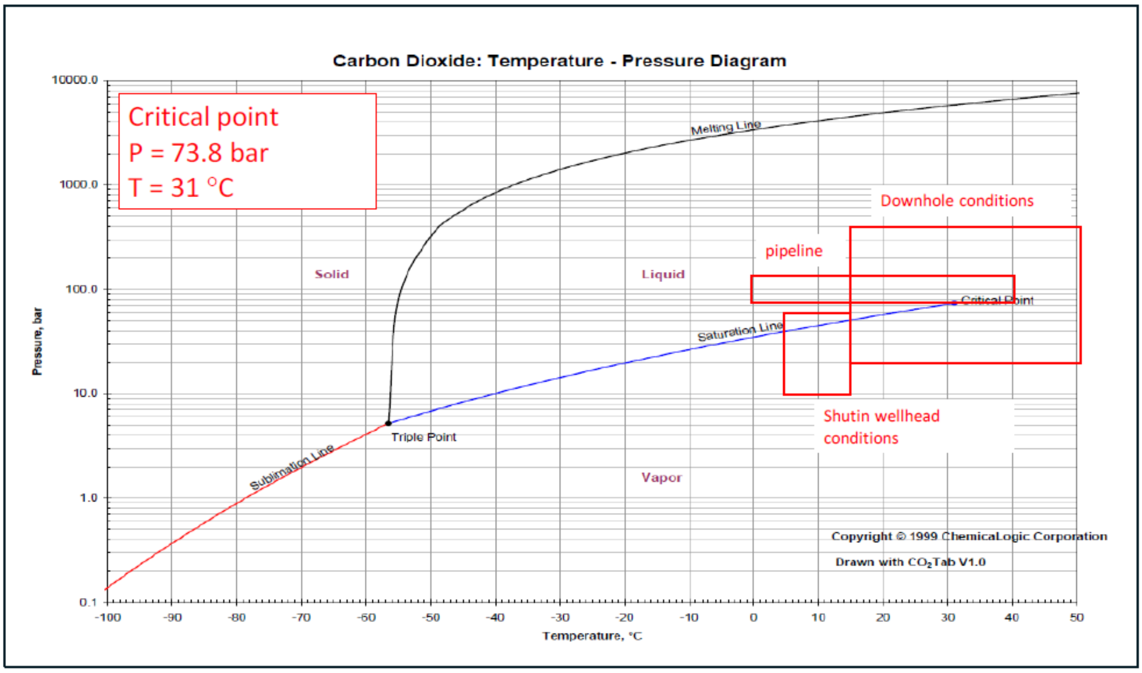


Figure 3 Typical conditions in pipeline and injection well, for pure CO_2 transported in liquid phase

The size of the different boxes represents the range of conditions throughout a typical CCUS project that injects and stores CO_2 in a depleted gas field. It is obvious that the conditions in the pipeline and wells are all close to the phase line that separates gas phase and liquid phase, and close to the critical point. This means that two-phase conditions are likely to occur in the injection wells and in the depleted reservoir. Issues related to two-phase conditions can be avoided by operating the transport and storage system with CO_2 in the gas phase. However, with a pipeline operating at about 30 bar, the system will not be able to utilise the total storage capacity in a depleted field.

4.5 Storage possibilities

There are several options for CO_2 storage, and the current **options for storage** are export or indigenous storage i.e.

I. Export: by ship to another country for injection into their geological formations,

II. Indigenous storage: injection into Ireland's geological formations.

While other options will become available in the future, for REALISE the Northern Lights Project in Norway will be considered in this study as the potential receiving faculty for the produced CO_2 for the export option (Option I).

The Kinsale Head depleted gas field will be considered for the indigenous storage option (Option ii).

Some of the key areas relating to Storage options that require assessment include:

- The potential available CO_2 permanent storage locations.
- The injection profile of the storage location and the variability of injection rates to the storage locations.
- The infrastructure requirements to control & monitor of transportation pipelines and intermediate storage vessels.

A simple schematic layout of the Cork cluster including the three emitters, transport routes and storage options is shown below in Figure 4.

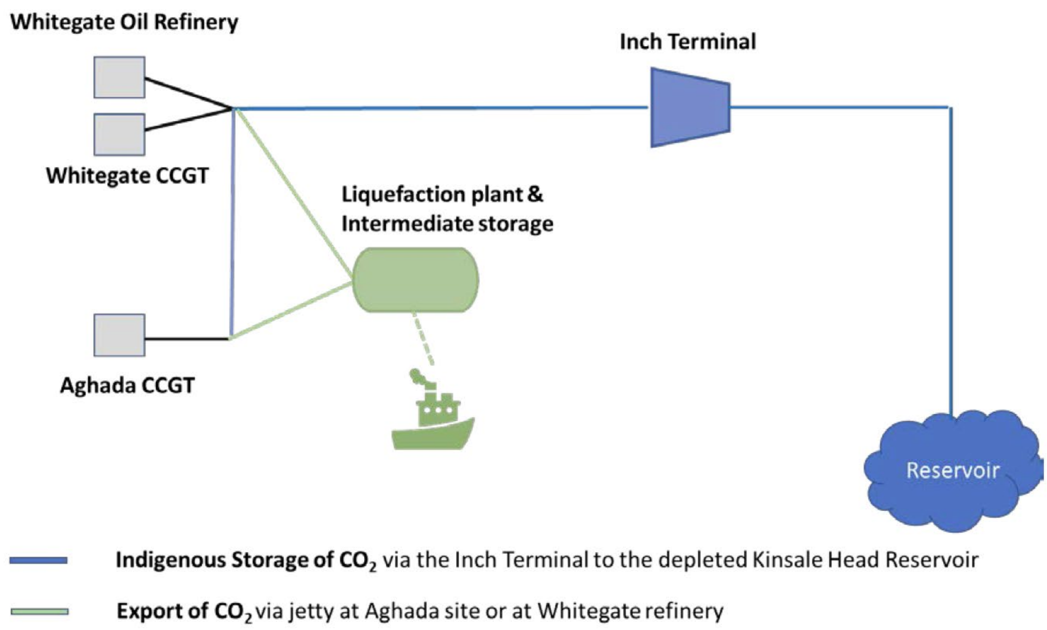


Figure 4 Schematic layout of the system

4.6 CO_2 Utilisation Assessment

An assessment of the potential market for the utilisation of CO_2 in Ireland from the identified clusters is clearly of interest and forms an integral part of the REALISE project. The study will review the existing market for captured CO_2. This will include a review of the existing producers & retailers of CO_2, current consumers of CO_2 categorised by usage type, CO_2 purity, location and quantity consumed.

In addition to this research will be into the potential to increase the demand of CO_2 by displacing other process and working gasses such as in the refrigeration and energy storage sectors.

Within this CO_2 utilisation assessment, the project team will

- Model the impact on the market that introducing a large source of CO_2 would have on the commodity price of CO_2.

- Evaluate the techno-economic impact of CO_2 utilisation in the full CCUS chain and decide to which extent (if any) utilisation should be included in the chain for each cluster.
- Research the potential for increases in CO_2 demand for alternative uses.

4.7 Socio-political risks

The CCS industry is relatively small, but several examples of socio-political risks have already caused problems during development. In this regard, an overview of both risks and framework to compile in an indicator of the readiness of refineries for the application of CCS is given. These assessments have been investigated:

- management of socio-political risks in carbon capture and storage (CCS) projects
- policy and regulatory frameworks that enable or incentivise investment in CCS.
- financing options for CCS projects
- CO_2 capture technologies specifically relevant to refineries
- barriers and policy considerations relevant to the transport and storage of CO2.

5 CO_2 capture from the sources and integration

This chapter presents the key assessments, technical and economic, that were carried out in REALISE in relation to CO_2 capture at the Irving oil refinery including;

- Integration of CO_2 capture plant at the refinery (Deliverable 3.2)
- the development of an open access CO_2 capture tool (Deliverable 3.8)
- a techno-economic assessment of the full-scale CO_2 capture plant (Deliverable 3.3)

For each assessment, the background, methodology and key conclusions will be presented in turn.

5.1 Integration of CO_2 capture at the refinery (Deliverable 3.2)

5.1.1 Assumptions and methodology

Ten continuous flow flue gas streams characterized by different CO_2 content, temperature and flowrate are generated at the Irving Oil Whitegate refinery site. Discontinuous flows were disregarded in this analysis and for simplicity, each stack is assumed to contain only of CO_2, H_2O, O_2 and N_2, while impurities such as NO_x and SO_x are present is small amounts and can be neglected for the purpose of this study.

For each of the analysed scenarios, a preliminary sizing of the main unit operations and an energy analysis were carried out. For the column diameter estimation, 70% flooding velocity was adopted as design basis. The Aspen Plus V11.0 HS3 model developed within WP1 was used as modelling tool.

For the sake of comparison of the performances of the new solvent with a benchmark, the same simulations were run using the default MEA 30 wt% model proposed by AspenTech. The study showed that a single-absorber configuration is preferential for this specific application, given the flowrates and composition of the stacks to be treated.

A detailed sensitivity analysis was proposed following a standardized methodology to define the optimal operating conditions for the CO_2 capture process in terms of CO_2 lean loading, the columns' packing heights and the stripper pressure. For consistency, the same criteria were adopted for both HS3 and the reference solvent.

5.1.2 Results

The assessment of energy integration options included both heat recovery with internal sources (refinery gas stacks available at high temperatures), and eternal utilities available within the Cork industrial cluster. This analysis demonstrated that up to 55% and 74% of the steam required for solvent regeneration when the capture plant is run with MEA and HS3, respectively, can be produced by means of a thermal coupling between the hot flue gas from the refinery and saturated water at 130°C to be vaporized for steam generation to be exploited as reboiler utility. A train of heat recovery exchangers was designed for this heat integration by means of Aspen EDR.

A preliminary costs estimate was prepared within this study to demonstrate that, despite the increase in the total investment cost, considering a dedicated heat recovery for each of the stacks to be treated in the capture plant is recommended in terms of total costs reduction, thanks to the great potential in steam requirements reduction. Remarkably, the final proposed process configuration allowed internal heat recovery to be maximised.

Two different scenarios were proposed for the remaining heat duty to meet the total energy requirements: the refinery could either generate steam onsite in burning and consuming a fuel (natural gas) or exploit part of the steam generated by one of the two NGCC power plants located at short distance from the oil treatment site. For the first scenario, the flue gas generated by the natural gas fed boiler was considered as an additional stack to be treated, to still reach a 90% overall capture rate.

A comparison between the two alternatives was presented in terms of columns and heat exchanger size as well as energy consumption. The results showed that steam integration has the potential to reduce the gas and solvent flowrates circulating in the plant, which results also in an appreciable decrease in the total duties, thus is a lower steam and cooling water requirement.

Indeed, when steam integration is accounted for, the steam demand was cut by 18% and 23% if HS3 or MEA were used as solvents, respectively. For the integrated scenario, an estimation of the corresponding decrease in the power plant electricity output production capacity due to steam spilling for the Irving Oil Whitegate capture plant was also carried out considering the ESB Aghada power station.

This analysis pointed out that steam spilling would result in a decrease in the electricity output of the steam cycle in the combined cycle power plant of only 1.52% and 0.68% when using MEA and HS3 as solvents, respectively.

Concerning the HS3 solvent assessment for the proposed application, it is remarkable that the new solvent was associated with a specific reboiler duty of only 2.98 MJ/kg CO_2 captured, when for the benchmark a corresponding value of 3.78 M/kg CO_2 was estimated when considering for both solvents the optimized configurations for the Irving Oil Whitegate CO_2 capture plant (average CO_2 initial concentration of 7.6 vol%). Moreover, the solvent flowrate required to reach the specified capture rate lowered from 1.91 to 1.47 kg per kg of treated gas.

The reduced steam demand was expected to provide a sensible cut of the plant utility costs, and, as a reflex, of the total operating costs. The only drawbacks for HS3 were the lower kinetics and the higher volatility of the tertiary amine constituent. These resulted in a higher packing height in the absorber (and stripper) to reach the same capture rate and in a higher water wash section packing needed to comply with amine emissions legislation. In turn, this also affected the electricity consumption due to the higher pressure drops to be overcome as well as the higher elevation gains to be achieved by circulation pumps. A total costs assessment was required to quantify the economic benefit obtainable with HS3 solvent.

This study also assessed different possible layouts for the design of a facility dealing with the treatment of both the Irving Oil refinery flue gas and the ESG Aghada power station flue gas. Three scenarios were proposed. See Figure 5 below:

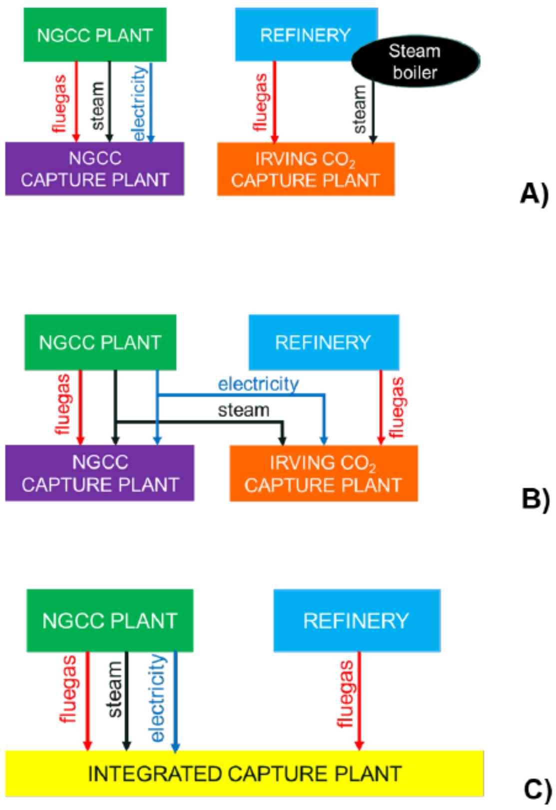


Figure 5 Schematic layout of the three scenarios

The main outcome of the comparative assessment between the separated and the integrated capture plants was that the fully integrated facility could guarantee the same overall CO_2 capture rate observed for the two separated facilities, a comparable electricity output and a slightly reduced overall steam consumption (-0.3%), but a significantly lower investment cost should be expected for the realization of one single plant. The real potential for the fully integrated scenario must be determined based on total costs and considering an assessment of flue gas and steam transport feasibility.

5.2 TEA of the full-scale CO2 capture plant (Deliverable 3.3)

5.2.1 Assumptions and methodology

A Techno-Economical Assessment (TEA)was performed where four scenarios for large-scale multi-stack CO_2 capture from the Irving Oil Whitegate refinery were defined.
A cluster of eight different CO_2 sources (flue gas stacks) were selected in the refinery from which to capture CO_2. The total yearly amount of CO2 captured may vary from 0.25 to 0.275 million metric ton per year. Two scenarios were based on the use of the benchmark solvent monoethanolamine (MEA), widely used in the CO_2 capture industry for capturing CO_2 from flue gasses. The other two scenarios were based on the new advanced amine based solvent HS3 developed by SINTEF. For all the scenarios, heat recovery was considered from the hot flue gasses to produce low pressure steam which is used as heat source for amine solvent regeneration.

The first scenario is by utilizing auxiliary natural gas fired boilers (Case A scenarios). The second scenario is the import of additional steam from an adjacent power plant (Case B scenarios). For the Case A scenarios, the flue gas from the auxiliary boiler is combined with the flue gas from the different stacks and processed in the CO_2 capture plant.

Since the heat recovery from the hot flue gasses can only supply part of the required heat for solvent regeneration, 2 external heat sources were considered to supply the remaining heat i.e., 1. a natural gas fired boiler and 2. Import steam from one of the nearby power plants. Those two configuration scenarios were considered for both solvents.

Based on the material balances for the four scenarios, the property data from the respective corresponding Aspen+ process simulations, process equipment summary sheets were prepared reflecting the key process parameters, material selection and dimensioning/sizing of the equipment.

The data from the equipment summary sheets formed the basis for the equipment costing and the costs for each piece of equipment were summarized in costing summary sheets per considered scenario. The pricing was done for the year 2023.
The Total Plant Costs for the four (4) scenarios were estimated by the so-called Enhanced Detailed Factor (EDF) method, developed by the University of South-Eastern Norway in cooperation with SINTEF Norway and updated in 2020 for use. The estimated TPC's were for the year 2023.

For each individual piece of equipment, the total installed cost or TPC was estimated based on the price of the delivered equipment cost, whereby an expensive piece of equipment got a lower installation factor than low priced equipment. Adjustments to this were based on certain plant specific construction factors.

The available plot space at Irving Oil Whitegate refinery was evaluated to be adequate to locate the equipment associated with the design.

CO_2 capture fixed operational expenditures such as labour, maintenance, insurance, and variable operational costs such as for utilities like electricity and natural gas and consumables like solvent make-up were identified.

Base prices for utilities and consumables were established for the economical assessments together. Also, the assumed plant life, yearly on-stream time and discount rate for the annualized capital expenditure calculations was defined.

Based on the resulting annualized CAPEX and OPEX costs and the yearly amount of CO2 captured for each case, the specific CO2 capture costs were determined for each scenario.

Finally, sensitivity analyses were performed on fixed capital, opex and carbon emission costs on the specific CO_2 capture costs.

5.2.2 Results

The main results of the TEA shows that the CO_2 capture cost from the MEA cases is between 78-82 €/t and for the new solvent HS3 is about 93 €/t. The CAPEX and OPEX distribution can be seen in Table 2 for the four different scenarios:

Table 2 Cost of carbon capture for the four scenarios

CO2 capture costs estimation sheet	Irving Oil Whitegate Refinery CO2 capture costs				
Capture scenario -->	MEA Case A	MEA Case B	HS3 Case A	HS3 Case B	
Fixed Capital cost (CAPEX)	**value**	**value**	**value**	**value**	**Unit**
Total Plant Cost (TPC) or Total Fixed Costs (FIC)	65,210,282.37	60,410,971.18	66,652,094.58	62,706,404.79	€
Initial amine solvent filling cost	146,880.00	132,192.00	3,870,900.00	3,453,516.00	€
Project lifetime	25	25	25	25	yr
Discount rate	8%	8%	8%	8%	%
Capital Recovery Factor (CRF)	0.09368	0.09368	0.09368	0.09368	--
Annualized Capital Cost (AAC)	**6,122,579.17**	**5,671,609.61**	**6,606,508.03**	**6,197,780.60**	€
Variable OPEX cost (VOC)	**value**	**value**	**value**	**value**	**Unit**
Total yearly electricity cost	3,877,874.32	3,486,669.33	3,375,966.15	3,226,108.69	€
Total yearly Natural gas cost	5,433,820.04	N.A.	2,464,254.69	N.A.	€
Total yearly LP steam cost	N.A.	5,493,121.92	N.A.	2,468,063.52	€
Total yearly demin water cost	35,085.96	35,085.96	30,073.68	30,073.68	€
Total yearly amine solvent cost	1,288,872.00	1,153,870.76	6,712,617.23	6,414,329.28	€
Total yearly Caustic soda cost	151,632.00	135,749.50	52,647.98	50,308.46	€
Total yearly act. carbon cost	53,071.20	47,512.33	39,803.40	38,034.66	€
Total yearly variable OPEX	**10,840,355.52**	**10,352,009.80**	**12,675,363.12**	**12,226,918.30**	€
Fixed OPEX cost (FOC)	**value**	**value**	**value**	**value**	**Unit**
Yearly maintenance cost	1,956,308.47	1,812,329.14	1,999,562.84	1,881,192.14	€
Yearly insurance cost	1,304,205.65	1,208,219.42	1,333,041.89	1,254,128.10	€
Yearly labor / supervision & overhead costs	472,500.00	472,500.00	472,500.00	472,500.00	€
					€
Total yearly fixed OPEX	**3,733,014.12**	**3,493,048.56**	**3,805,104.73**	**3,607,820.24**	€
CO2 captured	**value**	**value**	**value**	**value**	**Unit**
Hourly CO2 capture rate	31.41	28.12	29.48	28.17	MT/h
Yearly CO2 capture rate	264,597.84	236,882.88	248,339.52	237,304.08	MT/yr
Total yearly plant cost (TAC)	**20,695,948.81**	**19,516,667.96**	**23,086,975.88**	**22,032,519.14**	€
CO2 capture cost (ex working capital)	**78.22**	**82.39**	**92.97**	**92.85**	€/MT
Estimated initial working capital (10% of TPC)	6,535,716.24	6,054,316.32	7,052,299.46	6,615,992.08	€
Estimated initial working capital (15% of TPC)	**9,803,574.36**	**9,081,474.48**	**10,578,449.19**	**9,923,988.12**	€
Estimated initial working capital (20% of TPC)	13,071,432.47	12,108,632.64	14,104,598.92	13,231,984.16	€

The main and most important conclusion from this assessment is that the benchmark MEA solvent is more economic than the HS3 solvent despite the ca. 20% lower specific energy consumption for the CO_2 capture process for this new solvent. For the base case assumption that the HS3 solvent is 15 times more expense than the benchmark MEA solvent, the CO_2 capture cost for the HS3 solvent was estimated to be ca. 13-19% higher than for the MEA solvent depending on the external heat supply scenario. For the advanced HS3 solvent to be become economically competitive with MEA solvent, the cost of the solvent would need to be reduced to below 7.5 times the cost of 30wt% MEA solvent for Case A and below 10 for Case B scenario.

The scenario with the natural gas fired boilers to supply the remaining heat for the MEA solvent regeneration appeared to be more economical attractive than the steam import scenario, mainly due to carbon taxation i.e. natural gas burning inside the refinery not being taxed or penalized due to 90% CO_2 capture from that flue gas where steam import will be taxed because no CO_2 capture is considered for the export steam generation from the nearby power plant. The export steam is considered to be produced by the CCGT power plant flue gas duct burners fired by natural gas.

As part of the sensitivity analysis carried out two potential cost saving measures were evaluated

Firstly, the potential OPEX savings of nonlinear model-based predictive control (NMPC) has been evaluated with respect to optimized control against lowest possible steam use at any given time and against intensifying capture rates when energy prices are lower and vice versa. The calculated payback time of using NMPC in each individual scenario is evaluated to range from 4 to 25 weeks.

Secondly, the use of plastics as material to metal for the columns and for the packings for the column was compared to the conventional use of metal. For the columns, metal is still the lowest cost material to use, whereas plastics has the lowest cost for the packing.

5.3 Open access CO2 capture tool (Deliverable 3.8)

The OCTOPUS tool (**O**nline **C**alculator **T**o **O**ptimise CO_2 capture **P**rocesses for m**U**ltiple **S**tacks) is a web-based open access application (https://octopus.sensorlab.tno.nl/), designed for refineries, chemical clusters or other companies to perform a high-level evaluation of the feasibility of post-combustion CO_2 capture for their processes. The tool is created in close collaboration between TNO and NTNU

The tool is designed in such a way that it is user friendly and is able to give high-level design and cost estimations for carbon capture processes within a few clicks, using relevant process data from the user. The tool is additionally able to evaluate the integration of multiple process stacks into a single carbon capture process. Integrating CO_2 capture from multiple emission sources can potentially decrease the cost of the overall process and is an interesting option for refineries and chemical clusters to consider in their approach to decarbonise their sites.

Where CO_2 capture simulations require long computational time for simulations and design and costing software normally require a lot of manual effort, this is not the case in the OCTOPUS tool. Using a simulation database instead of actual simulations and combining this with embedded sizing and cost calculations allows case studies to be worked out instantly.

For security reasons, it is required for everyone to request a username and password with TNO for usage of the tool. These credentials will have to be entered when navigating to the website.

A user manual has been provided together with the tool to give the users of the tool an introduction to the tool as well as guiding the current capabilities of the tools.

6 Transportation of CO_2 and storage

This chapter presents the key assessments, technical and economic, that were carried out in REALISE in relation to the transportation and storage of CO_2 captured at the Cork refinery cluster including;

- Cluster transportation of CO_2 and storage assessment (Deliverable 3.1)
- Assessment of options to provide such flexibility in the design and operation of the transport and storage network (Deliverable 3.6)
- Implications of injection profile on storage (Deliverable 3.5)
- High level schematics Emitter to Storage (Deliverable 3.7)

The flexibility of the systems was analysed in terms of accommodating variations in CO_2 supply, or in growth of the captured volumes to be stored.

For each assessment, the background, methodology and key conclusions will be presented in turn.

6.1 Cluster transportation of CO2 and storage assessment (Deliverable 3.1)

6.1.1 Assumptions and Methodology

The purpose of this study was to show the possibility of transportation of the captured CO_2 at the Cork cluster. The cluster allowed comparison of indigenous CO_2 storage versus export via a newly constructed jetty at the Aghada Power Plant site to ship the CO_2 to the Northern Light project in Norway.

The estimated volume of CO_2 that could be captured from the cluster of three emitters ranges from 1.61 million tonnes to 2.77 million tonnes per annum (Mtpa) under the low and high scenario respectively. The base case anticipated 2.23 Mtpa of CO_2 could be captured annually over a period of 25 years.

The base case assumed the two power plants are operated at 55% load factor while the refinery is operated at 96% load factor and all plant are fitted with post combustion carbon capture rate of 90%. The study also looked at smaller industrial emitters in the area with respect to transport of CO_2 to the cluster centre; in particular comparing cost of transport via road or pipeline.

6.1.2 Results

The study identified that the Cork cluster offers a creditable potential for a cost effective CCUS Project. The potential development of the cluster utilising the options for CO_2 export and/or indigenous permanent storage could share common CO_2 transport infrastructure, and also has potential for ancillary services. This conclusion is based on these results:

- The review of the emitter site locations and the footprint requirements for the various equipment that would be required would not be a limiting factor as each site has adequate space to install the required equipment.

- In the assessment of CO_2 compression and conditioning technology, the study concluded that centrifugal rather than traditional reciprocating or screw compressors will be required to cope with the volume of CO2. In addition, CO_2 drying, which is essential for pipeline transportation will be necessary, while most of the water content will be removed at each compression stage this will not be adequate to meet the required CO2 specification. Therefore, further drying will have to be provided by either adsorption or absorption, as well as removal of other impurities prior to transport.

- Export and interim storage require that the CO_2 to be converted from a gas to liquid form by either internal or external refrigeration loop. Prior to liquefaction and to maintain the specification for export requirements, cryogenic distillation will be required to remove Oxygen and Nitrogen to acceptable levels.

- The intermediate storage of CO2 is required as a buffer to facilitate export of CO2. Intermediate storage can also facilitate more variable production of CO2 and importation of CO2, although these have not been considered in detail in the study. The CO2 is stored in pressurised storage tanks in liquid form (dense phase) until the ship berths at the quay for the export. High pressure storage tanks are required to minimise the storage volumes.

- The indigenous storage section of the study established, that the KHGF has a total storage capacity of up to 300Mt. The Cork cluster based on this study would involve injecting circa 2.2 Mt/p.a. over 25 years equal to 55 Mt in the base case scenario. Therefore, there is significant additional capacity to accommodate CO_2 from other emitters in Ireland or elsewhere. The study has also determined that initially CO_2 be injected in gas phase. As pressure in the reservoir gradually increases over time with continuous injection, the switch to inject liquid (dense phase) CO_2 will come as the reservoir pressure rises to meet the injection pressure. It was also determined that up to three new injection wells (7-inch) would be required for injection along with the associated infrastructure.

- In considering the potential for repurposing of existing pipelines (both onshore and offshore) and other appropriate infrastructure, it can be concluded that there are limited opportunities. Most of the offshore infrastructure has been assessed and ruled out on technical limitations and cost factors. There is potential to repurpose the 24-inch diameter offshore pipeline (linking shore to reservoir) for CO_2 transport to the KHGF in gas phase only. Repurposing this 24-inch pipeline would require further examination in the event that it was to be considered for CCUS as the pipeline is shortly due to be decommissioned. In addition, there are some sections of the now redundant natural gas network which could be repurposed for CO_2 transport. The existing KHGF platforms and wells are currently being decommissioned, similarly given their age, condition and design life, offer little scope for repurposing. An overview of the KHGF platforms and wells are given below:

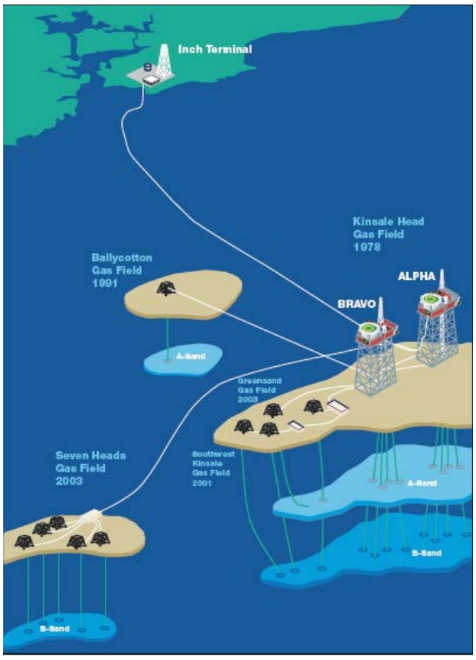


Figure 6 Diagram of KHGF and ancillary fields

- The profile of CO_2 production and injection has been examined and it is anticipated that given the increased level of renewable production expected on the Irish electricity system by 2030, this would lead to variable production of CO_2 from the power plants in the cluster. In the scenario where CO_2 is exported the capacity of interim storage is determined by the expected ship capacity, which is currently assessed to be 7,500 m3 of CO_2. This results in interim storage capacity requirement with 20% contingency to accommodate potential delays in shipping.

- Shipping requirements for the cluster were reviewed with the conclusion that the total travel time and ship size determine the frequency of the ships required to transport a given flowrate. Given the assumed size of the ship of 7,500 m3, ten vessels will be required, with a ship calling at Cork Harbour every 19 hours.

- Given the high level of ship traffic a separate jetty pier is necessary. Either a new Jetty or extension of the existing jetty will be necessary to facilitate export. The prospect of a new jetty was considered although, given the water depth in the vicinity it is likely to be located very close to where a jetty extension would be built. Also, the extension to the existing jetty pier option would be less costly than building a completely new jetty. This assumes the existing jetty causeway can accommodate the flow and return CO_2 pipeline required for ship loading.

- The cost benefit study examined both the option of developing a CO_2 storage site locally and exporting the CO_2 to a storage site in Norway each under similar range of production levels in the relevant emitter sites. It was found that the two scenarios of Export and Indigenous scenarios vary in their capital and operating costs. The outcomes for the cluster including the three largest emitters would avoid up to 2.23 Mtpa CO_2 emissions per year in the base case scenario and cost:
    - Indigenous Storage in KHGF has a total capital spend of €2.2 bn including two new Power Islands costing €0.66Bn and annual operating costs of €207M including fuel for the power plants. The levelised cost of abatement in this case is €84.10 per tonne of CO_2 captured for the power plants.
    - Export to Norway via ship and storage has a total capital spend of €1.78bn including two new Power Islands costing €0.66bn and annual operating costs of €287M for the cluster including fuel for the power plants. The levelised cost of abatement in this case is €113.40 per tonne of CO_2 captured.
    - In both scenarios higher load factors in the emitter plants will result in lower abatement costs. While the export scenario requires significantly less capital investment, the indigenous storage development is much more economical over the lifetime of the project. A key factor here is the cost of shipping and receiving CO_2 overseas.

- Expanding the cluster to smaller industrial emitters in the area was also evaluated from a transport cost perspective. It was found that in 3 of the 4 cluster cases examined that there was a significant negative difference in Capex cost compared to a small positive difference in Opex cost in constructing a pipeline versus transporting by road. However, this difference is exacerbated by the 2 largest emitters excluding the Aghada and Whitegate cluster being approximately 50 KMs north and west respectively.

- The proposed GNI biomethane facility in North Cork and Indaver incinerator in the Harbour area will add significant volumes that could change the economic case for road transport and would require reassessment upon completion. While there is a prospect of importing CO_2 into the Cork area where an indigenous store is developed, this was not examined in this work. However, it is reasonable to conclude the KHGF could accommodate further CO_2 from elsewhere in Ireland or imported CO_2.

6.2 Assessment of options to provide flexibility in the design and operation of the transport and storage network (Deliverable 3.6)

6.2.1 Methodology and assumptions

A design study was undertaken to ensure flexibility in the proposed transport and storage network. The storage capacity and feasible injection rates of a transport and storage system are determined by the properties of the pipeline, the injection wells, and the properties of the reservoir. With reservoir properties fixed, injection rates and total storage capacity can be engineered to a certain degree through the choice of operational conditions, well design and number of wells.

This study presented an outline of the systems required to transport and store CO_2 captured at two natural gas fired power plants and an oil refinery near Cork either to indigenous storage – the depleted Kinsale Head gas field – or by ship transport to the Northern Lights storage system in Norway. Systems were designed to meet the captured rates mentioned above.

The flexibility of the systems in accommodating variations in CO_2 supply, or in growth of the captured volumes to be stored was discussed. A high-level description of the systems needed to monitor and control the transport and storage of CO_2 was provided.

6.2.2 Results

The main conclusions of the study are as follows:

- If the current variability in the rate of emitted CO_2 from the power plants is a measure of future capture flow rate variations, the transport and storage must be able to accommodate flow rates between zero and the maximum rate. The onshore and offshore transport pipelines can be shut in when the capture rate is zero. Injection wells have to be shut in when the rate falls below the minimum rate for the well; depending on the well completion and the condition of the CO_2 in the system (liquid or gaseous), minimum rates can be as high as 30 kg/s (or about 1 Mtpa; gaseous phase) or 60 kg/s (about 2 Mtpa; liquid phase). Wells must be shut in at rates below their minimum rate to avoid too low temperatures and, hence, unsafe conditions. The number of wells needed to reach the targeted capture (and injection) rate is 2 in case the CO_2 is injected in gaseous phase, or 1 in case of liquid CO_2 injection.
- For a single well, flexibility in accepting variable flow rates will be limited to flow rates within its window of operation. The minimum and maximum flow rate can be engineered and made fit-for-purpose through the choice of tubing size or by setting the number of perforations. Furthermore, if CO_2 is in gaseous phase, the pressure in the transport pipeline will also influence the location of the operational window. If CO_2 is in liquid phase, this option offers little flexibility. However, in case the minimum flow rate of a well is reduced to avoid frequent shut-ins when supply rates are low, also reduce the maximum flow rate. This results in a higher well count and higher cost to meet target flow rates. An optimisation of the system was not performed, as too many currently unknown factors play a role in the definition of an optimum.
- System flexibility to accommodate higher CO_2 supply rates, as a result of, for example, import by ship, is obtained by drilling additional wells. It is noted that these new wells will similarly have a window of operation with a minimum and maximum flow rate that determines system flexibility at the well level.

- The indigenous storage section of the study established that the KHGF has a total storage capacity of up to 300 Mt. The Cork cluster based on this study would involve injecting circa 2.2 Mt/p.a. over 25 years equal to 55 Mt in the base case scenario. Therefore, there is significant flexibility to accommodate CO_2 from other emitters in Ireland or elsewhere. The study has also determined that initially CO_2 will be injected in gas phase. As pressure in the reservoir gradually increases over time with continuous injection, the switch to inject liquid (dense phase) CO_2 will come as the reservoir pressure rises to meet the injection pressure. It was also determined that up to three new injection wells (7-inch) would be required for injection along with the associated infrastructure. The intermediate storage of CO_2 is required as a buffer to facilitate export of CO_2. Intermediate storage can also facilitate more variable production of CO_2 and importation of CO_2, although these have not been considered in detail in the study.

6.3 Implications of injection profile on storage (Deliverable 3.5)

6.3.1 Methodology and assumptions

The transport of CO_2 from the capture site to the storage location is not always trivial. The particular properties of the fluid, e.g., CO_2, can result in issues regarding reliability and structural integrity as the temperature of the transported fluid can change rapidly or a phase boundary is being crossed.

This will have its influence on the design choices to be made. Also, the supply of CO_2 will not be constant in time, a feature the system must be able to accommodate.
In this study a high-level assessment of the challenges to transport the CO_2 in a safe and reliable manner was outlined.

6.3.2 Results

The main conclusions of the implications of injection profile in storage were as follows:

Injection profile (indigenous storage).

- System flexibility to accommodate higher CO_2 supply rates, as a result of, for example, import by ship, is obtained by drilling additional wells. It is noted that these new wells will similarly have a window of operation with a minimum and maximum flow rate that determines system flexibility at the well level.

- The indigenous storage section of the study established that the KHGF has a total storage capacity of up to 300 Mt. The Cork cluster based on this study would involve injecting circa 2.2 Mt/p.a. over 25 years equal to 55 Mt in the base case scenario. Therefore, there is significant flexibility to accommodate CO_2 from other emitters in Ireland or elsewhere. The study has also determined that initially CO_2 will be injected in gas phase. As pressure in the reservoir gradually increases over time with continuous injection, the switch to inject liquid (dense phase) CO_2 will come as the reservoir pressure rises to meet the injection pressure. It was also determined that up to three new injection wells (7-inch) would be required for injection along with the associated infrastructure.

- The intermediate storage of CO_2 is required as a buffer to facilitate export of CO_2. Intermediate storage can also facilitate more variable production of CO_2 and importation of CO_2, although these have not been considered in detail in the study.

Infrastructure requirements for monitoring and control.

- Infrastructure to control and monitor the transport and storage system for indigenous storage will benefit from current practice and experience in the gas transport sector. CO_2 storage projects that plan to start injection earlier than the Cork CCS project will lead the way in the development or selection of CO_2 flow meters. No barriers are foreseen in measuring, monitoring and verifying CO_2 flows onshore or on an offshore platform.

- Temporary storage for export will also benefit from early full-scale CCS projects, although the buffering of CO_2 for transport by coaster is existing and operational technology. No barriers have been identified for the scale-up required for large-scale CO_2 transport by ship.

The main premise for the basis of design, is that CO_2 is received from the capture plant output battery limit (boundary fence), where the CO_2 can be conditioned and compressed for transport by pipeline to either intermediate storage for ship transport for export or transportation to indigenous storage at a depleted gas field.

6.4 High level schematics Emitter to Storage (Deliverable 3.7)

6.4.1 Methodology and assumptions

This report looked at the high level schematics of the CCUS chain and the development of PFDs. The layout of the system can be found in Figure 4. Here the three capture locations are depicted together with the options for transport and storage.

Only two options were assessed. The storage in the indigenous field and the storage using the Northern Light location via ships. Though three cases were defined because the location of the liquefaction and intermediate stage facility, used for the CO_2 export option, could either be at the Aghada site or at Whitegate refinery there are only two cases for storage. However, for the analysis carried out in this report that difference has no significant influence on the results and therefore they are combined into one case.

6.4.2 Results

The two Process Flow Diagrams (PFDs) are also depicted in Figure 7 and Figure 8. The two options will now be dealt with separately.

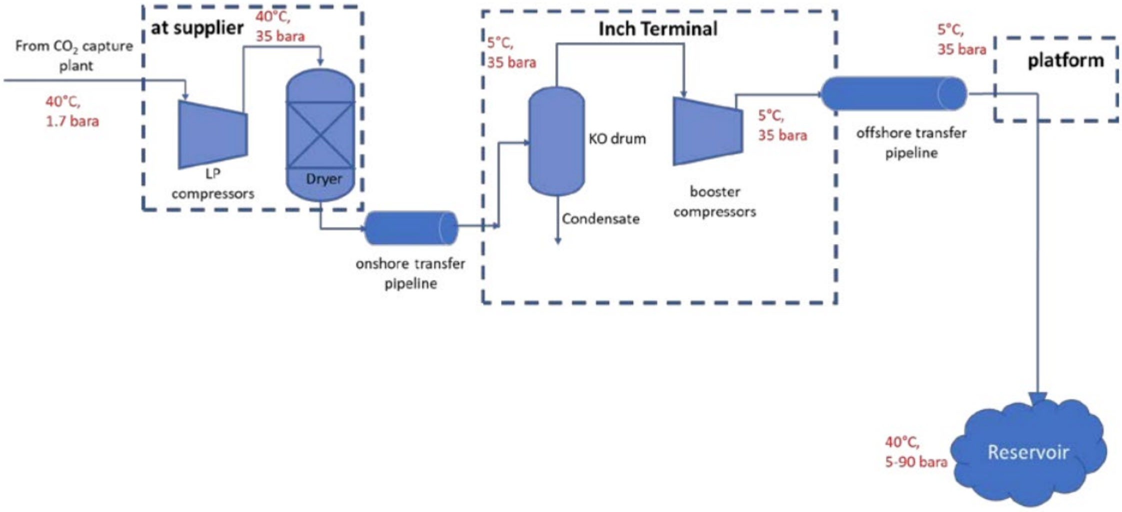


Figure 7 PFD of storage to indigenous field

In Figure 7 the option to the indigenous field is depicted. At the capture site at the supplier a low-pressure compressor is installed to raise the pressure to ~35 bar. Then after the onshore pipeline the fluid arrives at the Inch Gas Terminal where the pressure is raised again to go in the offshore pipeline which takes the CO_2 to a platform where it enters the well to the subsurface storage location.

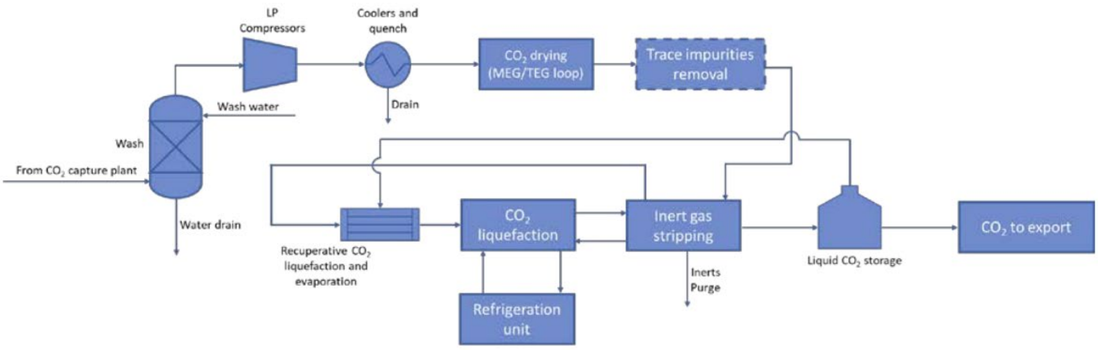


Figure 8 PFD of export option

In Figure 8 the flow diagram for the export option is depicted. Here more processes must be completed such as drying of the CO_2 and the liquefaction, and an intermediate storage facility is required to store the CO_2 before it can be transported in the ship which brings the CO_2 to its final destination.

CO_2 compression and conditioning and liquefaction technology were considered in the context of the cluster and some outline solutions developed for the cluster emitters and for the interim and permanent storage solutions. The study has also considered the CO_2 flow rates and injected profile and has determined that injection would be in gas phase until such time as pressure in the reservoir gradually increases and it would be necessary to inject in liquid phase. It was also determined that up to three new injection wells would be required for injection along with the associated infrastructure.

7 CO_2 utilisation assessment

This chapter presents the assessment carried out in REALISE WP3 in relation to the potential utilisation within Ireland of CO_2 captured at the Cork refinery cluster.

7.1 Introduction

Carbon capture and utilisation (CCU) creates the opportunity to capture emitted CO_2 and convert it for use in various products and processes. CO_2 is already utilised in several industries, either directly in the food and beverage industry or indirectly, through the manufacture of urea, a feedstock for fertilisers. However, expanding CCU, particularly through the capture of CO_2, creates opportunities to reduce the amount of CO_2 emitted through the creation of chemicals and fuels and a variety of building materials and products, some with the ability to permanently lock away CO_2. In the long term, this can support the transition to lower-emissions products and processes. For example, the development of lower-emissions fuels, particularly in industries like commercial aviation where alternatives such as batteries and hydrogen are not viable in the near-term.

In order to evaluate CO_2 utilisation in Ireland, including from the Cork cluster, this Deliverable firstly looked at the major emitters of CO_2 and the relevant clusters in Ireland, and then looked at existing demand for captured CO_2 and potential market opportunities for offsetting those emissions though utilisation of CO_2

7.2 CO_2 utilisation assessment (Deliverable 3.4)

As an alternative to permanent storage of CO_2, utilisation in different products may be a way to reuse the CO_2. A review of the Irish CO_2 market was undertaken which identified two primary categories of CO_2 users.

- Self-producers – breweries
- Importers

In the absence of published data on CO_2 demand in Ireland, primary suppliers of CO_2 (Praxair/YARA and BOC gases) were interviewed and identified the national demand for CO_2 in Ireland as being approximately 45,000t of CO_2 per annum. This equates to 2.3% of potential captured emissions from the Cork CCUS cluster.

It should be noted that because the existing market is so small and competitive, primary suppliers were not willing to share detailed customer information on the basis that it was commercially sensitive.

On the other hand, Ireland has one of the highest greenhouse gas emissions per capita in the EU, at nearly 12.5 metric tons of CO_2 equivalent per person. Ireland produced 62.11 million metric tons of CO_2 emissions in 2021.

An analysis of current CO_2 emitters was relevant in terms of assessing the potential to capture CO_2 in the future to supply potential future demand from industries not currently using CO_2. There was understandably a lot more data available on current CO_2 emitters than on the existing dedicated demand and supply of captured CO_2.

The end uses of CO_2 in Ireland range from bottling of soft drinks & beer, aerosol propellants, abattoirs and food preservation. Some of the significant points of CO_2 in relation to the existing utilisation in Ireland were that:

- CO_2 must be of food grade quality and compressed to 50bar.
- Demand is currently met by imports from the UK.
- Suppliers are actively looking for new supplies of CO_2.
- The value for CO_2 purchased ranges from €60 - €100/Tonne delivered.
- The range in prices varies on volume delivered & individual contracts.
- Large end users are conscious of the source of the CO_2.

A review of the impact of a large source of CO_2 on the existing market was undertaken and concluded that due to the relatively low cost of the existing sources of CO_2 in comparison to the higher anticipated cost of CO_2 captured from fossil fuels, that a new source of captured CO_2 coming onto the market will not lead to a reduction in the current market price for CO_2.

To assess the future potential of CCU, a high-level technology comparison study was performed. Thirteen potential CCU products from different fields of application were analysed. The products were categorized under Building materials, Chemicals, Polymers or Fuels.

In the comparative assessment, several KPI's were used to evaluate the technologies against each other. The highest weight KPI's used were economic feasibility, energy use/efficiency and lifetime of CO_2 in the product.

Especially the latter KPI is important, since most of the potential CO_2 captured will come from fossil sources, and long-term mitigation of the CO_2 is necessary to claim CO_2 avoidance. Using these KPI's the following three routes were identified as the products with the most potential: (1) Building materials, (2) polymers and (3) methanol (for chemicals).

These routes were evaluated more in detail in the report. The global potential uptake of these routes is high: a few hundred million tons for building materials, 80 million tons for methanol and 10-15 million tons for polymers. It must be noted that these industries are currently not present in Ireland.

8 Socio-political considerations and refinery readiness

The CCS industry is relatively small, but several examples of socio-political risks have already caused problems during development. Over the past ten years, at least 87 recorded cases of CCS projects were abandoned at some point between their design and construction phases. Socio-political risks played at least a contributory role in around 5% of those abandonment decisions.

This chapter emphasizes the importance of managing socio-political risks, supportive policy and regulatory frameworks, financing, and the readiness of refineries for CCS deployment in reducing CO_2 emissions from European refineries. It also underlines the role of government in facilitating the development of CCS projects and associated infrastructure.

8.1 Methodology and assumptions

Refineries are complex industrial plants with small, lesser complex plants still having many varied CO_2 emission sources. Within a refinery environment, it is essential that planning for staged deployment of capture projects is undertaken. Refineries have a range of point sources with varying costs and scales, and it is likely that these would be deployed in separate stages rather than as a single, integrated project.
this section examines how socio-political risks have been managed, successfully or otherwise, in previous CCS projects. The learnings from this review will be used as an important input to producing a practical risk assessment framework for socio-political issues in CCS projects.

Socio-political risks are considered at the broadest level, covering the three dimensions of the “triangle of social acceptance” – society in general, the market and the local community.

Potential stakeholder management learnings and best practices were reviewed in case studies of five CCS projects; Barendrecht, White Rose, Peterhead, Zerogen and Tomakomai. These projects’ experiences were explored through a brief summary of the project details and main learnings as well as common graphics to illustrate the impact of socio-political events and decisions on the project’s prospects.

The work was based on an initial literature review to produce a practical understanding and definition of socio-political risks. With that guidance on scope, the relevant issues are considered for CCS projects, firstly on the basis of general principles and then, with the help of several project case studies, using common applied themes and insights. The report concludes with a discussion of the main learnings and recommendations for managing socio-political risks for future CCS projects.

8.2 Results and conclusions

The application of CCS to European refineries can reduce annual emissions of CO_2 by many millions of tonnes. The successful execution of a CCS project requires a robust and effective risk management process that includes socio-political risk. Some early CCS projects failed as a direct consequence of ineffective management of socio-political risk.

A clear lesson from previous experience is that socio-political risks should be managed with the same rigour as all other significant risks and this management should commence at the conception of the project. This will involve including socio-political risks in the project's risk management framework and the availability of deep community engagement, social science, and external engagement expertise. Failure to do so is a failure to manage a risk that can, and has, caused the complete failure of projects, even where they were sound from a commercial or engineering perspective.

CCS is an immature industry that materially contributes to a significant public good - a stable climate. Government has a critical role in establishing the policies and regulations to create a business case for private sector investment in this critical technology. There are several examples of policies and regulations that have successfully supported CCS investments around the world that are applicable to European refineries.

There are no fundamental technical barriers to the retrofit of CCS to refineries. A range of CO_2 capture technologies to suit the variety of gas streams created by refineries is commercially available. Large gas streams with higher concentrations of CO_2, such as from hydrogen production, are lower cost and should be the first to benefit from CCS.

The transboundary movement of CO_2 by ship must comply with the specific requirements of the London Protocol. Parties to the protocol wishing to import or export CO_2 must advise the International Maritime Organisation that they will comply with those requirements. CO_2 transport also requires infrastructure such as pipelines and port facilities. Government has a role in supporting the development of this infrastructure which is essential to meeting ambitious climate targets.

The suitability or readiness of a refinery to have CCS retrofitted to the plant depends on many factors. A Refinery Readiness Indicator was developed and applied to European refineries. It is a benchmarking tool that provides an indication of how close a refinery is to being "CCS Ready" compared to other refineries. The indicator uses seven criteria, each with an appropriate weighting, to calculate the Refinery Readiness Indicator Score for each refinery. These criteria are:

1. Policy and Regulation
2. CO_2 partial pressure and total CO_2 emissions
3. Distance to geological storage resource and transport mode (ship and/or pipeline)
4. Regulations for transport of CO_2, both domestic and transboundary
5. Potential to form a CCS hub, considering other nearby CO_2 sources
6. Location Cost Factor
7. Presence of other active CCS projects in the host country

Overall, the highest-scoring refineries are large (>2Mtpa CO_2), adjacent to suitable storage and in a country with an enabling environment for CCS.
The following high-level messages are clear:

- Strong policy and regulatory frameworks create an enabling environment for CCS deployment

- The larger refineries (>2Mpta CO_2) are the highest-scoring, offering the lowest costs per tonne of CO_2

- Access to adjacent and viable storage formations promotes the highest score; however, longer distances to better storage also improve the overall result.

For the refinery in the Cork area, this is the analyse of refinery readiness level for Ireland:

Table 3 Refinery readiness level for refineries in Ireland

CCS LRI Band score	
CCS-specific legislation enacted	✓ (Due to a prohibition on CCS projects over 100 kilotonnes, there is no CCS-specific regulatory framework in place in Ireland; however, the EU CCS Directive has been transposed within domestic legislation)
Clarity and efficiency of the administrative process under the CCS legal	• Although Ireland has transposed the EU CCS Directive, its domestic legal framework does not establish a clear role amongst government agencies in relation to authorising and overseeing CCS projects. • There is currently no specific approvals process for CCS projects, as only CCS projects for the storage of CO_2 under 100 kilotonnes is allowed. • The role of project operator and regulator is not clearly defined.
Comprehensiveness of the legal framework in providing for all aspects of a CCS project	• Ireland does not possess an advanced legal and regulatory framework governing CCS activities, due to the prohibition of CCS projects over 100 kilotonnes. As such, key aspects remain unaddressed, including ownership of the subsurface, construction of CCS projects, surface access and reclamation, CO_2 leakage, monitoring and verification requirements and site closure.
Legislation addresses appropriate siting of projects and adequate Environmental Impact Assessment (EIA) processes	• There is no dedicated EIA process applicable to the capture and transport of CO_2; however, an EIA is required to be conducted for certain CO_2 capture installations pursuant to the EU Directive and that is covered by Irish planning regulations. • EIA requirements are triggered where projects are carried out in accordance with Irish planning legislation. • There are no specific mitigation or risk management requirements for CCS projects in Ireland, although approvals under general planning legislation may still be required. • There are no specific technical requirements for CCS projects in Ireland.
Stakeholder and public consultation	• There is no public engagement framework in place specifically for CCS projects. • Stakeholders have full access to the court system in Ireland to resolve disputes.
Liability - closure, monitoring and accidental releases of stored CO_2	• There is no closure regime for CCS projects in Ireland, although general provisions in relation to industrial activities are still applicable.

9 Conclusions

The purpose of the study was to examine the possibility of CCS at the Cork cluster, determine what may be included in the cluster and examine the options to store CO_2 either in an indigenous store or export to an alternate store in another country utilising pipelines or ships to transport as necessary.

The study has identified that the Cork cluster with three major emitters operating within a small geographical radius offer a creditable potential for a cost effective CCUS Project. The potential development of the cluster utilising the options for CO_2 export and/or indigenous permanent storage could share common CO_2 transport infrastructure, and also has potential for ancillary services. This conclusion has been taken based on the following:

1. The capture results focus on the assessment of energy integration options, including both heat recovery with internal sources (refinery gas stacks available at high temperatures), and eternal utilities available within the Cork industrial cluster. This work demonstrates that up to 55% and 74% of the steam required for solvent regeneration when the capture plant is run with MEA and HS3, respectively, can be produced by means of a thermal coupling between the hot flue gas from the refinery and saturated water at 130°C to be vaporized for steam generation to be exploited as reboiler utility. A train of heat recovery exchangers has been designed for this heat integration by means of Aspen EDR.
2. The main outcome of the comparative assessment between the separated and the integrated capture plants is that the fully integrated facility could guarantee the same overall CO_2 capture rate observed for the two separated facility, a comparable electricity output and a slightly reduced overall steam consumption (-0.3%), but a significantly lower investment cost should be expected for the realization of one single plant. The real potential for the fully integrated scenario must be determined based on total costs and considering an assessment of flue gas and steam transport feasibility.
3. The main and most important conclusion from this assessment is that the benchmark MEA solvent is more economic than the HS3 solvent despite the ca. 20% lower specific energy consumption for the CO_2 capture process for this new solvent. For the base case assumption that the HS3 solvent is 15 times more expense than the MEA solvent, the CO_2 capture cost for the HS3 solvent is estimated to be ca. 13-19% higher than for the MEA solvent depending on the external heat supply scenario. For the advanced HS3 solvent to be become economically competitive with MEA solvent, the cost of the solvent needs to be reduced to below 10 to 7.5 times the cost of 30wt% MEA solvent.
4. The conclusion of the Investigating in ship transport possibilities, either a new Jetty or extension of the existing jetty will be necessary to facilitate export. The prospect of a new jetty was considered although, given the water depth in the vicinity it is likely to be located very close to where a jetty extension would be built. Also, the extension to the existing jetty pier option would be less costly than building a completely new jetty. This assumes the existing jetty causeway can accommodate the flow and return CO_2 pipeline required for ship loading.

5. In considering the potential for repurposing of existing pipelines (both onshore and offshore) and other appropriate infrastructure, it can be concluded that there are limited opportunities. Most of the offshore infrastructure has been assessed and ruled out on technical limitations and cost factors.

6. The indigenous storage section of the study established that the KHGF has a total storage capacity of up to 300Mt. The Cork cluster based on this study would involve injecting circa 2.2 Mt/p.a. over 25 years equal to 55 Mt in the base case scenario. Therefore, there is significant additional capacity to accommodate CO_2 from other emitters in Ireland or elsewhere.

7. A cost benefit analysis has been undertaken for the cluster under both the indigenous storage option and the export option. It has been found that the indigenous storage option is more economical over the life of the project. The profile of investment and operating costs vary whereby the indigenous storage option has higher upfront capital expenditure and lower operating costs compared to the export option. Importantly the greater the utilisation of CO_2 injection leads to lower cost per tonne of CO_2 abatement. The levelised cost of abatement for the power stations using indigenous storage is €84.10 per tonne of CO_2 captured compared to €113.40 per tonne of CO_2 captured for the export option.

8. A review of the Irish CO_2 market was undertaken which identified two primary categories of CO_2 users. Self-producers – breweries and Importers. The end uses of CO_2 in Ireland range from bottling of soft drinks & beer, aerosol propellants, abattoirs, and food preservation.

9. To assess the future potential of CCU, a high-level technology comparison study has been performed. Thirteen potential CCU products from different fields of application are analysed. The highest weight KPI's used are economic feasibility, energy use/efficiency and lifetime of CO_2 in the product. With these KPIs the following potential new markets/products are identified: (1) Building materials, (2) polymers and (3) methanol (for chemicals).

10. A review of the impact of a large source of CO_2 concluded that due to the relatively low cost of the existing sources of CO_2 a new source of captured, relatively costly CO2 coming onto the market will not lead to a reduction in the current market price for CO_2.

10 References

[1] Brian O'Brien et al., REALISE D3.1 Cluster transportation of CO_2 and storage assessment.
[2] Matteo Gilardi, Davide Bonalumi, REALISE D 3.2. Integration of CO_2 capture plant in refineries
[3] Peter Wiers, Søren Jensen, REALISE D3.3 Techno Economical Assessment (TEA) of CO_2 capture from Irving Oil Refinery (Draft)
[4] Brian O'Brien et al., REALISE D3.4 - Carbon Dioxide (CO_2) Utilisation Assessment
[5] Paul Murphy et al., REALISE D3.5 - Assessment of injection profile and infrastructure requirements to control & monitor of transportation pipelines and intermediate storage vessels.
[6] Paul Murphy et al., REALISE D3.6 - Assessment of options to provide flexibility in the design and operation of the transport and storage network.
[7] Paul Murphy et al., REALISE D3.7 - High-level schematics (process flow diagrams) from Emitter to Storage
[8] Jasper Ros, Jan-Pieter Wijbenga , Andressa Nakao, REALISE D3.8 - The OTCOPUS tool (manual), Open access CO_2 capture tool for refineries.
[9] Matthew Loughrey et al., REALISE D4.3: Analysis of socio-political considerations of CCS.
[10] AMEC, 2015. TVU CCUS, Work pack 5-Onshore Infrastructure. Pipeline Network CO_2 Quality Specification.

11 List of Figures

12 List of Tables